"The shifting habitat mosaic in a coastal river and climate services in Indigenous communities"

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Abstract

The shifting habitat mosaic in a coastal river and
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Much of the theoretical foundation in ecology has viewed ecosystems as though they were typically in a state of equilibrium, ignoring the dynamic and complex dynamics we appreciate more today. A paradigm shift in the late 1980s increased recognition of disturbance regimes and patch dynamics as playing an important role in the ebb and flow of physical and biotic processes that generate variation in habitat conditions. A sixteen-year record of continuous habitat data provides a rare opportunity to test the Shifting Habitat Mosaic (SHM) concept, an emerging paradigm in river ecosystems where habitat patches change spatially over time in response to disturbance (e.g., flooding, erosion). I used an exceptional dataset from 65 km of a free-flowing coastal river in Elk River, OR, USA, to characterize the temporal and spatial distributions and associations between large wood, a key dominant habitat-forming feature of rivers, four fish taxa, and geomorphic features. A dynamic wood distribution and intact watershed was observed in the Elk River. A high degree of heterogeneity in wood density between adjacent reaches that varied up to 2 orders of magnitude in any year, with greater density in the tributaries and higher temporal variation in the mainstem, was observed. Wood

density varied up to 3 orders of magnitude within years and among reaches. A major flood event that occurred in 1996 had a system-level effect and homogenized the spatial distribution of wood which was most apparent at finer spatial resolutions. I then tested the SHM to determine if fish-habitat relationships were maintained despite substantial changes in the spatial distribution of habitat features. This analysis revealed that three of four fish taxa were positively associated with large wood and channel depth, a dynamic and relatively static habitat feature, respectively. Results from this study point to a need for river management to maintain disturbance regimes and support aquatic-terrestrial linkages across the river corridor that characterize dynamic components of aquatic habitat.

The status of climate services, including availability and usability, remains unexplored in the context of Tribal decision-making in the contiguous U.S. and Alaska. I conducted a national survey of tribal staff and environmental professionals to assess tribal use of climate services and critical barriers to tribal adaptation efforts. Survey respondents who identified as users of climate services shared that lack of staff time and funding were the greatest barriers to climate preparedness efforts of tribal organizations. Grants and workshops were identified as extremely valuable, and geographic domains important to tribal decision-making were ranked as extremely relevant. Across the user and provider community, short answer responses frequently commented on specific data needs, relationships, and capacity building, when asked about barriers to conducting climate preparedness activities and suggested improvement in the provisioning of climate services. As the impacts of climate change become more pronounced and disproportionately affect tribal and Indigenous communities, this study provides a first landscape view of the usability and effectiveness of climate services used by staff of tribal and non-tribal entities and can be used to refine climate services produced by the science community.

Table of Contents

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CHAPTER 1: SPATIAL AND TEMPORAL VARIATION OF LARGE WOOD IN A COASTAL RIVER

Abstract

As a habitat forming feature in rivers, large wood has been understudied due to its historic removal from waterways. Few studies have the necessary spatial and temporal resolution to assess wood dynamics in response to flood disturbance. We used an exceptional dataset from 65 km of a free-flowing coastal river in Elk River, OR, USA, to characterize large wood dynamics over a 12-year period (1989-2000). Our objectives were to assess the spatial dynamics of wood over multiple scales and characterize the changes in these patterns in response to a major flood event in November 1996. Generally, higher wood densities were in the tributaries, and higher temporal variation of density existed in the mainstem. We found a high degree of heterogeneity in wood density between adjacent reaches that varied by up to 2 orders of magnitude in any year. Within years and among reaches, wood density varied by 2 to 3 orders of magnitude across the river. Scale-dependent patterns of wood distribution were not detected at resolutions < 6 km. A large flood in 1996 flood had a system-level effect on wood levels with homogenization of wood distribution, particularly at fine spatial scales. We discuss the potential wood regime of the Elk River and describe possible links between observed patterns of large wood and recruitment, transport, and storage regimes. Our data demonstrate a dynamic wood distribution in the Elk River with a notable response to a major flood.

Keywords: large wood, wood density, spatial resolution, spatial patterns, disturbance, flood effects

Introduction

Large wood (LW) is a critical component of the habitat found in rivers and lakes, supporting various ecosystem processes and habitat structures (Harmon et al., 1986; Le Lay et al., 2013). It is particularly important for regulating many geomorphic conditions and processes in the river corridor. Specifically, LW exerts strong controls on sediment transport and deposition (Gurnell, 2013; Gurnell et al., 2002; Montgomery et al., 2003; Wohl & Scott, 2017), which affects the storage and release of organic matter and nutrients that aquatic organisms rely on for their life history needs (Bisson et al., 1987), and provides habitat cover for fishes and other aquatic organisms (Beechie & Sibley, 1997; Carlson et al., 1990; Fausch & Northcote, 1992; Reeves et al., 1993).

The widespread historic removal of LW from rivers is a serious impediment towards understanding of the natural patterns and consequences of LW in riverine ecosystems (Montgomery & Piégay, 2003; Sedell et al., 1988). Throughout the Pacific Northwest (PNW) and North America, splash damming and channel clearance (Sedell et al., 1988) had short- and long-term consequences on stream habitat. Since the 1970s and 1980s, there has been a paradigm shift in the management of LW in the river corridor (Gurnell et al., 2002). To help restore stream processes, LW is now reintroduced as a stationary habitat feature in efforts to increase habitat complexity needed to support the life history of salmon in the PNW and create secondary channels, among other targeted habitat features in stream restoration efforts.

The spatial and temporal variation in LW observed in rivers is considered to be controlled by three general processes (Wohl et al., 2019b): recruitment, transport, and storage. Despite this generic model for the essential features of the wood regime in rivers, a distinct need remains to improve the understanding of the mechanisms and rates of delivery and redistribution of LW in historical and contemporary wood regimes. The natural wood regime and the natural flow and sediment regimes are the fundamental physical processes that underlie river science and management (Wohl et al., 2019b).

Recruitment of instream wood to rivers responds to a variety of chronic and episodic processes (Reeves et al., 2003) that are modified by the composition of standing forest and land use and management (Benda & Sias, 2003; Iroumé et al., 2010). In a coastal Oregon stream, 54% of estimated wood volume came from the riparian areas along the stream and 46% came from upslope sources (Reeves et al., 2003). Chronic processes, including tree mortality and bank undercutting, add relatively small amounts of wood at frequent intervals. Less frequent, episodic events, such as extreme floods, snow avalanches, and windthrow can add large amounts of wood over extended time scales (Harmon et al., 1986; Lienkaemper & Swanson, 1987). In coastal Washington, stand-replacing fires with a 500-year recurrence interval may provide an LW supply for up to 50 years after tree fall (Benda et al., 1998).

The fate of LW in rivers is dependent on the flow regime, channel morphology, and wood dimensions (Kramer & Wohl, 2017; Ruiz-Villanueva et al., 2016). Wood transport may be influenced by channel-floodplain connectivity (Wohl et al., 2018; Wohl et al., 2019a), i.e., flood events that can substantially impact transport (Millington & Sear, 2007; Wohl et al., 2019b), and the size of LW relative to bankfull width or other physical stream attributes (Bilby, 1984; Lienkaemper & Swanson, 1987).

Slow decomposition rates of instream wood make it a long-term component of river ecosystems, lasting anywhere from less than a year to more than 10,000 years if it becomes buried or otherwise trapped within the river (Wohl et al., 2019b). Submerged instream wood in the PNW decomposes at roughly 2-3% per year, depending on the species (Benda et al., 2003;

Bilby et al., 1999). The residence time of wood can last 20-220 years in the PNW and Southeast Alaska (Hyatt & Naiman, 2001), and more than 80 years for smaller streams in Oregon and 12 years for larger streams (Lienkaemper & Swanson, 1987). The magnitude, duration, and mode of LW storage have received more attention than the recruitment and transport of LW (Wohl et al., 2019b).

A need exists to understand the spatial and temporal patterns of LW distribution across rivers and how these patterns fit into the broader scheme of spatial heterogeneity in stream ecosystems. The lack of long-term observations of LW dynamics across and between networks in different geographies has hampered the ability to refine the understanding of LW (Swanson et al., 2020). Further, there are more studies of individual pieces of large wood and there is a lack of studies that incorporate a census of wood counts. Disturbances that affect ecological processes and environmental conditions can affect different levels and systems within streams, where the response to disturbance may vary across individuals and populations depending on impact (Reeves et al., 1993). Disturbance regimes and habitat heterogeneity play an important role in maintaining and stabilizing populations and life history diversity in ecosystems (Schindler et al., 2015).

In this study, we use an exceptional dataset from 65 km of a free-flowing coastal river to characterize LW dynamics over a 12-year period. Our objectives were twofold: (1) assess the spatial dynamics of LW over multiple spatial scales in a coastal river and (2) characterize the temporal variation of these patterns in response to an extreme flood disturbance. Often, habitat data are spatially discontinuous or short-term, limiting the opportunity to analyze the effects of disturbances because they are expressed at multiple spatial and temporal scales. This dataset offers deep insight into the patch dynamics of habitat conditions, increasing understanding of the implications of disturbance on LW dynamics in rivers, which are critical for developing stream restoration and forest management practices in the river corridor.

Methods

Study Area

The Elk River Basin is in southern coastal Oregon (Fig. 1). The basin is approximately 240 km^2 with headwaters in the Grassy Knob Wilderness and Copper-Salmon Wilderness Areas in the Klamath Mountains physiographic province (Burnett, 2001; Franklin & Dyrness, 1988). It discharges into the Pacific Ocean between the towns of Port Orford and Cape Blanco, OR (42°5' N latitude and 124°3' W longitude; Fig. 1). The average annual precipitation is 260 cm with a temperate maritime climate and moderate year-round temperatures. The maximum elevation in the watershed is 1138 m. The mainstem of the Elk River is a 6th order channel, and the tributaries we studied are either 3rd or 4th order channels (Strahler, 1957).

The study area is within the traditional territories of the Tolowa Dee-ni' Nation, who refer to the Elk River watershed as K'vms-me' Tr'ee-ghii~-li~ (E. Partee, Tolowa Dee-ni' Nation, personal communication). A large tract of the land is federally managed by the U.S. Forest Service (USFS, 76%), the U.S. Bureau of Land Management manages 1% of the area, state lands are less than 1%, and the remainder is under private ownership divided into industrial and non-industrial lands (Maguire, 2001). Land designations also include 46% of the watershed to late-successional reserves under the Northwest Forest Plan (U.S. Department of Agriculture [USDA], USFS, 1998). The Elk River is designated a National Wild and Scenic River and State Scenic Waterway and is entirely free-flowing. Under Section 303(d) of the Clean Water Act, mainstem Elk River is listed as water quality limited for summer water temperatures (USFS, 1998).

The upper basin provides spawning and rearing habitat for Chinook salmon (*Oncorhynchus tshawytscha)*, coho (*O. kisutch*), coastal cutthroat trout (*O. clarkii clarkii)*, and winter-run steelhead (*O. mykiss*). In addition, a small population of chum salmon (*O. keta*) has been observed in the lower mainstem (Burnett, 2001).

The forest composition in the Elk River watershed includes early seral to an old-growth forest with a predominant habitat of mature hemlock/Douglas-fir temperate forest (Burnett & Reeves, 2006; Franklin & Dyrness, 1988). Primary tree species are Douglas fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), Port Orford cedar (*Chamaecyparis lawsoniana*), tanoak (*Notholithocarpus densiflorus*), Pacific madrone (*Arbutus menziesii*), and California bay laurel (*Umbellularia californica*). In the riparian areas, western redcedar (*Thuja plicata*), big leaf maple (*Acer macrophyllum*), and red alder (*Alnus rubra*) are common (Burnett & Reeves, 2006).

The geology in the coastal lowlands consists of quaternary marine and non-marine terrace deposits, with soils that are deep, silty clay loams to sandy loams (Maguire, 2001). In the upper basin, the geology is a mixture of highly fractured rock point sandstone and siltstone, shales of the Galice Formation, graywacke, granite, diorite, serpentine, and ultramafic rock (Maguire, 2001; USFS, 1998), and the soils in the upper basin consist of silt loam to gravelly loam (Maguire, 2001). Ongoing uplift creates a steeped terrain with gorges throughout (USFS, 1998).

The principal historical and natural disturbances in the Elk River include timber harvest, natural fire, and windthrow. Colonial settlement started in the 1820s when fur trappers and traders settled in Port Orford, OR. In 1853, gold was discovered, and a short mining period followed. In the late 1800s, commercial fishing began on the southern Oregon coast. Commercial logging started in the mid-1800s and was small-scale until the 1930s, peaking in the 1960s. A mill on the Elk River closed in the early 1970s. Timber was harvested from National Forest lands in the 1950s, after which land designations reduced the land available for further harvesting. Approximately 36 km^2 of the 186 km^2 of National Forest land have been harvested between 1938-1998 (USFS, 1998). In the upper and middle mainstem of the Elk River, 8.6 km^2 of land was harvested for timber in the upper and middle mainstem of the Elk River. In the tributaries, 4.4 km^2 in Bald Mountain Cr., 6.5 km^2 in Panther Creek, and 4.22 km^2 in Butler Cr., have been harvested. In addition to timber harvests, approximately 5.27 km^2 of the forest has been cleared by windthrow, fire, and manual removal between the early 1900s and 1995. Approximately 12.1 km^2 have been harvested within managed stands on federal lands in the riparian area (USFS, 1998). Fire before colonial settlement was estimated to have a 100- to 300-year disturbance interval. With fire suppression in the 1930s, this interval increased to 300-400 years. Timber harvest has decreased these intervals to an estimated 100-200 year disturbance interval (USFS, 1998).

Stream Habitat and Wood Surveys

Channel units were classified as pools, riffles, glides, rapids, cascades, or steps and sampled contiguously along 47 km of the mainstem Elk River and 17 km of fish-bearing tributaries (Anvil Cr., Bald Mountain Cr., Butler Cr., Panther Cr. including east and west forks, Red Cedar Cr., and the South Fork Elk River; Fig. 1) using visually based estimation methods (Hankin & Reeves, 1988). Surveys were conducted during summer low flow between late July to mid-August for approximately 3 weeks per survey in 1985-2001 (Burnett & Reeves, 2006). Channel units in the mainstem Elk River and tributaries were sampled to the upper end of fish distribution, which was determined as the point where snorkelers did not observe fish for eight consecutive units. Of the sixteen years of habitat data available, eight years were used in this analysis as they had the greatest spatial extent. Landmarks, including bridges and tributary junctions, were noted in these data, and subsequently used as anchor points for mapping the location of channel units.

The survey crew for stream habitat consisted of 2-3 individuals. One group member was designated to identify the channel unit type and estimate width, length, and mean depth. Following the protocol of Hankin and Reeves (1988), a unit's dimensions were measured with a measuring tape following the observer's estimate of approximately every 10th unit of each habitat type. The observer did not know the measured dimensions. A comparison of the 2 measures allowed for the correction of unit length based on the proportional bias of the observer (Hankin & Reeves, 1988). Another observer was responsible for counting the number of pieces of LW (length $\geq$ 3.0 m and a diameter $\geq$ 0.3 m; USDA, 2000), with 50% of its length located in the bank full zone. The bank full zone is the area of the stream channel up to the regular high-water mark. The LW pieces in small aggregations were counted. In larger aggregations, where counting every piece of wood was not possible, the dimensions of the aggregate were measured, and wood pieces were estimated. Flow variation and other factors resulted in different endpoints of the surveys and sampled stream lengths from year to year. This analysis included 8 years of survey data with the largest spatial extent.

Channels separated by a gravel bar or island and containing less than 10% of total flow were classified as side channels. Channel units in a split flow separate from the primary channel were assigned as secondary channels, and subsequent split flows from secondary channels were classified as tertiary channels. Side channels with less than 10% flow were labeled as such. Split channels (i.e., secondary, tertiary) and side channels were a small percentage of the total channel unit length surveyed each year (3.0- 4.4%) and were excluded from this analysis. Of the total surveyed length of habitat in the 8 years analyzed, secondary, tertiary, and side channels accounted for 2.6% (1.8-3.4%, *SE* = 0.22), 0.1% (0-0.3%, *SE* = 0.04), 0.9% (0.4-1.4%, *SE* = 0.11) of the total channel length, respectively.

Data Analysis

Linear referencing methods were used in ArcGIS 10.4 to georeference each channel unit on digital hydrography in a geographical information system (GIS; Environmental Systems Research Institute, 2003, 2014). Cumulative channel unit lengths along the main stem were calibrated and positioned between known geographic locations, including tributary junctions, bridges, and other flagged locations. Geographic locations were noted in the original surveys. Geographic locations were not equidistant, i.e., they were spaced 0.2 to 4 km apart. Habitat data were georeferenced to the U.S. Geological Survey (USGS) topographic quadrangles (USGS, 2019) for earlier years (1988-1996) and to NHD (2000) for later years (1997-2000). Channel units were georeferenced to the stream sections in the mainstem Elk River and 6 tributaries (Fig.1). The mainstem Elk River includes the North Fork Elk River, and Panther Cr. Includes the east and west forks.

We characterized the flood regime of the Elk River to explore the relationship between the intensity of flood disturbance and the spatial and temporal distribution of LW. Based on systematic and historical records, the peak discharge of 818 $m^3 s^{-1}$ in November 1996 had an estimated return period of > 75 years (Cooper, 2005; OWRD 2020; USFS, 1998; Fig. 1). To assess flood magnitude, we used the regression-based MOVE method (Hirsch, 1982; Vogel & Stedinger, 1985) and the Streamflow Record Extension Facilitator (Granato, 2008) to augment missing streamflow records for USGS stream gage 14327250 (Elk River above Anvil Cr.) from 1988 to 1993, 1994, and 1999. This method required long-term continuous flow from a nearby gaging station; USGS stream gage 14325000 (S. F. Coquille R. at Powers, OR) was used. For the remainder of the paper, the November 1996 flood event is referred to as the 1996 flood.

We normalized the spatial and temporal patterns of LW density using pieces per km, and coefficient of variation (CV) was used to characterize the spatial variation in LW density within and among years. Wood abundance was displayed at multiple spatial scales. The display of linearly referenced data was visualized at the reach scale of 0.4 km. This reach scale was used to map the mean density (pieces of LW km^{-1}) and CV of the mean density of LW across 8 years within individual reaches. Results were not appreciably different at finer spatial resolutions. The mean density of LW was displayed on a log scale due to the extensive range in LW density among reaches. The mean density of LW was used for comparisons between tributaries surveyed at different lengths. Longitudinal patterns of LW pieces were assessed by binning the data at 5 different spatial scales (resolutions): 24, 6, 1.5, 0.4, and 0.1 km, according to the methods of Welty et al. (2015) using R (RStudioTeam, 2019). Eight of 16 years (1989, 1990, 1992, 1994, 1996, 1997, 1998, and 2000) of habitat data with the largest spatial extent were binned for multiscale analysis of habitat distribution in the main stem of Elk River. The CV of LW distribution in the mainstem Elk River was calculated for each of 5 spatial scales across 8 years to create a gridded heat map using the R package ggplot2. The annual peak mean discharge was derived for each water year in the heat map from the augmented annual mean daily discharge.

Results

Spatial and Temporal Patterns of Wood Abundance

Among years, the density of LW was higher and generally more variable in the tributaries except in AN, compared to the mainstem Elk River (Fig. 2, Table 1; see Table 1 for abbreviations of stream names). In the tributaries, the annual mean density of LW was 1.4 to 5.5

times higher than the mean LW density in the mainstem ER, ranging from 31 pieces km^{-1} in BU to 121 pieces km^{-1} in BM (Table 1). Coefficient of variation among years was 0.32 in the mainstem ER, while the average CV of LW density in the tributaries was 0.46, ranging from 0.25 in AN to 0.68 in PA (Table 1).

The highest mean LW density was observed at the reach level in the uppermost reaches of the mainstem ER and the upper reaches of 5 tributaries among the 8 years of study (Fig. 3a). In the ER, reaches with high mean LW density (> 56 pieces km^{-1}) were located at the confluence with the SF and upstream from this confluence (Fig. 3a). There were no reaches immediately downstream of the confluence with the SF in the ER that compared to the hotspots in the tributaries with reaches that had high mean LW density (> 56 pieces km^{-1}; Fig. 3a). The upper reaches of the tributaries all had high mean LW density except the main fork PA and BU (Fig 3a). RC and the SF had the greatest proportion of high mean LW density reaches (Fig. 3a).

There were more reaches with a relatively high CV of LW density (CV > 1.52) downstream of PA in the mainstem ER (Fig. 3b). In the tributaries, no reaches had relatively high wood density CV (Fig. 3b). All the reaches in AN and RC had stable LW density (CV < 0.57) compared to the reaches in other tributaries (Fig. 3b).

There was a coordinated decline in LW density across the river system in 1997 in response to the 1996 flood (Fig. 2). From 1996 to 1997, a 30% decrease in LW density occurred in the mainstem ER, while in the tributaries, LW density decreased from 12% in PA to 89% in the SF (Fig. 2). Initial signs of post-flood recovery were apparent in the increase in LW abundance from 1997 to 1998 in the mainstem ER and the tributaries, except in BU (Table 2). Most notably, there were 4- and 8-fold increases in LW density from 1997 to 1998 in RC and SF, respectively, and a 110% increase in LW density in the mainstem ER (Fig. 3).

At the reach scale, LW density was highly variable among years in the main stem ER and some stream sections of the tributaries (Fig. 4). In any given year, densities of LW frequently varied by 1 to 2 orders of magnitude in adjacent 0.4-km reaches. Among years in the same location, there was a wide range in densities of LW by 2-3 orders of magnitude. In the lower mainstem, LW densities were highest in 1989, while densities were relatively low in subsequent years (Fig. 4a). In the reaches between RC and PA, LW densities were highest in 1992 and variable in the other years (Fig. 4b). Upstream of the confluence with the SF in the mainstem, LW densities were relatively higher and less variable from 1989 to 1996, especially in 1994, which included the highest LW density (> 2.50 pieces km^{-1}) compared to all other years (Fig. 4c). Furthermore, high LW density (> 2.50 pieces km^{-1}) was observed in BM (Fig. 4d) in 1989, 1990, 1996, and 1998, and PA in 1992 (Fig. 4f). Lastly, LW density was relatively high and less variable at the reach level from year to year in BU except 1997 (Fig. 4e).

Longitudinal Patterns in the Main Stem at Multiple Scales

Across most spatial resolutions, little evidence existed for spatial dependence in the patterns of LW accumulation in the mainstem ER (Fig. 5). The patterns of LW abundance observed at the 6-km scale were also evident at finer spatial scales (0.1-1.5 km). For example, distinct aggregations of LW at rkm 42 and 48 in 1989 at the 6-km scale were also apparent at finer spatial scales (Fig. 5). Similarly, in the upper mainstem, an exceptionally high abundance of LW was observed in 1994 at 6-km and finer spatial scales (Fig. 5). At the coarsest scale (24 km) in 1989, a different pattern emerged in which LW abundance was higher in the lower mainstem (0-24 km) compared to the distribution of LW in other years at 24 km (Fig. 5).

There were 2 general patterns of LW abundance in the mainstem ER. First, LW abundance was high in the downstream- and upstream-most reaches; this was most apparent at the 6-km scale in 1989, 1997, and 2000 (Fig. 5). In other years, high LW abundance was observed in the upstream-most reaches of the mainstem, and low LW abundance was observed in the lower mainstem (e.g., 1990 and 1994 at 6 km and 1.5 km; Fig. 5). A stark contrast was shown in the spatial pattern of high LW abundance with more patchiness before the 1996 flood and low LW abundance after the 1996 flood, particularly at finer spatial scales (0.1-0.4 km; Fig. 5).

High levels of spatial variation were especially expressed at fine spatial scales in most years of the study in the mainstem ER (Fig. 6). The CV of LW abundance distinctly increased at 0.1 km from 1989 to 1994. Furthermore, the 2 highest LW aggregations in any given year were observed in 1994 in two channel units alone, which accounted for 30% of LW that year (Fig. 6, Appendix A). The 1996 flood homogenized the spatial variation in LW. Within 1 to 2 years, CV increased, and the heterogeneity in LW abundance returned (Fig. 6).

Discussion

Our objectives for this paper were to (1) assess the spatial dynamics of LW density over multiple spatial scales and (2) characterize the changes in these patterns in response to a major flood event in 1996 in a free-flowing coastal river. An unpublished, unprecedented dataset collected over 65 km of stream reaches in the Elk River, OR, over 12 years provided the opportunity for a spatially explicit analysis. The patterns that we document in the ER show that the spatial distribution of LW in rivers is a dynamic characteristic of rivers that can quickly recover the high spatial variation in LW abundance after a major flood. Among years, the density of LW was greater in the tributaries compared to the mainstem, while the mainstem had a higher variation in LW density compared to the tributaries except one (AN). At the 0.4 km scale between adjacent reaches, densities of LW varied by 1 to 2 orders of magnitude within years.

Comparing the exact location among years, the densities of LW varied as much as 2 to 3 orders of magnitude. Scale-dependent patterns of LW distribution were not detected at resolutions < 6 km; the spatial patterns in LW were consistent at all finer spatial scales. The variation of LW abundance in the mainstem was especially pronounced at finer spatial scales and highest in 1994 before the flood. The 1996 flood flushed LW from the system and homogenized LW spatial distribution across the river. Despite this, the high spatial variation in LW abundance was quickly recovered after the major flood, providing evidence of a dynamic river system.

The ER is mainly intact and provides an excellent opportunity to describe a coastal river's natural wood regime (Wohl et al., 2019b). A holistic overview of the natural wood regime, which includes recruitment, transport, and storage, should be analyzed at broader scales and not only at the channel scale (Wohl et al., 2019b). In addition to broader scales, we analyzed LW distribution patterns over 12 years. Without high-resolution data, we might not have detected the fine-scale variation of LW density pre- and post-flood, nor the high degree of heterogeneity at the 0.4 km scale. At finer spatial scales, spatial variation in LW density in the mainstem was apparent, including an acute response to the 1996 flood that homogenized the variation in LW abundance for 1-2 years. A high degree of heterogeneity in LW density at the 0.4-km scale from reach to reach provided insight into the patch dynamics of instream habitat in the ER. A log scale representation of LW was used due to a large variation in LW density from reach to reach within each year and among years. This variation may be attributed to supply-rich stream sections and tributary inputs (Benda et al., 2004). Process domains contribute to the spatial variation in habitat that may be at nonequilibrium at the patch or sub-reach scale and stable at the reach scale (Naiman et al., 2010).

Another advantage to a spatially explicit analysis was determining if scale dependency existed at 5 different spatial scales. Although we did not test for scale dependency explicitly, we observed no scale dependency except at the coarsest resolution of 24 km. Specific patterns of LW distribution may have been missed if habitat data were noncontinuous or excluded the upper reaches of the mainstem and the tributaries.

In the Elk River, variation in LW recruitment mechanisms is likely contributing to the high variation in LW density at the reach scale throughout the mainstem from year to year. A frequent and discrete recruitment regime (Wohl et al., 2019b) seems plausible for the ER. This regime is similar to the chronic processes that deliver wood at frequent time intervals, including tree mortality, bank undercutting (Murphy & Koski, 1989; Reeves et al., 2003), and fluvial input such as landslides, which may deliver a substantial amount of wood and sediment to streams in the PNW (Johnson et al., 2000; Swanson et al., 1998). Prominent stream terraces in the upper mainstem ER may also contribute to lateral wood recruitment. Previous work in the ER showed low variation in LW density with lithology and forest cover, which led to speculation that wood is delivered from sources other than stream adjacent areas (Burnett & Reeves, 2006). Debris flows have been found to occur on all lithologies, including higher-order channels in the ER (Ryan & Grant, 1991). Debris flows may contribute to the higher mean LW density observed in the upper reaches of the tributaries compared to the lower and middle reaches of the main stem over the 12 years. Infrequent mass recruitment from avalanches or infrequent sustained recruitment from a disease (Wohl et al., 2019b) are other recruitment regimes that seem unlikely and did not occur during the study period, but potentially could occur in the future.

The 1996 flood event provided an opportunity to observe the effects of a large flood event on LW distribution and insight into wood transport. The first-order controls of streamflow on wood transport (Wohl et al., 2019b) were apparent in the ER after the flood, or what exceeded the proportion of ongoing transport of wood under bankfull which has been estimated to be <30% of stored wood (Kramer & Wohl, 2017; MacVicar & Piégay, 2012). The first major flood after recruitment was observed to influence wood distribution substantially relative to subsequent flows (Millington & Sear, 2007; Wohl et al., 2019). The system-level effect of the 1996 flood on LW density included homogeneous patterns of LW distribution that were especially apparent in 1997 and 1998. Furthermore, the increase in LW density was 4- and 8-fold in 2 tributaries in 1998 after the 1996 flood. This finding is similar to the estimated 80-90% turnover when high flows recruit and transport large amounts of wood, compiled from an analysis of wood mobility in field studies worldwide (Kramer & Wohl, 2017). Where there has been historic wood removal in rivers, passive recovery of the wood load has been estimated to take 2.5 centuries, give or take 23 years (Stout et al., 2018). A dynamic system, the ER displayed resilience in wood flux as some tributaries quickly regained LW levels after the flood. Our data do not include extensive records of logjams and aggregations of LW that may be present from year to year in some reaches. Data concerning jams and aggregations could offer additional insight into whether some LW pieces offer locational stability between events that cause substantial wood transport (Kramer & Wohl, 2017; Wohl et al., 2019b). Our observations potentially support that the ER is a dynamic self-regulating regime that reorganizes after disturbance (Naiman et al., 2010). Future work is needed on a finer temporal scale that extends beyond 12 years of study to further characterize locational stability between major events.

The relationship between flood magnitude and wood flux has also been highly variable in wood transport (Iroumé et al., 2015; Kramer & Wohl, 2017). Estimating wood transport is challenging without a wood budget, and distance traveled for LW pieces. However, LW in the

ER may behave similarly to other studies in the PNW region. Wood mobility rates are influenced by numerous factors, including geomorphology, stream discharge, and wood dimensions. These processes yield a wide range of annual wood transport ranging from 18% in NW Washington (Berge et al., 1998) and 32-56% in the Oregon Coast Range (Dixon & Sear, 2014; Keim et al., 2000). Most apparent in the ER is that LW is constantly moving throughout the system, especially in the mainstem. However, without direct measurements of LW transport, we can only speculate about the transport regime in the ER.

The temporal variation of LW spatial distribution and low LW abundance in the mainstem fit the profile of a "frequent and uncongested" transport regime. Rain pulses potentially cause this regime and peak flows with low LW abundance (Wohl et al., 2019b), which appears to be the case in the mainstem. In the tributaries, a "predictable but infrequent" transport seems likely. High mean LW density was sustained in the upper reaches of most tributaries over 12 years, and peak flows appear to be a primary form of transport. Aside from these 2 transport regimes, an infrequent hypercongested or congested wood transport are possible, which may be caused by a significant LW mobilization by a flash flood or logjam (Wohl et al., 2019b). In the same region but dissimilar in LW movement in the ER, a study in Mack Creek, OR, found that only 11% of wood moved more than 10 m after the 1996 flood, while wood pieces that moved more than 300 m were longer than 2 m in length (Lienkaemper & Swanson, 1987; Wohl & Goode, 2008). Additional data on the bankfull stage, which may serve as a mobility threshold, might provide insight into wood mobility (Kramer & Wohl, 2017) along with the length of the piece of wood, thus, further characterizing the mechanics of wood transport (Bilby, 1984; Lienkaemper & Swanson, 1987; Swanson & Lienkaemper, 1984).

Considerable variability in wood loads has been reported within and between river networks (Wohl et al., 2019b). For example, a study in 5 streams over 9 years in Oregon determined a residence time of 83 years in small streams and 12 years for the largest streams (Lienkaemper & Swanson, 1987). This finding may be similar or lower for the ER, but additional data are necessary to estimate residence time in the mainstem and each tributary. Without the data to report wood load as the volume of wood per spatial unit (Wohl et al., 2019b) in the ER, we use LW density as a substitute. In some years, the mainstem ER presented a pattern of LW distribution with low abundance in the lower main stem and high abundance in the upper reaches of the mainstem.

Similarly, in the ER, Burnett (2001) determined a greater mean LW density in the tributaries associated with pools compared to the mainstem in each year analyzed between 1988 and 1994. This result partially supports our findings that wood load relative to wood transport decreases downstream with decreasing gradient and increasing drainage area (Wohl & Jaeger, 2009). However, these relationships between wood load and predictor variables were highly variable (Wohl et al., 2019b) across bioclimatic regions, where wood load and drainage area correlate directly and inversely (Scott & Wohl, 2018).

Large aggregations of LW, potentially storage, observed in the upper tributaries may be an example of "key-member" pieces that accumulate a large volume of wood over time (Abbe & Montgomery, 2003) until high flow. The high LW density observed in the upper reaches of the mainstem and tributaries appear to be supply-rich and transport-limited with high storage potential. There may be exceptional LW recruitment in RC and SF, as suggested by 2 tributaries in the ER that instantly regained high LW abundance post-flood. Without extensive sampling that includes the uppermost reaches of the tributaries, supply-rich reaches and contributions of

LW from hillslopes and upland areas (Pfeiffer & Wohl, 2018) may be undermined. In some cases, aggregations of wood may be in flux, maintaining the same volume (Kramer & Wohl, 2017), or the flux could be a dynamic equilibrium with little net change in LW volume (Kramer & Wohl, 2017; Schenk et al., 2014) until a major disturbance occurs. Wood storage was found to last from less than a year to more than 10,000 years (Nanson et al., 1995; Wohl, 2017; Wohl et al., 2019b). Unfortunately, LW was not tagged or dated for age in this study. Further analysis is needed at a finer timescale to characterize the residence time of LW pieces in the ER.

Regarding wood storage, we propose that there are 2 storage regimes in the ER. The mainstem might have “short residence times” where LW is continuously recruited and transported, and the average abundance of LW remains stable (Wohl et al., 2019). This average stability was observed in the mainstem. Alternatively, the tributaries could be aligned with “long residence times” where the reach is supply-rich and transport limited (Wohl et al., 2019). In this case, LW is transported infrequently until a major event (Wohl et al., 2019), such as the 1996 flood, occurs. Future work should include extensive lengths of the river corridor, considering the lack of studies on wood load in the floodplain (Lininger et al., 2017; Wohl et al., 2019b).

The habitat heterogeneity that we observed throughout the mainstem appears to be the backdrop of a dynamic river system with high LW spatial and temporal variation. Surprisingly, after the 1996 flood, large aggregations of LW were absent. The mainstem as a collector of wood appears to keep wood moving throughout the system with no persistent patterns of LW aggregations in the mainstem, except from 1992 to 1994 in the uppermost reaches of the mainstem. Logjams are a sign of a healthy riverine ecosystem, where wood loads are an essential driver of the spatial distribution of wood within a channel, and the recovery of a natural wood load is mainly dependent on logjams (Stout et al., 2018). What is potentially a LW jam in the upper mainstem, apparent at the finer spatial scales from 1992 to 1994, was mobilized and flushed out by the 1996 flood. A similar observation was made in a 10-year study in the Rocky Mountains, which showed that logjams were flushed out by a flood in 2013, resulting in a quick return to pre-flood distribution of wood by 2019 (Wohl & Scamardo, 2021). Observations in the Rocky Mountains found logjam distribution increased with an increase in the ratio of wood length to channel width. The dimensions for each LW in the ER were unaccounted for and should be considered in future work. The large aggregation of LW in the upper mainstem from 1992 to 1994 may have had a high turnover of individual pieces (Latterell & Naiman, 2007; Marcus et al., 2002; van Der Nat et al., 2003), while wood loadings remain relatively constant (Marcus et al., 2002). The results support that LW distribution appears dynamic and variable from year to year in the ER. The ER provides an excellent example of the discontinuity and dynamism of wood flux, an essential component of the wood regime that may be more important than wood stability (Kramer & Wohl, 2017).

Our results do not provide insights on LW dynamics before logging or river designations in the ER. One approach for management is to age the composition of trees in the stream riparian to identify the potential for sustained wood entry (Martens et al., 2020). Timber harvest has affected the late-successional habitat in the ER, where planting conifers for future recruitment has been suggested in the past (USFS, 1998). Keim et al. (2000) found that the placement of small woody debris in 3 heavily logged streams in Oregon showed an instant increase in wood abundance by 86% to 155% and an increase in wood presence 3 years after treatment in all the streams. Active restoration with the placement of LW features is a reasonable option if historical activities have compromised the wood regime with apparently irreversible damage. However, we present a highly dynamic wood regime characterized by continuous recruitment and high transport rates. The best cost-effective option is to ensure that a river has a supply of new wood, which allows the stream to naturally redistribute wood repeatedly (Kail et al., 2007; Kramer & Wohl, 2017).

A challenge is that it may not be possible to fully characterize the ecological role of downed trees in rivers due to historic wood removal (Sedell & Froggatt, 1984) nor fully understand rates of wood recruitment influenced by disturbances and processes that occurred anywhere from decades to centuries ago (Kramer & Wohl, 2017). Furthermore, large-scale effects of climate change, including fire and landslides, may result in increased LW (Martens et al., 2020) and a shift in the wood process regime. Future restoration projects in the ER and elsewhere are needed to ensure that habitat heterogeneity supports diverse stream communities across the channel reach to watershed scales. We suggest that future work focus on processes that affect the recruitment and transport of wood (Beechie et al., 2010) in the floodplain and on a finer temporal scale to track individual pieces of LW in transport or storage. The wood process regimes mentioned in this study for the ER are representative of the study period only, and these hypothetical examples are not an exhaustive review of the different process regimes that could be found in a wood regime (Wohl et al., 2019b). Reach-scale process domains in the ER may transition from one domain to another (Kramer & Wohl, 2017) and one wood regime over time (Wohl et al., 2019b). River management goals that strive to maintain and protect the geomorphic and ecological processes in river corridors could support lasting benefits of a river and restore its ecological integrity (Beechie et al., 2010). Management plans are needed that consider climate impacts that may exacerbate the effects of flood disturbance and change the balance across the natural wood regime, recruitment, transport, and storage domains.

Table 1. Drainage area, range of surveyed length, and range of mean channel wetted width of 6 tributaries and the Elk River, OR. Survey years were 1989, 1990, 1992, 1994, 1996, 1997, 1998, and 2000.

Subbasin	Abbreviation	Drainage area (km^2)	Surveyed length (km)	Mean channel wetted width (m)	Mean large wood density (pieces km^{-1})	CV
Elk River (main)	ER	222.0	44.4-49.6	1.8-40.3	22.4	0.32
Anvil Cr.	AN	6.9	0.5-0.6	1.5-10.6	73.0	0.25
Bald Mtn. Cr.	BM	27.5	5.1-6.3	1.6-16.3	121.3	0.57
Butler Cr.	BU	17.7	2.1-2.7	1.5-11.1	30.9	0.52
Panther Cr.	PA	36.0	4.8-5.6	1.4-15.5	58.8	0.68
Red Cedar Cr.	RC	7.4	2.0-2.4	1.0-10.7	88.0	0.36
S. F. Elk R.	SF	20.0	1.3-1.6	2.0-10.3	86.4	0.37

The Elk River includes the mainstem and the N. F. Elk River. Panther Cr. Includes both the east and west forks. Coefficient of variation (CV) for large wood density in the tributaries and the mainstem over 8 years of sampling (Fig. 2).

Table 2. Total large wood counts (number of pieces) in the mainstem and 6 tributaries in the Elk River, OR. Survey years were 1989, 1990, 1992, 1994, 1996, 1997, 1998, and 2000.

Subbasin	1989	1990	1992	1994	1996	1997	1998	2000
Elk River (main)	1661	799	1302	1028	1241	832	940	593
Anvil Cr.	ND	ND	34	41	52	31	52	30
Bald Mtn. Cr.	1343	671	ND	720	1162	338	493	228
Butler Cr.	177	98	56	58	70	58	49	35
Panther Cr.	507	184	793	242	212	190	204	123
Red Cedar Cr.	285	233	197	226	169	47	173	197
S. F. Elk R.	138	142	147	135	157	17	117	120

No Data=ND. The Elk River includes the mainstem and the N. F. Elk River. Panther Cr. Includes both the east and west forks.

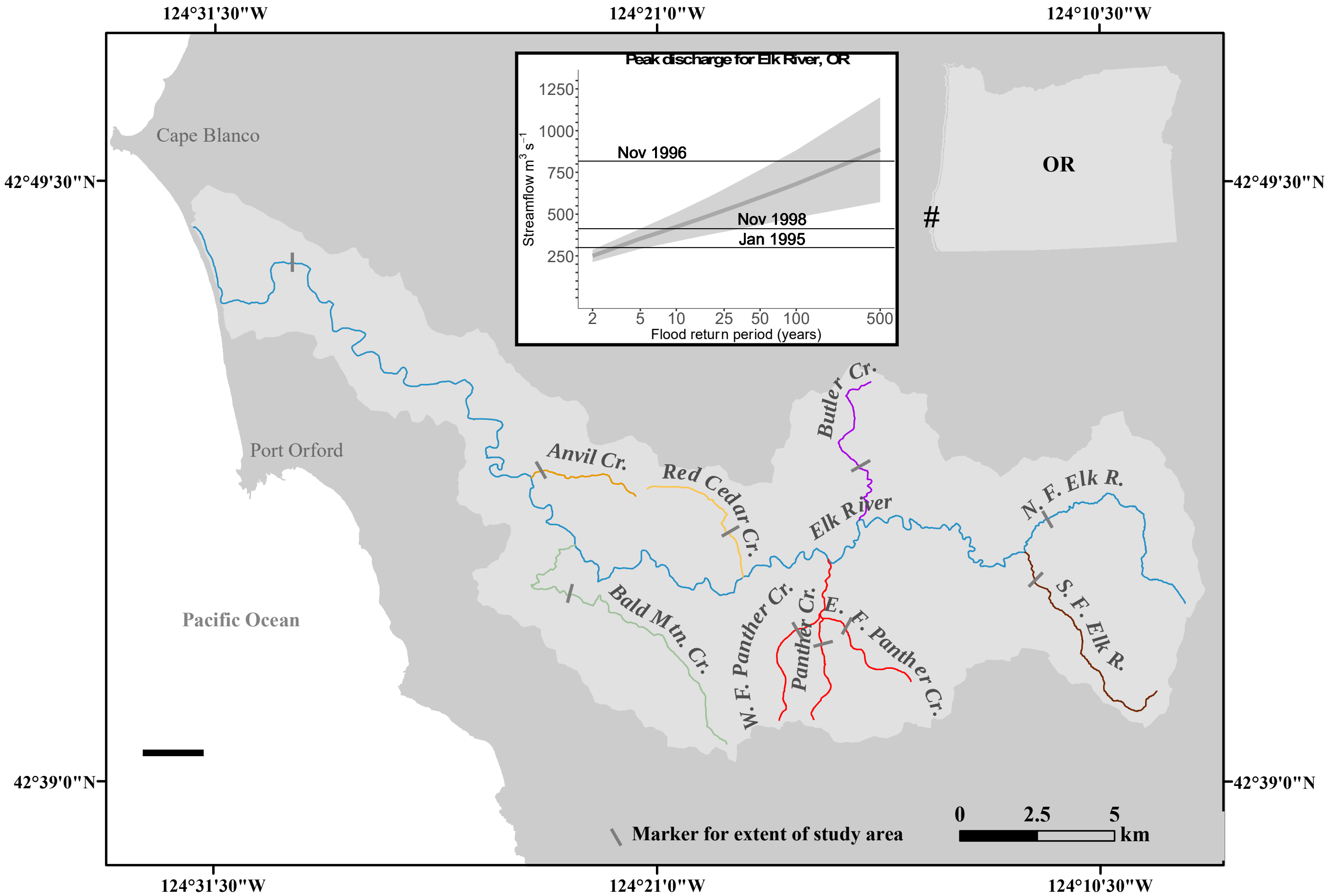


Fig. 1. Map of the study area and an inset figure of flood recurrence in the Elk River, OR. The maximum extent of spatially continuous habitat data analyzed is indicated by the grey bars placed perpendicular to the streamline. This includes the mainstem and 6 tributaries. The Elk River includes the mainstem and the N. F. Elk River. Panther Cr. Includes both the east and west forks. The inset figure of flood recurrence includes 3 horizontal lines for 2 small flood events in 1995 and 1996 and an extreme flood event in 1996 with a greater than 75-year flood recurrence. The light grey band in the inset figure are 95% confidence intervals of flood magnitude, and the dark grey line is the mean.

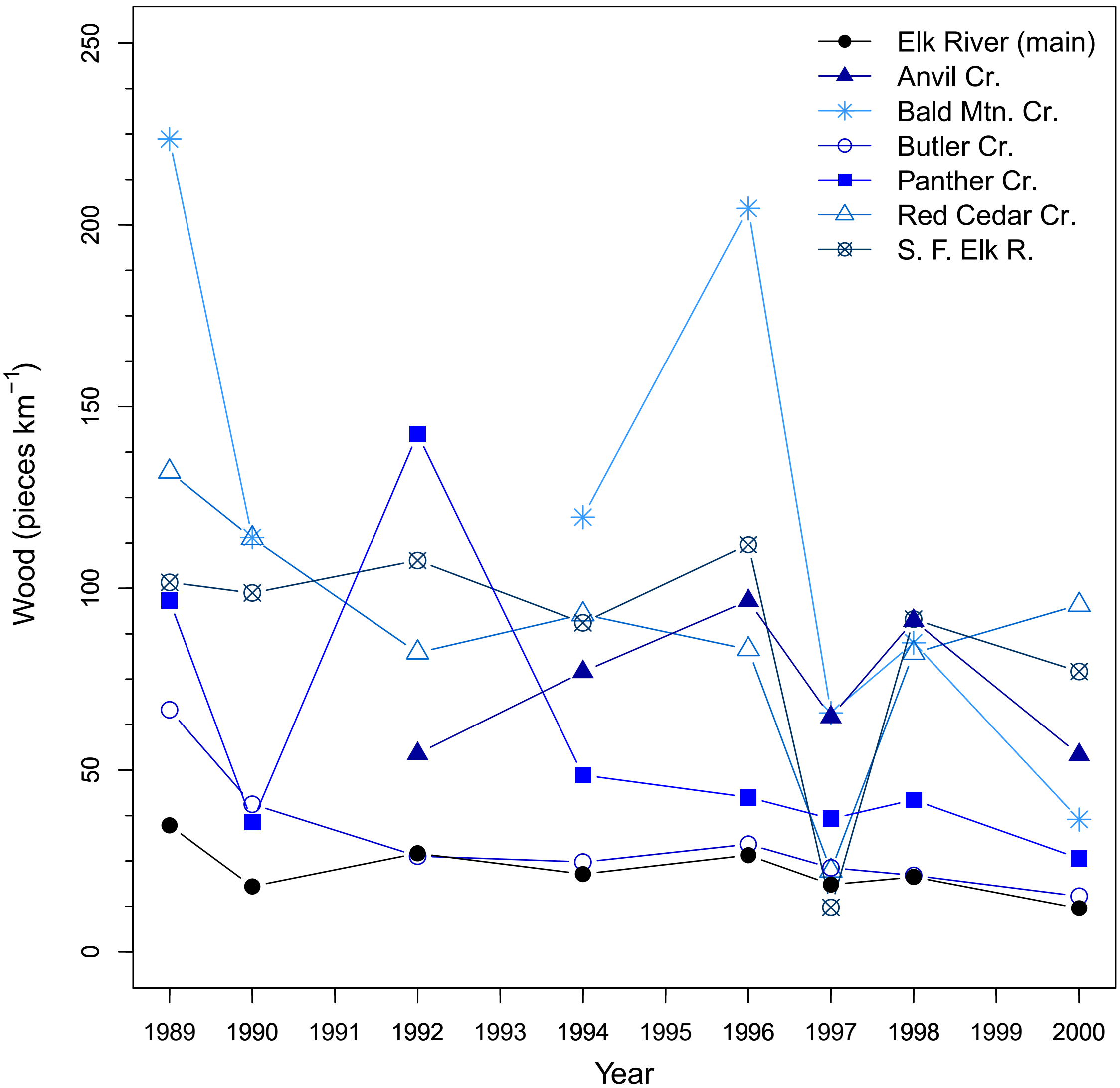


Fig. 2. Time series of LW density (pieces km^{-1}) in the 6 tributaries and the Elk River in 1989, 1990, 1992, 1994, 1996, 1997, 1998, and 2000. The tributaries are in blue. The Elk River includes the mainstem and the N. F. Elk River. Panther Cr. Includes both the east and west forks. Bald Mountain Cr. Was not sampled in 1992, and Anvil Cr. Was not sampled in 1989 and 1990.

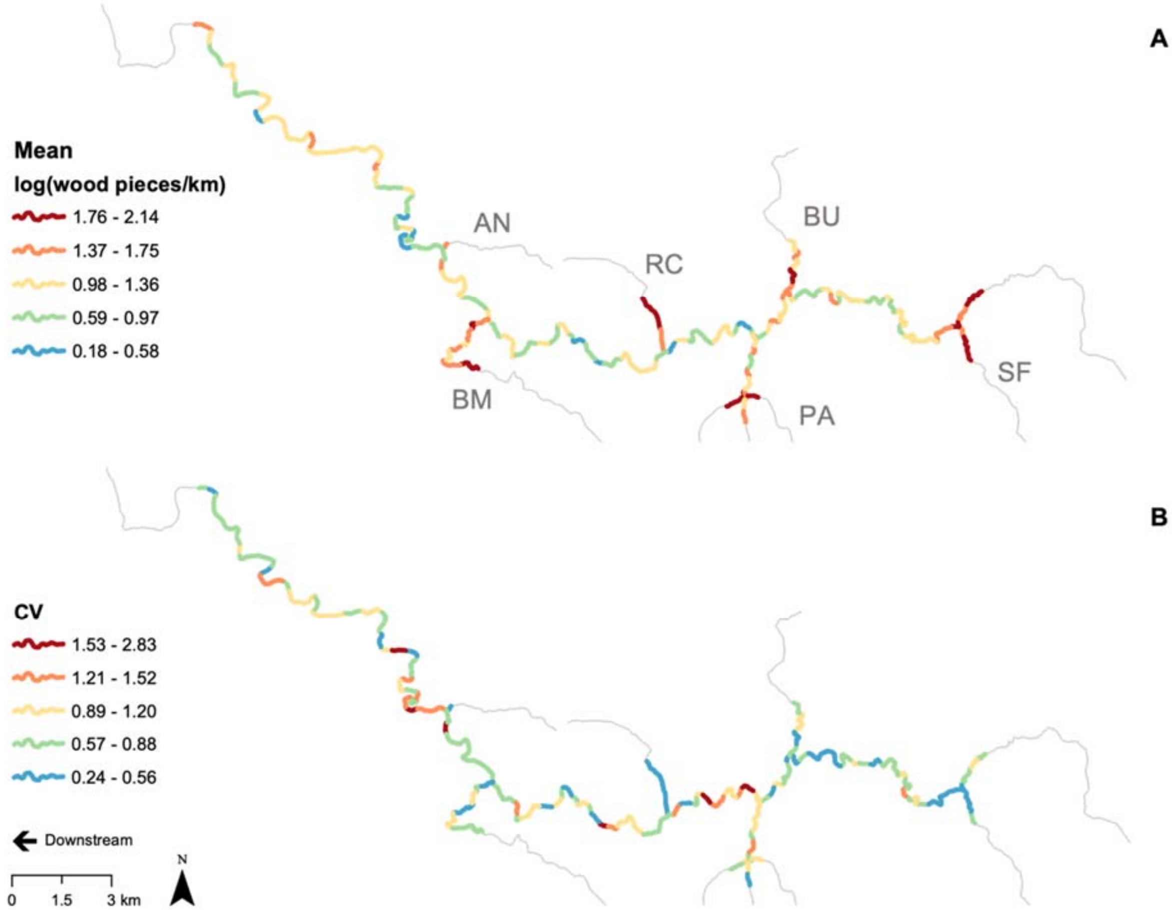


Fig. 3. Large wood in 0.4 km bins summarized by (**A**) mean and (**B**) coefficient of variation (CV) in the Elk River and 6 tributaries across 8 years of study. The Elk River includes the mainstem and the N. F. Elk River. Mean wood density is $\log_{10}$ transformed. Tributaries are annotated as described in Table 1. Categories in the legend are at equal intervals for mean and CV. The category for the highest CV has a large interval due to an outlier with a value of 2.83.

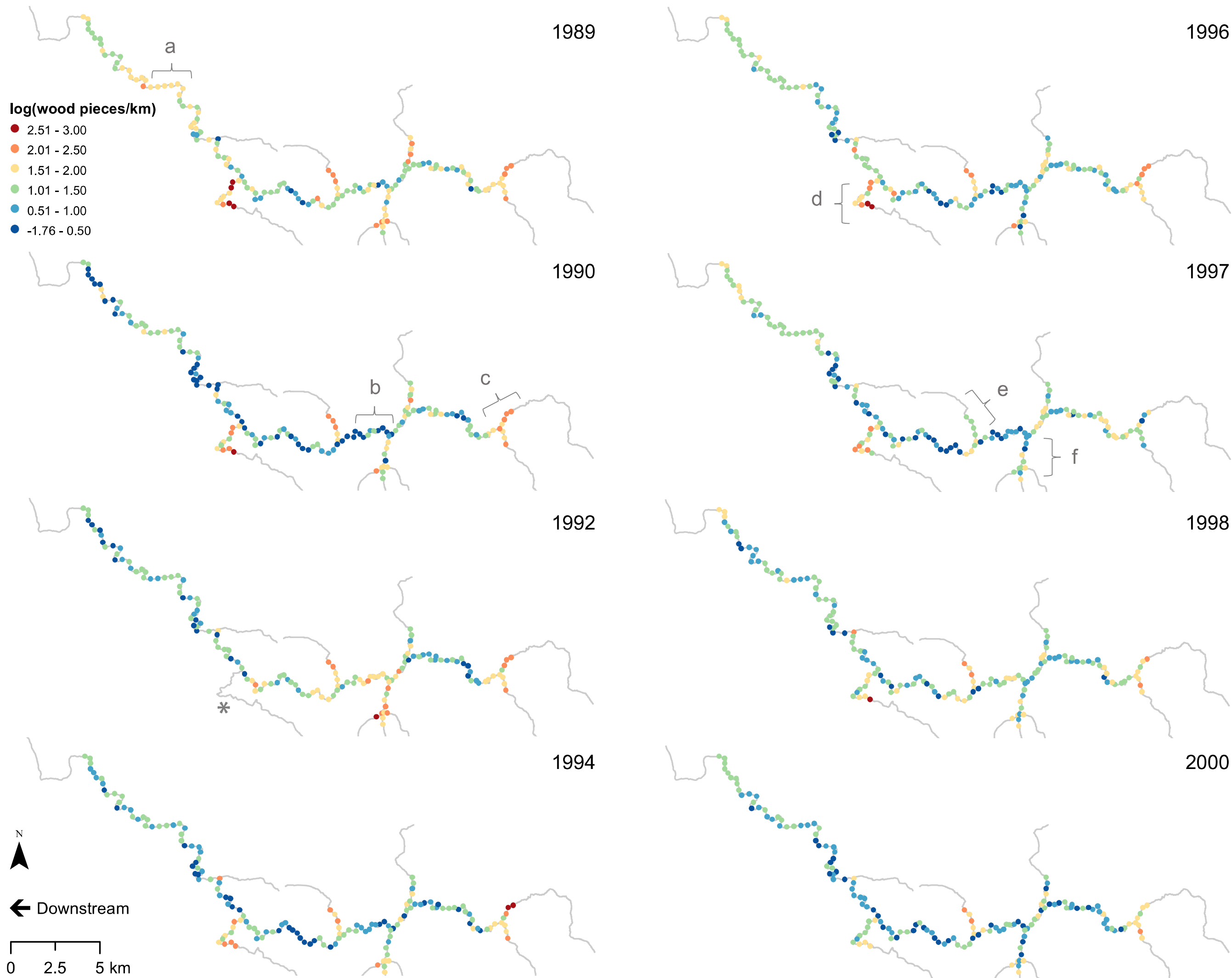


Fig. 4. Spatial patterns of wood density in the Elk River and 6 tributaries across 8 years of study. The Elk River includes the mainstem and the N. F. Elk River. Densities are calculated for 0.4-km bins and $\log_{10}$ transformed. Bald Mountain Cr. Was not sampled in 1992 (see asterisk). Markers "a," "b," and "c" are in the Elk River mainstem. Marker "d" is in Bald Mountain Cr., "e" in Red Cedar Cr., and "f" in Panther Cr. Categories in the legend are at equal intervals. The category for the lowest LW density has a large interval due to 15 values <0 that were spread across the 8 years.

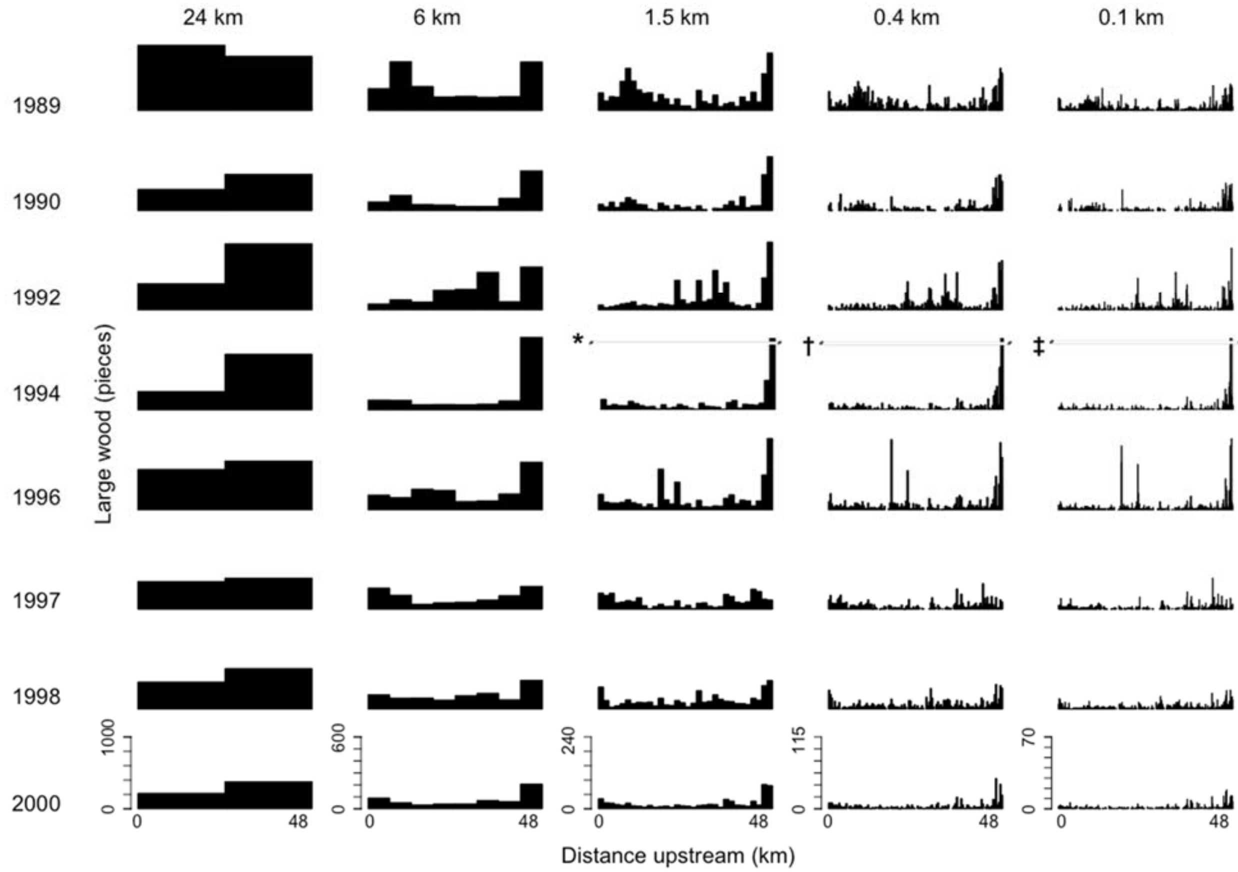


Fig. 5. Longitudinal patterns of large wood counts in the Elk River binned (Welty et al., 2015) at 5 spatial scales (24, 6, 1.5, 0.4, and 0.1 km) across 8 years. The x-axis indicates the distance upstream from the lowermost point of the survey to the uppermost point in the N. F. Elk River (see Fig. 1). The Elk River includes the mainstem and the N. F. Elk River. In 1994, maximum y-values are 466 (1.5 km scale) (*), 224 (0.4 km) (†), and 194 (0.1 km) (‡).

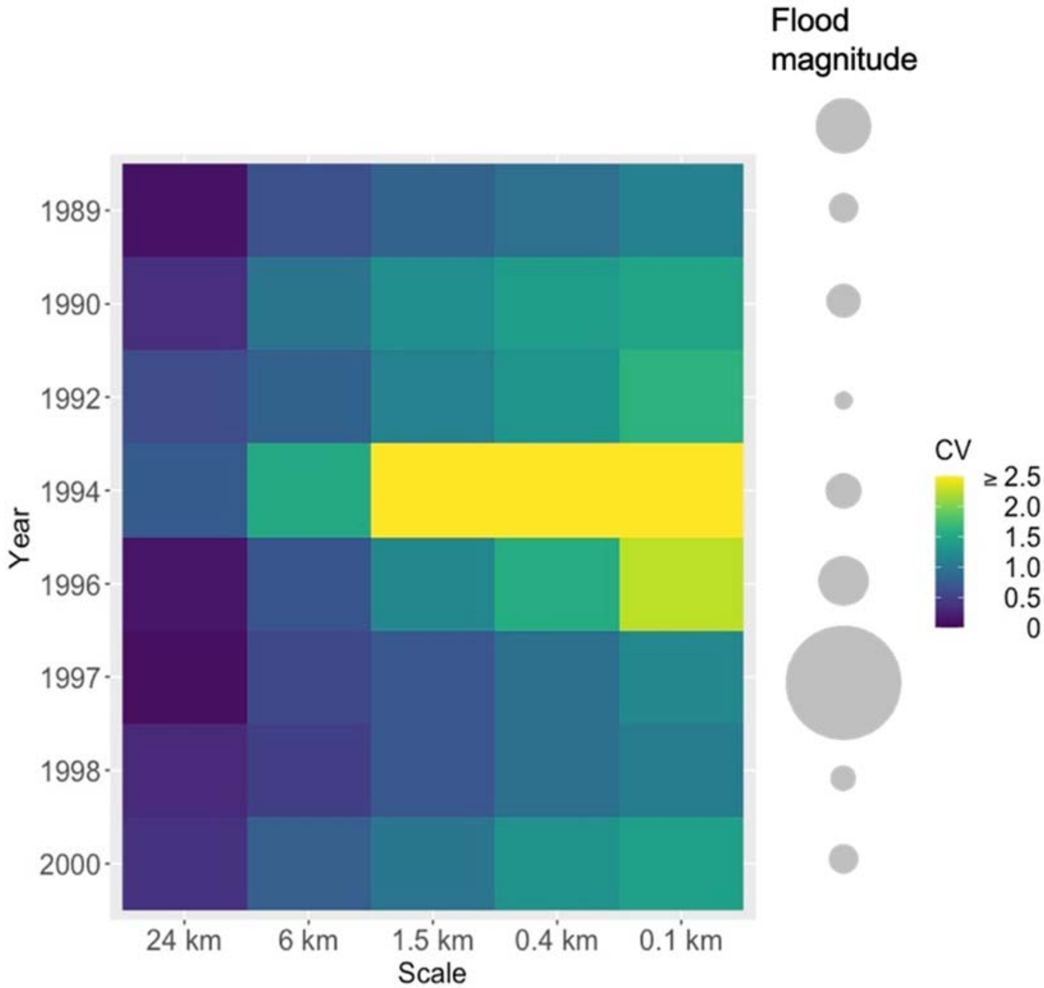
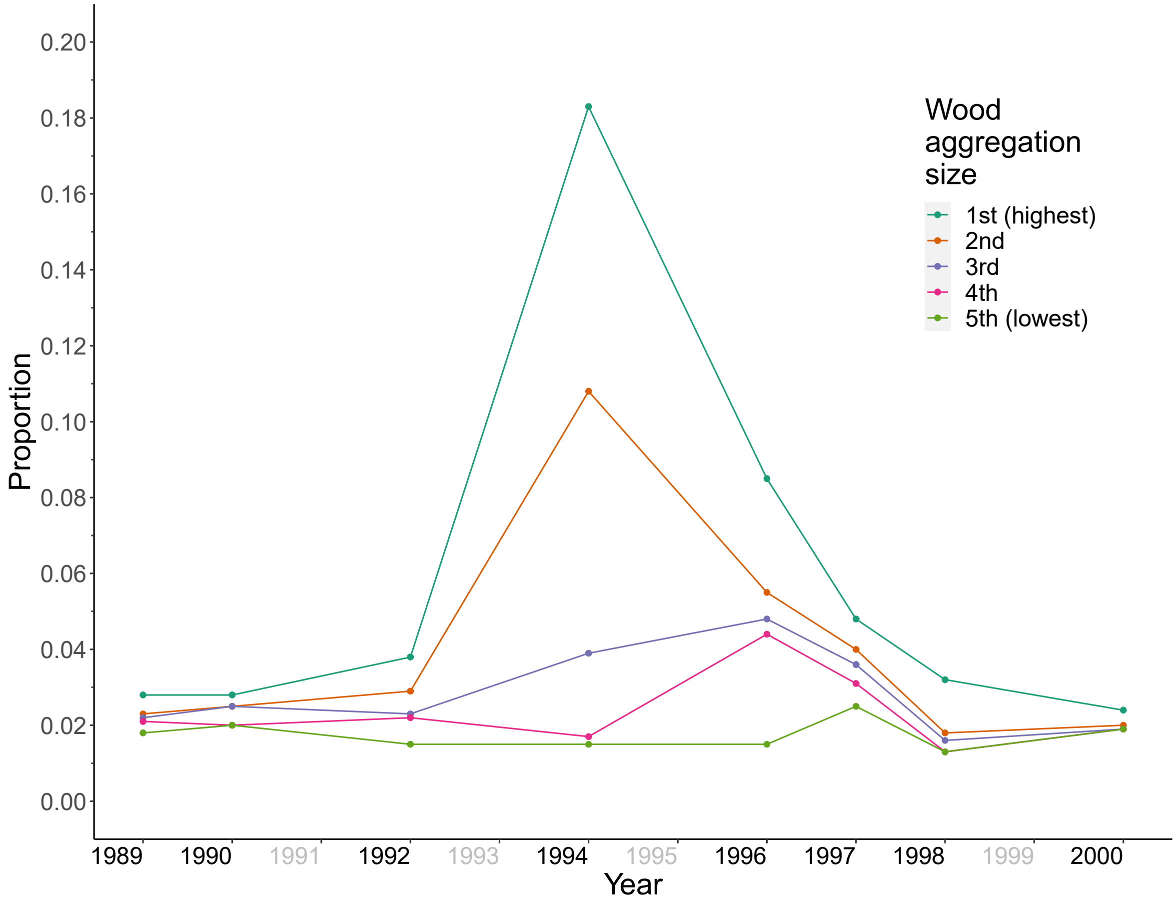


Fig. 6. Coefficient of variation (CV) of large wood counts in the Elk River at 5 different spatial scales across 8 years. The Elk River includes the mainstem and the N. F. Elk River. The range of CV (0-3.6) was truncated at 2.5 for visual differentiation. Flood magnitude is represented by grey circles positioned according to when they occurred. The diameter of the circles is proportional to the annual peak mean discharge in the water year (Oct. 1-Sept. 30) of occurrence. Using proportional diameters representative of flood magnitude, annual peak mean discharge was plotted in the gridded heat map next to each year. For example, the top circle represents the water year 1988. The 1996 flood occurred in the water year 1997. The smallest circle represents a discharge of 60.7 m^3s^{-1} in 1992, and the largest circle is 402 m^3s^{-1} in 1997. The regression-based MOVE method (Hirsch 1982; Vogel & Stedinger, 1985) and Streamflow Record Extension Facilitator (Granato, 2008) were used to calculate flood magnitude.

Appendix A



APPENDIX A. In the mainstem ER, the top 5 wood abundances (total sum of large wood) per channel unit over time. The Elk River includes the mainstem and the N. F. Elk River. The highest large wood count per channel unit was observed in 1994.

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CHAPTER 2: THE SHIFTING HABITAT MOSAIC AND FISH DISTRIBUTIONS IN A COASTAL RIVER

Abstract

Understanding how aquatic biota respond to the spatial and temporal complexity of rivers remains a major challenge for developing appropriate management and conservation practices for these critical ecosystems. The shifting habitat mosaic (SHM) is a conceptual model of how rivers evolve to provide resilience to disturbances and maintain the habitat complexity needed to support aquatic biodiversity; however, the model remains untested at relevant scales. We tested the SHM in a free-flowing coastal river in Oregon with a unique, high-resolution record of habitat conditions and the abundance of four Pacific salmonids. We found that over a 10-year period, the spatial and temporal variability of large wood, a dynamic habitat feature, and channel depth, a static habitat feature, were positively associated with the abundances of three of four fish species. Furthermore, these fish-habitat associations were maintained among years, despite considerable spatial reorganization of the dynamic components of aquatic habitat. These results point to a clear need for river management to maintain the disturbance regimes and aquatic-terrestrial linkages that characterize the dynamic components of aquatic habitat conditions and key ecosystem functions.

Introduction

There is increased recognition that aquatic habitat is dynamic, and that this dynamism is expressed across a range of time scales (Lake et al., 2007; Pringle et al., 1988; Schlosser, 1991; Wiens, 2002). In addition to dynamic habitat elements, less labile habitat features contribute to spatial and temporal heterogeneity found in streams and rivers (Beechie & Bolton, 1999; Naiman et al., 1992; Reeves et al., 1995; Torgersen et al., 2006) Together, the combination of dynamic attributes and more stable attributes generate habitat mosaics that express variation across a range of spatial scales that shift in response to changing environmental forcing, erosion, and depositional patterns. The shifting habitat mosaic (SHM) (Stanford et al., 2005) has been proposed as a conceptual model to describe the ecological phenomenon that characterizes the habitat heterogeneity found in properly functioning lotic ecosystems, which form the basis for supporting aquatic biodiversity. Despite the strong conceptual and physical underpinnings of the SHM, how biological components of riverine ecosystems respond to the spatial and temporal dynamics of habitat features remains largely untested. Although the SHM has been demonstrated at relatively small spatial scales (Armstrong & Schindler, 2013; Baldock et al., 2016; Rypel et al., 2012), few examples illustrate this phenomenon quantified across large spatial scales (Brennan et al., 2019). In particular, there are no explicit tests of whether the spatial distributions of mobile organisms track the changing spatial arrangement of dynamic habitat features and respond to the spatial distribution of more static habitat components. A critical aspect of maintaining ecological function and integrity across aquatic landscapes is understanding the redistribution and resilience of habitat mosaics in response to ecological disturbance, anthropogenic activities, and a changing climate (Rieman et al., 2006)

Large wood, once widely removed from river corridors throughout the Pacific Northwest (PNW) and United States (Sedell & Froggatt, 1984; Wohl, 2014), is now increasingly recognized as an essential but dynamic component of riverine habitat. Large wood is recruited to rivers via disturbance events that transport trees from riparian forests to active river channels. In protected watersheds, large wood in rivers varies in abundance and exhibits highly heterogeneous distribution patterns through space and time (Benda et al., 2005; Hassan et al., 2005; Stanford et al., 2005). Various stochastic factors affect large wood recruitment (e.g., fire, windthrow, flood events), transport, and burial within rivers and contribute to the patch dynamics of large wood in the PNW (Benda et al., 2003; Wohl et al., 2019).

Large wood affects various habitat processes in rivers, including providing low-velocity refugia (Curran & Wohl, 2003; Marston, 1982), cover from competition and predation (Fausch & Northcote, 1992), pool formation, and terrestrial nutrient cycles and carbon budgets (Bilby, 2003; Harmon et al., 1986). Furthermore, it is an essential component of stream restoration activities (Roni et al., 2008, 2015) and climate mitigation planning.

The associations between Pacific salmonids (*Oncorhynchus* spp.) and stream habitat have been widely studied and found to be complex and multi-scalar (Ebersole et al., 2009; Pess et al., 2014; Schlosser, 1995). However, investigations of habitat-fish associations typically use data that provide a snapshot of these relationships at any point in time. Studies such as these have demonstrated the importance of different abiotic (e.g., stream channel width, channel gradient) and biotic factors (e.g., predation, competition) that impact the distribution and abundance of juvenile salmonids (Rosenfeld, 2003; Steel et al., 2004). Less understood is whether fish track dynamic and static habitat features as these more properly characterize habitat conditions in rivers.

We present the first explicit test of the SHM to characterize the relationships between dominant fish species and both static and dynamic features of habitat that characterize a PNW coastal river. We used a uniquely detailed, spatially explicit dataset to analyze the habitat associations of Pacific salmonids, steelhead (*O. mykiss*) young-of-the-year and age-1+, juvenile ocean-type Chinook (*O. tshawytscha*), and coastal cutthroat trout (*O. clarkii clarkii*) any age class, with dynamic and relatively static habitat features. In light of the SHM, we expected that the spatial distribution of dynamic habitat features, such as large wood, would vary across rivers among years, but static features such as channel depth, would vary little over interannual time scales. However, under a functioning SHM, the functional relationships between fish abundance and both dynamic and static habitat features will be maintained through time.

Methods

Study Area

The Elk River basin is located within the traditional territories of the Tolowa Dee-ni' Nation, who refer to the Elk River watershed as K'vms-me' Tr'ee-ghii~-li~ (E. Partee, Tolowa Dee-ni' Nation, personal communication). The basin is approximately 240 km^2, located in southern coastal Oregon, USA (Figure 1A). The headwaters of the Elk River are in the Grassy Knob Wilderness and Copper-Salmon Wilderness Areas in the Klamath Mountains physiographic province. The Elk River discharges into the Pacific Ocean between Cape Blanco and the town of Port Orford. The river is entirely free-flowing and designated a National Wild and Scenic River and State Scenic Waterway. The upper basin provides a spawning and rearing habitat for Chinook salmon, coho (*O. kisutch*), coastal cutthroat trout, and winter-run steelhead (Burnett, 2001). In addition, a small population of chum salmon (*O. keta*) has been observed in the lower mainstem (Burnett, 2001).

Stream Habitat and Fish Surveys

A census of aquatic habitat was completed in 28 km of the mainstem Elk River using visual-based estimation methods (Hankin & Reeves, 1988). The focus of this study is the Elk River mainstem, upstream of the Elk River salmon hatchery near Anvil Creek to the forks of the upper mainstem (Figure 1A). Surveys were completed during low summer flow between late July and mid-August for approximately 3 weeks per year from 1992 to 2001. Over these weeks, channel units were classified as pools, riffles, glides, cascades, and steps. Survey crews consisted of 2 to 3 individuals. One person identified channel unit dimensions: length, width, and depth (Hankin & Reeves, 1988). Channel unit dimensions were measured at approximately every 10th unit of each habitat type to allow for correction of unit length based on the proportional bias of the observer (Hankin & Reeves, 1988). An observer counted large wood pieces (length $\geq$ 3 m and diameter $\geq$ 0.3 m; U.S. Department of Agriculture, Forest Service, 2000) positioned with 50% or more of their length in the bankfull zone. Pieces in small aggregations were counted, and dimensions of wood pieces were measured in larger aggregations to estimate their abundance.

The abundance of fish was sampled via snorkeling at every fourth pool, every 10th fast-water channel unit (i.e., riffle), and every second side channel (Burnett, 2001). Sampled fish included steelhead-0, steelhead-1+, juvenile Chinook salmon, coastal cutthroat trout (all age classes), and juvenile coho salmon. In addition, landscape features such as bridges, buildings, and tributary junctions were used as physical markers to reference the channel units linearly (see Chapter 1).

Side channels, steps, and dry channels were excluded from the analysis. Split and side channels were a small percentage of the total channel unit length surveyed each year (3.0 to 4.4%; see Chapter 1). Steps, often step-pool reaches that are steep vertical sections that separate pool habitat (Montgomery & Buffington, 1997), were not sampled for fish. Coho were excluded from this analysis due to low abundance and inconsistent sampling. Ten years of habitat and fish data (5,499 channel units) between 1992 and 2001 were used in our analysis.

Analysis

Stream and Fish Habitat

Linear referencing methods were used in ArcGIS 10.4 (Environment Systems Research Institute [ESRI], 2003, 2014) to 43 referenced each channel unit to the stream network. Cumulative channel unit lengths were positioned between known geographic locations (e.g., tributary junctions, bridges) and calibrated using field-measured geographic locations (see Chapter 1).

Principle components analysis was used to reduce the dimensionality among habitat metrics used in habitat associations, nine variables were reduced to four with the least correlation. The initial nine variables were channel length, wetted width, mean depth, habitat type, distance, large wood abundance, small substrate, medium substrate, large substrate, and bedrock substrate. Based on these results, the final compilation of environmental predictors of fish distributions was channel unit length, mean depth, large wood abundance, absence and presence of pools, the distance of the channel unit to the ocean, and year. To demonstrate the differences in the variability of non-static and static habitat features among years, large wood abundance and channel mean depth were binned using the methods of Welty et al. (2015) in R (RStudioTeam, 2019) at six different spatial scales (resolution): 0.1 km, 0.4 km, 1.4 km, 3.5 km, 14 km, and 28 km (see Chapter 1). The coefficient of variation (CV) was calculated for each spatial scale across 10 consecutive years (1992-2001).

Modeling Approach

Generalized additive models (GAMs) have become increasingly used in fisheries research for predicting abundance (Denis et al., 2002; Venables & Dichmont, 2004) and species distribution (Leathwick et al., 2006; Venables & Dichmont, 2004; Wright et al., 2000). GAMs are semi-parametric extensions of generalized linear models that can fit complex non-linear ecological relationships (Guisan et al., 2002; Hastie & Tibshirani, 1990; Laanaya et al., 2017; Wood, 2011). We developed models using the mgcv package (Wood, 2018) in R (RStudioTeam, 2019). A univariate smooth was used for main effects, and a tensor product interaction was used for mixed effects. A cubic regression spline was used for main effects, and a random effect was used for covariates with more than one-factor level. For fish abundance, a negative binomial method was applied to account for overdispersion, and a log-link function was used instead of transforming count data (Hilbe, 2007; O'Hara & Kotze, 2010; Pedersen et al., 2019; Wood, 2017). The basis dimension parameter, knots (k), was constrained to 6 for GAM models that explained fish abundance. Models were fitted using REML (Wood, 2017), and outputs were assessed for normality of residuals (Maloney et al., 2012). A double penalty approach was used (Marra & Wood, 2011) for final variable selection in the GAM models. The degrees of freedom (*df*), delta Akaike's information criterion (ΔAIC), R^2, and deviance were calculated. Model performance was evaluated using delta AIC primarily (Burnham & Anderson, 2004).

Models

The association between fish abundance and habitat variables was analyzed with GAM models in the mainstem Elk River (Figure 1A) for age-0 and age-1+ steelhead, juvenile Chinook salmon, and cutthroat trout. We compared a range of models of increasing complexity to describe fish-habitat associations in the Elk River (Table 1). We considered a null model that included only the length of a habitat unit (log_{10} transformed) as a covariate explaining the spatial variation in fish abundance. Other habitat variables were included to add complexity to models, including habitat depth (log_{10}), distance from the ocean, and large wood abundance (log_{10}+1). Year and presence of pools were also considered as random effects.

Fish-habitat associations were analyzed from year to year and across an average of 10 years under four different model scenarios. The four models focused on two habitat covariates, large wood and channel mean depth, representing dynamic and relatively static stream habitat, respectively. To assess the influence of dynamic and static habitat features on the distribution of fish in the Elk River, we modeled the influence of large wood and channel depth in two ways. For each variable, we assessed model performance when using the annual observations of each of these habitat features and compared model performance against models that included a 10-year average based on GAMs, fit to the distribution of observations across the study period (Figures 1C and 1D). (Table 1). The 10-year averages (i.e., outputs from GAM models) are the expected average wood abundance and expected average mean depth as a function of distance from the ocean. All covariate combinations for each model scenario were considered using the four datasets for large wood and mean depth. Large wood and channel depth data were log-scaled first and then standardized using z-scores prior to model input. Channel length was included in all the fish models as a fixed effect, and year and pool absence and presence were entered into the models as random effects; year had 10 factor levels (1992-2001), and pool had 2 factor levels (presence and absence).

Results

Temporal Variability and Dynamism of Habitat in the Mainstem

Large wood is a dynamic stream habitat feature as indicated by large changes in the spatial distribution of wood from year to year (Figures 1B and 1C). High interannual CV values at a given site indicated that large wood was a more variable habitat feature than mean depth over the span of 10 years (Figure 1B). The range in CV is narrower for mean depth from fine to coarser resolutions (0.1 km to 28 km) in comparison to the CV range for large wood abundance (Figure 1B). The low CV values for mean depth indicate this variable is a relatively static habitat feature compared to the abundance and distribution of large wood (Figure 1B).

The spatial distribution of large wood changed markedly from year to year (Figure 1C). In some years, large wood was evenly distributed across the 28 km of the mainstem Elk River (e.g., 1999, 2000, 2001), but in other years there were striking concentrations of large wood at some sites but not others. The locations of these aggregations of large wood shifted from year to year (Figure 1C). In distinct contrast, the association between distance and mean channel depth in the mainstem were largely unchanged from year to year (Figure 1D), with channel depth decreasing smoothly with increasing distance from the ocean.

Fish abundance in the mainstem Elk River showed substantial spatial variation across the river, but the spatial distribution changed from year to year (Figure 2). Both age classes of steelhead were distributed throughout most of the Elk River across the study period. Higher densities of Chinook were observed in the lower mainstem, and cutthroat, which were lower in density than the other three fish, were observed primarily in the upper reaches of the mainstem in the earlier years (Figure 2).

Associations Between Instream Habitat and Juvenile Salmonids

Model 1, including annual wood abundance and annual mean depth as covariates, had the lowest AIC, thus best fit, for steelhead-1+, Chinook, and cutthroat fish abundances across 10 years (Table 1, Table 2). Thus, these taxa, their association with large wood was maintained through time, despite the spatial distribution of wood in the river corridor changing markedly among the years. The effect of habitat unit length was retained in all models considered, though it is important to note that abundance was related to the log of habitat unit length, and that this relationship showed a clear tendency to be saturating.

For steelhead-0, Model 2 had the lowest AIC, which included the expected 10-year average wood abundance and annual mean depth (Table 2). Model performance was highest when all covariates were included: channel length, distance, mean depth, large wood abundance, absence and presence of pools, and year (Table 2). The addition of distance from the ocean to the null model, which is the length of the channel unit, improved model fit considerably (Table 2).

Close examination of Model 1 (Fig. 3) yielded a positive association between mean depth and fish abundances across the 10 years for the three taxa with larger sized fishes (i.e., steelhead-1+, Chinook, and cutthroat, Figure 3). For young-of-year steelhead (i.e., age-0), Model 2 explained a negative association between mean depth and steelhead-0 abundance showing their distinct preference for shallow water. The positive associations between mean depth and three fish abundances reached a saturation point, but the associations remained positive (Figure 3). For large wood, Model 1 explained a positive association with all fish abundances, except steelhead-0 (Fig. 3). A weak association between large wood and steelhead-0 was observed.

Discussion

This unique dataset reveals a combination of dynamic and static habitat features that constitute the riverscape of the Elk River. We observed examples of the dynamism of large wood, a reflection of a heterogeneous cycle of recruitment and transport throughout the river corridor. This shifting habitat mosaic was observed in the dynamic distribution of large wood over time and the positive association of wood and the abundance of the dominant fish taxa in this ecosystem. Three fish in this study were found to track wood as its spatial distribution shifted over the course of a decade. We tested the shifting habitat mosaic by varying the effect of a dynamic habitat feature and a relatively static habitat feature on fish abundance. Ultimately, model fit improved when accounting for annual distributions of wood and annual mean depth, except in one case in which 10-year average wood and annual mean depth was a better fit (i.e., steelhead-0), which demonstrated the overriding importance of shallow water for this age class of steelhead. We also observed annual mean channel depth, a relatively stable habitat feature, to be the most important habitat covariate affecting the distributions of all fish species.

Processes that play out across a range of spatial scales, from the microhabitat to stream level, give rise to habitat mosaics that characterize rivers. The natural flow regime of a river is a factor that heavily influences these patterns and processes (Poff, 1997) of the shifting habitat mosaic, including short temporal events of seasonal flows and long temporal events, such as extreme flood events. The processes responsible for these patterns include the transport of organic matter and annual sedimentation that may influence flow velocity at the short time scales of a few hours to one year, as well as events such as large landslides and alluvial infilling that may cause stream migration and can form new first-order channels at the longer millennium time scale (Frissell et al., 1986). Channel depth is associated with changes that occur on a longer time scale associated with the geomorphic evolution of the riverscape. In contrast to channel depth, large wood is dynamic and responsive to changes across short-term seasonal processes and longer-term decadal to centennial processes influenced by hydrologic change and wood recruitment and transport (Wohl et al., 2019). We showed that the relationships between the spatial distribution of salmonids in the Elk River and stream habitat features are maintained for both persistent and dynamic habitats, i.e., channel depth and large wood, respectively. It appears that as disturbance mechanisms impact stream habitat in the Elk River, including a major flood event that occurred in 1996, fish-habitat associations were maintained through time.

This study also contributes to further understanding steelhead, a ubiquitous fish that exhibits a varied life history pattern. The data in this study showed a negative association between steelhead-0 and mean depth, supporting observations of juvenile fish preferring shallow habitat at that age. However, for steelhead-1+, Chinook, and cutthroat, a positive association with mean depth was observed in addition to a saturation point indicating habitat preference up to a particular channel depth. These two distinct patterns of fish associations with channel depth support the ecosystem nexus of a dynamic and complex habitat that is preferred and needed to support the different life history needs of Pacific salmonids (Bisson et al., 1997; Bjornn & Reiser, 1991; Hiers et al., 2016; Quinn, 2005).

The saturating relationship between local fish abundance and the log of habitat unit size is noteworthy because it suggests that the transition between different habitat units (i.e., riffles, pools, glides) is ultimately the most important habitat affecting fish distributions. Thus, rivers with substantial variation in habitat types are likely to be more productive than those characterized by lower spatial variation and larger habitat units with fewer breaks between habitat types.

The characterization of the shifting habitat mosaic in the Elk River was only possible with high-resolution habitat data collected over tens of kilometers and an extended period. Accounting for year was critical to capture the annual distributions of large wood and fish abundance. Furthermore, a longitudinal profile of the mainstem Elk River in a section of the stream network mostly undisturbed from anthropogenic activities provided the environmental conditions to test the shifting habitat mosaic. Long-term spatially continuous data are still rare (Anlauf-Dunn et al., 2014; Flitcroft et al., 2012; Isaak et al., 2007; McMillan et al., 2013); thus, the insights provided by studies such as this are particularly valuable because they highlight dynamics that are not detectable in less detailed or extensive studies.

The contemporary conservation and management of rivers should emphasize key functions of riverine systems, including shifting habitat mosaics, that are maintained through time to allow aquatic and terrestrial life to flourish into the future. The loss of freshwater habitat from past river restoration practices that diminished habitat connectivity and decreased thermal and habitat heterogeneity (Bisson et al., 2009; Clark et al., 2021) will likely be exacerbated by climate change (Mote et al., 2003). Maintaining natural disturbance regimes to ensure that habitat complexity supports diverse ecosystem communities is an important goal (Beechie et al., 2009; Bisson et al., 2009; Reeves et al., 2013). A shift in restoration approaches to restore watershed processes is taking place to focus less on individual habitat characteristics at the local scale (Beechie & Bolton, 1999), such as altering stream channel structure (Roni et al., 2008; Roni & Quinn, 2001). The emplacement of semi-permanent structures to mimic large wood may be more detrimental to riverine health and natural disturbances that sustain species diversity (Penaluna et al., 2018). We present a strong case that both dynamic and static habitat features provide important habitat attributes in rivers and that restoration and conservation efforts should directly embrace strategies to maintain both types of features. Past proposals establishing watershed-level reserves of functionally intact ecosystems, to provide the patch dynamics required for the life history needs of aquatic organisms (Reeves & Sedell, 1992; Reeves et al., 1995), might be the conservation and river management needed to ensure that shifting habitat mosaics continue to provide critical key functions into the future.

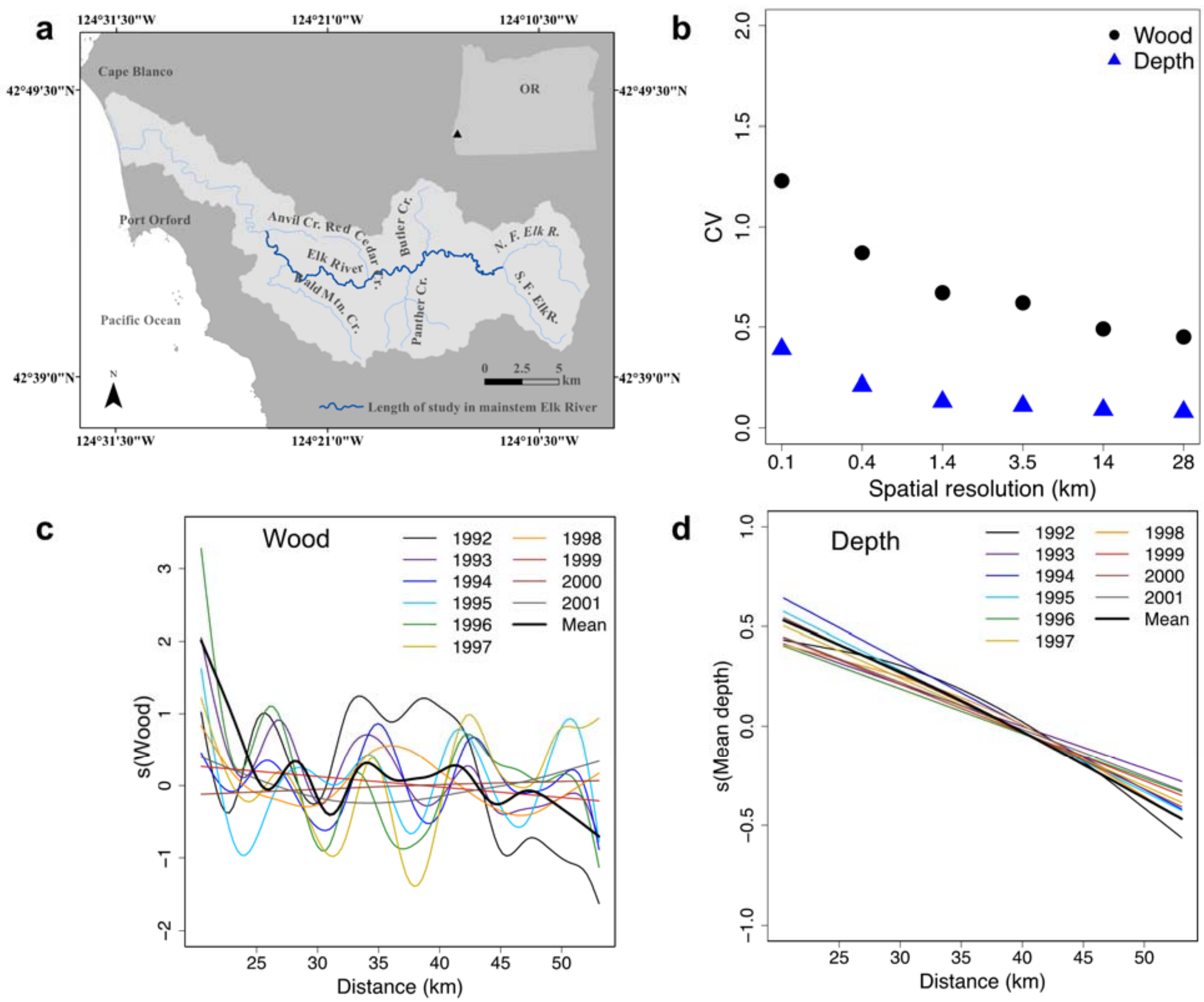


Figure 1 | The temporal and spatial variation of large wood and channel mean depth. A. Map of the study area in the Elk River, OR, USA. The spatial extent of the mainstem analyzed is marked in dark blue (28 km). B. Coefficient of variation (CV) across 10 years (1992-2001) for large wood and mean depth at six different spatial scales. C. Nonparametric response of large wood abundance. D. Nonparametric response of channel mean depth (m), as a function of distance (km) in the mainstem Elk River from 1992-2001. Lines show partial effects plots from 16-knot GAMs within each year of the study. The heavy black line in panels C and D are the long-term average distribution across all 10 years of the study.

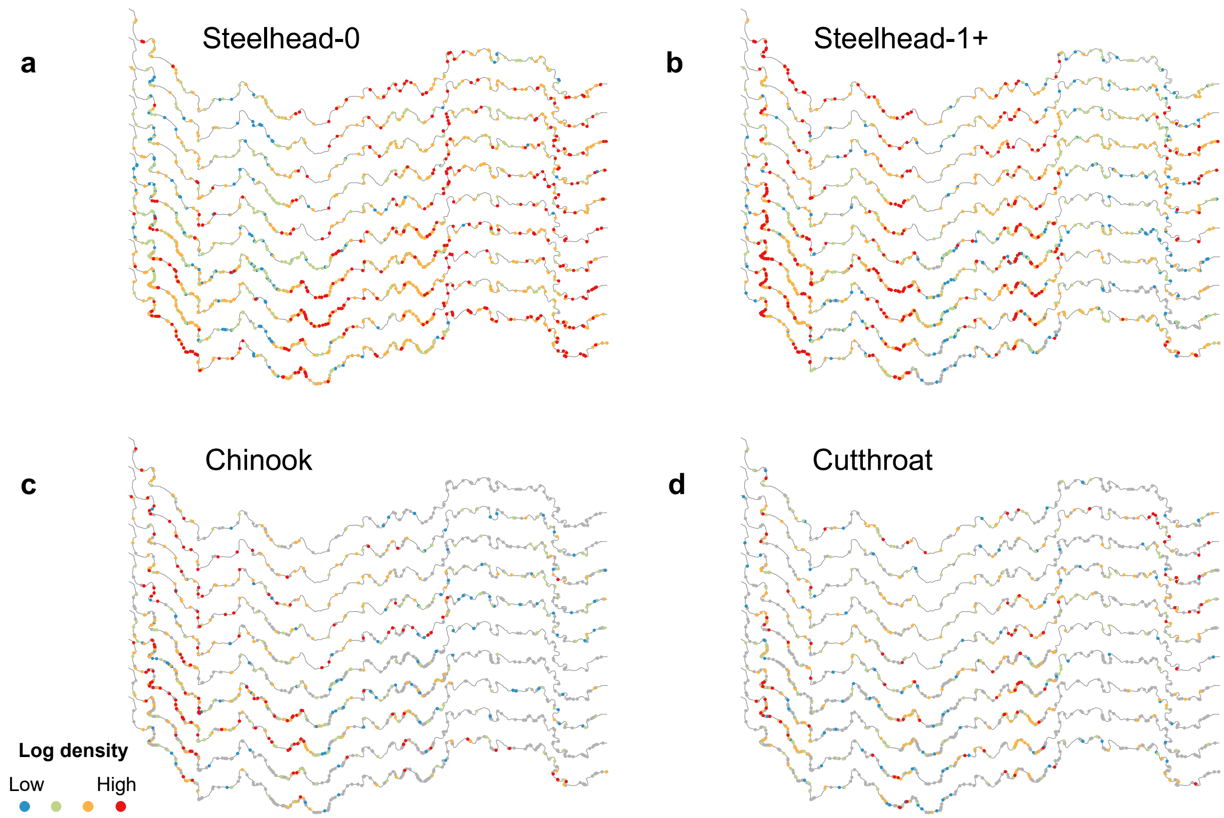


Figure 2 | Annual relative density of fish m^{-1} in the Elk River mainstem from 1992 to 2001. A. Steelhead-0, B. Steelhead-1+, C. Chinook salmon, and D. Cutthroat trout. The density of fish, expressed as fish/m of stream, is $\log_{10}$ transformed for each year and displayed at four intervals or four colors. The earliest year (1992) is shown as the top line, and the most recent year (2001) is shown as the bottom line in each quadrant.

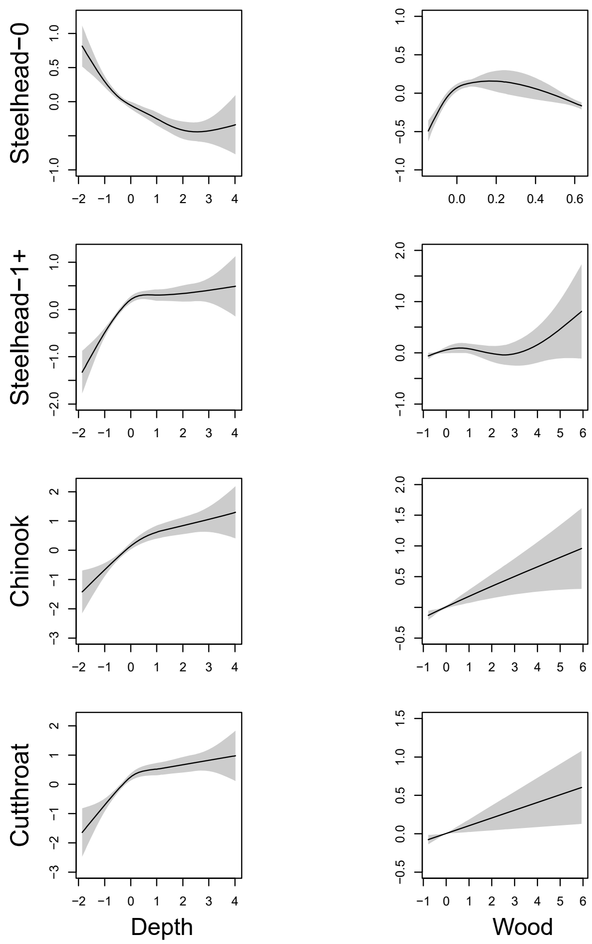


Figure 3 | Estimated effects of channel depth and large wood on the abundance of four fish species. Nonparametric response of fish abundances as a function of mean depth and wood in the mainstem Elk River from 1992-2001. Both channel depth (m) and wood abundance are logged (log_{10}) and z-scored. All Model 1 output except for Steelhead-0 (Model 2).

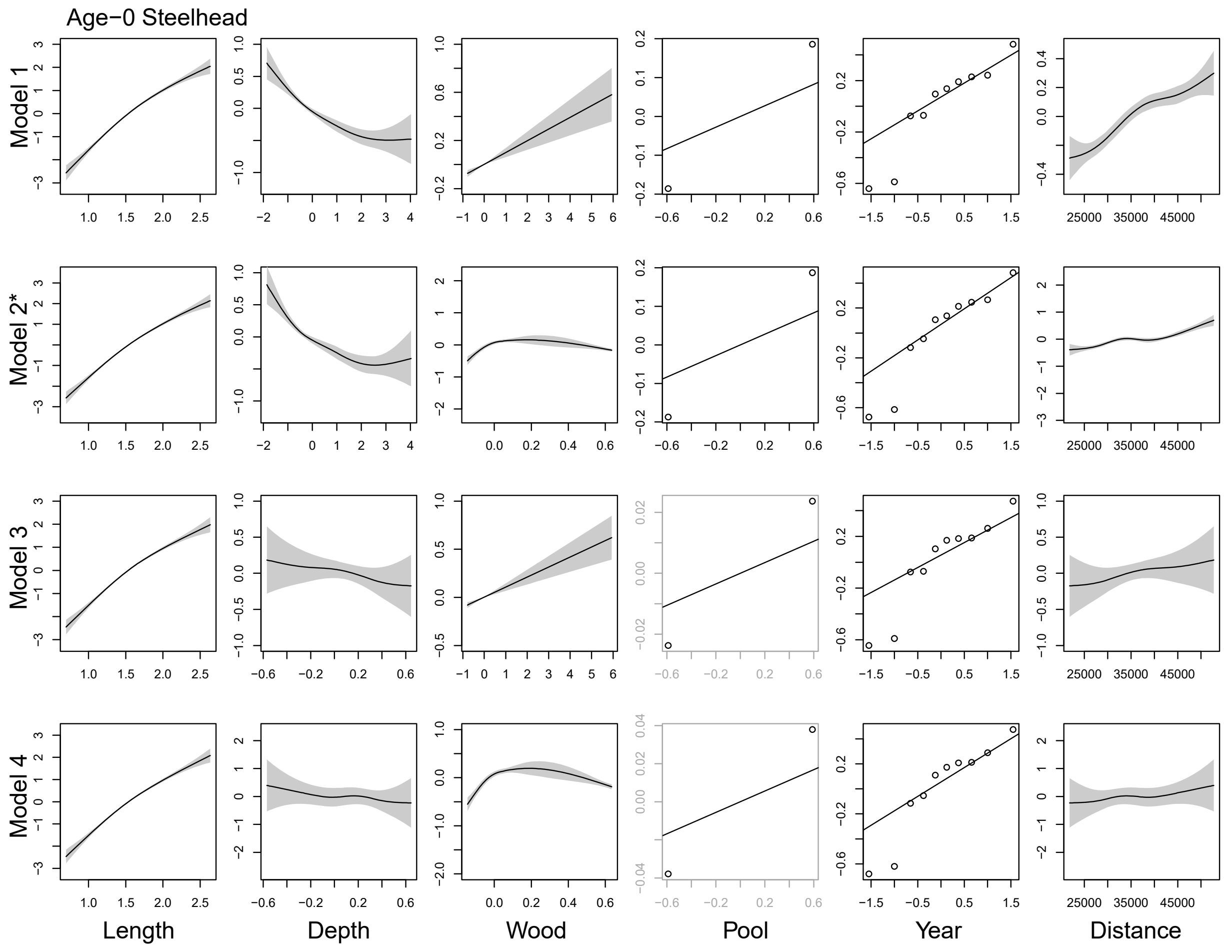
Table 1 | Alternative generalized additive models used to quantify associations between fish abundance and habitat features. Models 1, 2, 3, and 4 include all environmental predictors used to predict fish abundance. Model 5 is the null model that accounts for the effect of habitat unit size (as $\log_{10}$ of channel length) plus distance from the ocean, and Model 6 is the null model that accounts for only habitat unit size. Wood and mean depth were entered as annual wood (AWood), annual mean depth (Adepth), 10-year average wood abundance (Gwood), and 10-year average mean depth (Gdepth).

Model	**Environmental predictors**
1	Length+Distance+*Awood*+*Adepth*+Pools+Year
2	Length+Distance+G*wood*+*Adepth*+Pools+Year
3	Length+Distance+*Awood*+G*depth*+Pools+Year
4	Length+Distance+G*wood*+G*depth*+Pools+Year
5	Length+Distance
6	Length

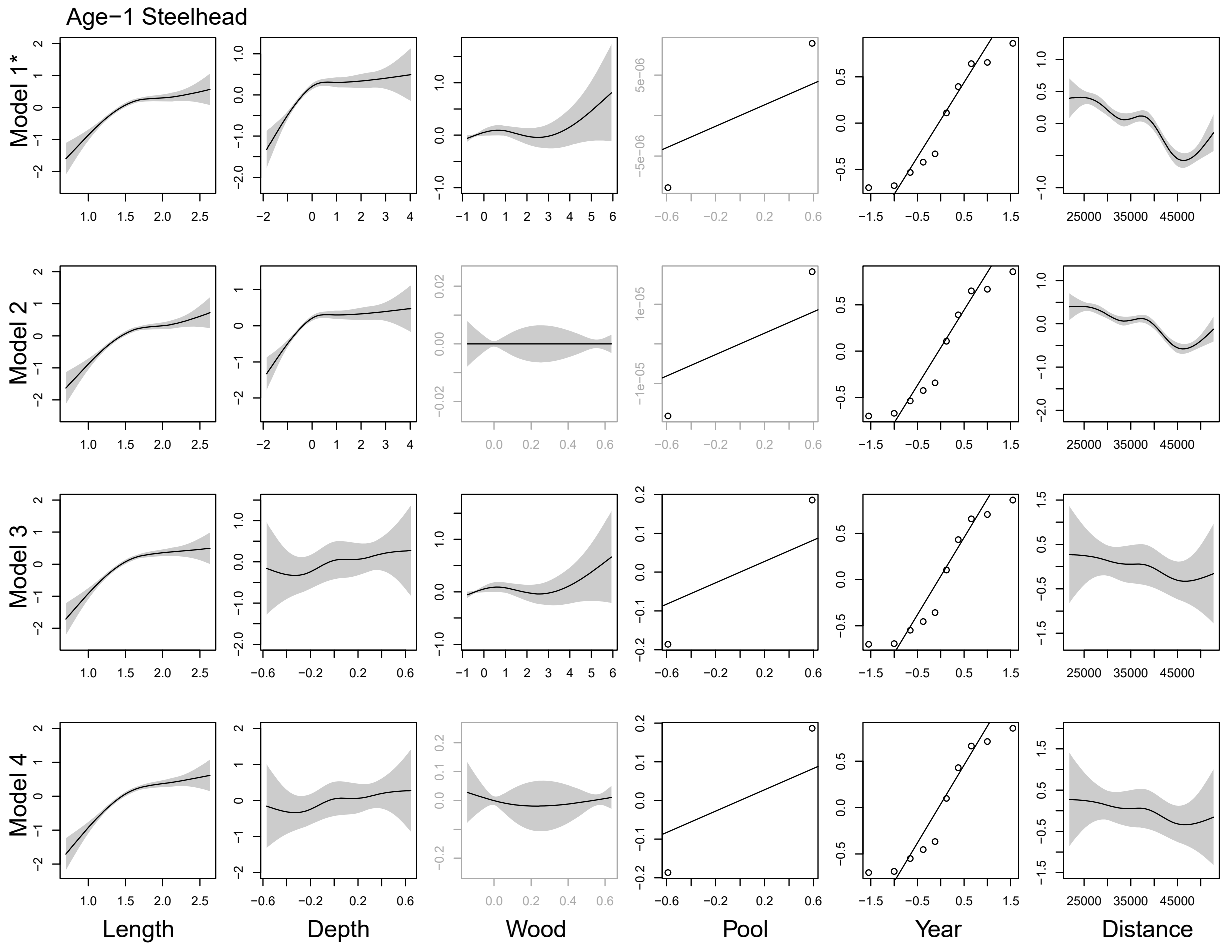
Table 2 | Analysis of model performance for Models 1-6. Degrees of freedom, delta Akaike's information criterion (Δ AIC), coefficient of determination (R^2), and deviance were calculated for each model and each fish.

Model	*df*	AIC	ΔAIC	R^2	Deviance
	Age-0 Steelhead				
2	26.16	18335.39	0.00	0.59	0.63
1	21.58	18367.61	32.22	0.58	0.62
3	21.79	18370.71	35.32	0.60	0.62
4	23.55	18382.33	46.94	0.60	0.61
5	9.02	18842.72	507.33	0.40	0.50
6	4.61	18964.92	629.53	0.36	0.46
	Age-1+ Steelhead				
1	23.36	12311.04	0.00	0.41	0.36
2	22.02	12317.65	6.61	0.38	0.36
3	23.20	12363.61	52.57	0.41	0.34
4	21.36	12366.75	55.71	0.38	0.34
5	5.44	12864.81	553.77	0.12	0.13
6	4.32	12918.67	607.63	0.10	0.10
	Chinook				
1	22.65	6228.51	0.00	0.44	0.64
2	21.57	6239.93	11.42	0.46	0.64
3	19.90	6268.12	39.61	0.46	0.63
4	19.53	6272.13	43.61	0.46	0.62
5	8.27	6854.80	626.29	0.26	0.35
6	4.43	6972.34	743.83	0.19	0.28
	Cutthroat				
1	20.37	3986.72	0.00	0.23	0.30
2	20.31	3993.23	6.52	0.23	0.30
4	18.28	4026.87	40.15	0.22	0.28
3	17.60	4028.54	41.82	0.21	0.27
5	5.05	4190.90	204.18	0.12	0.16
6	3.03	4193.09	206.37	0.12	0.16

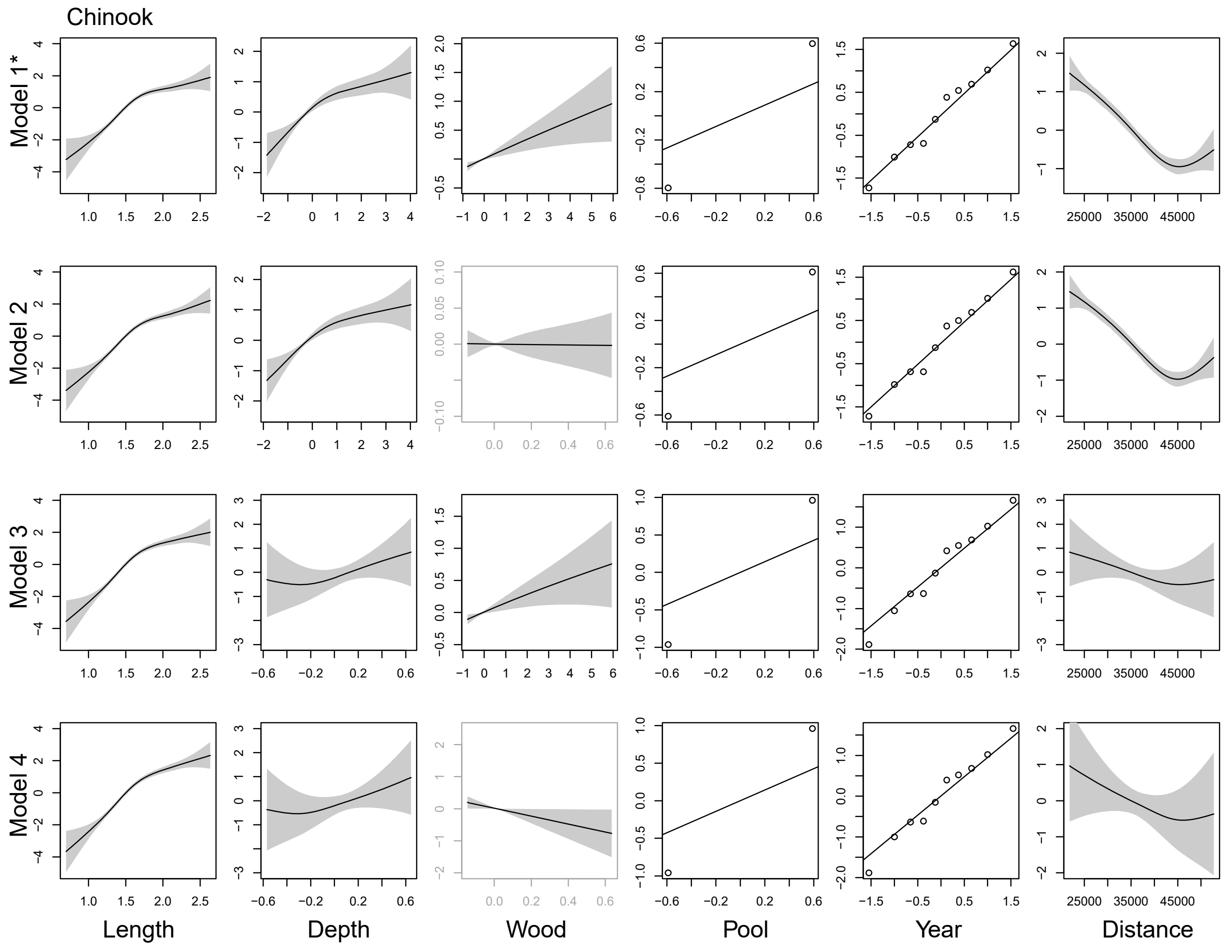
Extended Data



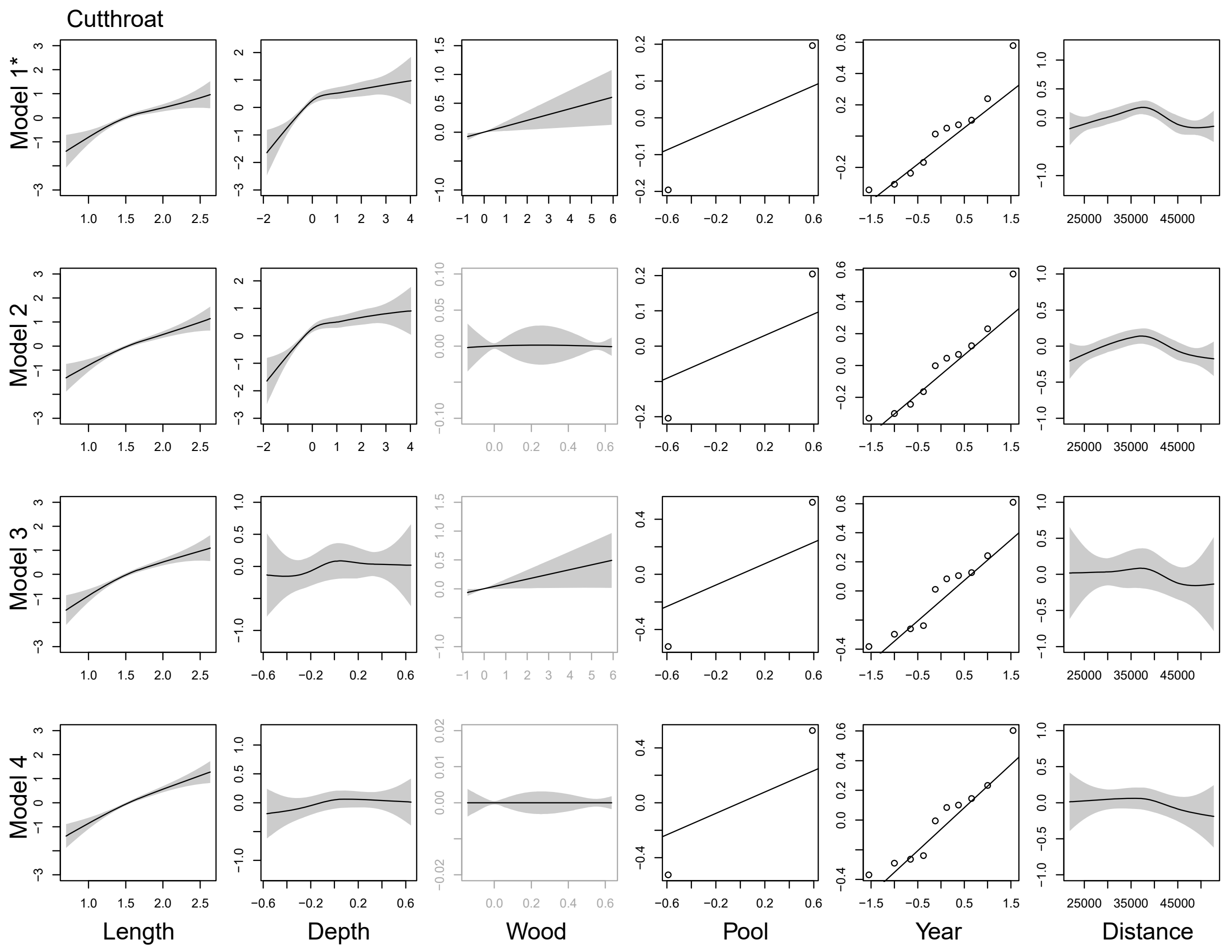
Extended Data Fig. 1 | Estimated effects of 6 covariates on steelhead-0 abundance. Length is logged (log_{10}), and both channel depth (m) and wood abundance are logged (log_{10}) and z-scored. Variable selection removed pools in Model 3 and Model 4 (indicated by grey axes).



Extended Data Fig. 2 | Estimated effects of 6 covariates on steelhead-1+ abundance. Length is logged (log_{10}), and both channel depth (m) and wood abundance are logged (log_{10}) and z-scored. Variable selection removed pools in Model 1, removed wood and pools in Model 2, and removed wood in Model 4 (indicated by grey axes).



Extended Data Fig. 3 | Estimated effects of 6 covariates on juvenile Chinook abundance. Length is logged (log_{10}), and both channel depth (m) and wood abundance are logged (log_{10}) and z-scored. Variable selection removed wood in Model 2 and Model 4 (indicated by grey axes).



Extended Data Fig. 4 | Estimated effects of 6 covariates on coastal cutthroat trout abundance. Length is logged (log_{10}), and both channel depth (m) and wood abundance are logged (log_{10}) and z-scored. Variable selection removed wood in Model 2, Model 3, and Model 4 (indicated by grey axes).

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CHAPTER 3: IMPROVING CLIMATE SERVICES FOR TRIBES: RECOMMENDATIONS FROM A NATIONAL SURVEY OF SERVICE USERS AND PROVIDERS

Abstract

As the impacts of climate change become more pronounced – especially among frontline communities – adequate provision of climate services will be critical for informing effective and equitable adaptation measures. To better understand the state of climate services available to Native American tribes, we surveyed tribal climate service users and providers across the contiguous United States and Alaska. At national and regional scales, the survey assessed the availability and usefulness of 28 distinct climate services among tribes and non-tribal entities and asked how these services could be improved. Although we showed that the available climate resources typically meet the needs of tribes to complete the early phases of the adaptation cycle; provider responses indicate fewer services support the later phases in their place of work. The greatest barriers to climate-preparedness activities reported were lack of staff time and funding. Grants and workshops are two climate-related services that survey respondents found valuable. Non-interactive resources such as blogs and newsletters scored were less valuable. Geographies unique to tribal decision-making (e.g., reservation-federal, trust land, ancestral territories) were rated extremely relevant to climate preparedness activities compared to more conventional geographic designations. Survey respondents frequently described specific data needs, relationships, and adaptive capacity when asked about challenges relevant to their climate preparedness activities and how disliked climate services could be improved. Our findings may be used by a wide range of climate service providers to better support tribes in their resilience efforts.

Introduction

Climate services have been developed to assist climate preparedness efforts by governments and communities, i.e., to bridge the gap between climate science products and the information needs of leaders and decision-makers (Findlater et al., 2021). Climate services include climate resources and tools that involve the generation, provision, and contextualization of information and knowledge for decision-makers (Vaughan & Dessai, 2014). However, climate services have well-documented limitations. These include institutional barriers which constrain service provision (Bierbaum et al., 2013; Lemos & Morehouse, 2005; Lemos et al., 2012), discrepancies between users' and providers' understandings of the usefulness and usability of specific services (Lemos & Boyd, 2010; Lemos et al., 2012), mismatches between services and needs (Cash et al., 2003; Stone et al., 2001), the lack of scalable climate services (Bray & Von Storch, 1997; Callahan et al., 1999), and needs for improved relationships between decision-makers and providers (Jacobs & Street, 2020; Smith & Kelly, 2003; Whyte, 2020). Yet, the status of climate service provision and use by Tribal and other Indigenous communities, including their availability and effectiveness, remains unexplored in the context of their decision-making.

Climate change disproportionately affects Indigenous People, whose livelihoods and ways of life are threatened by climate impacts, particularly those that result in sea-level rise and decreased access to land bases and subsistence foods critical to cultural survival and tribal economies. Ongoing socioeconomic inequities for frontline communities that stem from a legacy of colonialism and land dispossession are exacerbated by climate impacts that further strain tribal adaptive capacity and threaten sovereignty and self-determination. Despite these inequities, tribes continue to demonstrate a high resilience to a changing environment and have conducted over 800 tribal climate-preparedness activities in the decade before 2018 (Jantarasami et al., 2018). Maintaining tribal livelihoods and planning for sustainable futures in a changing environment requires context-specific user-driven decision support tools. Vulnerability assessments and adaptation planning are vital to informing land and water governance by influencing policy outcomes and climate initiatives that directly affect the lifeways of Indigenous communities.

A growing body of work on indigenous groups' climate adaptation and mitigation activities has emphasized the wide range of climate-preparedness activities underway or completed by tribal people in the United States (Jantarasami et al., 2018; STACCWG et al., 2021; Sampson, 2015). Studies examining collaborative partnerships across climate science organizations and tribal groups (Dhillon, 2021; Kalafatis et al., 2019) showed the need for equitable partnerships and revealed the nuances of building climate networks. The importance of establishing long-term relationships and identifying responsibilities to improve future adaptive climate capacity in indigenous communities (Whyte, 2013) is one factor that impacts climate adaptive capacity development. The cultural, social, and economic ramifications of climate impacts that disproportionately and uniquely affect indigenous communities (Maldonado et al., 2013) provide background on the highly contextual needs of these user communities. Research on land-based activities and the wide range of climate sustainability projects by Indigenous communities (Norton-Smith et al., 2016; Simmonds, 2011) included the highly variable and contextual nature of climate capacity and land and water governance across spatial and temporal scales.

To understand the state of climate services in tribal communities, we conducted an online survey to assess the availability and usability of 28 distinct climate services among indigenous groups and community entities and identify remaining gaps and opportunities for improvement. We emphasized the experiences and perspectives of tribal staff and tribal-serving professionals engaged in climate-related decision-making. Specifically, we assessed their use of climate services and critical barriers to their adaptation efforts and offered recommendations for improving service provision. The results may help ensure climate service needs are met in indigenous communities.

Methods

Survey Design and Analysis

We collected empirical data to understand the status of climate services available to Indigenous Peoples and capture the survey respondents' experiences, perspectives, and realities. We sampled from a closed population of staff and environmental professionals who engage with climate services available to these communities and those employed by the Indigenous Nations, the federal government, non-profit, or charitable funder entities. We focused our sample population on those who work within the contiguous United States and Alaska.

We designed a survey to provide insight into engagement with climate services and climate-related activities. The survey quantitatively assessed 28 different climate services and qualitatively described the perspectives and opinions on these services and activities. The survey was designed using Qualtrics ©, Version 2020 (Qualtrics, Provo, UT). The anonymous survey consisted of 11 questions that included multiple-choice and Likert scale questions and short answer questions. Logical reasoning was used to devise some specific questions for users and others for providers only. Three instruments were used: an intake form, the survey, and an additional short survey. If respondents opted-in to the short survey, they received a $20 gift card as an incentive. Weekly reminders to complete the survey were sent over four weeks. We used a deductive coding analysis, employing Dedoose (Version 9.0.46), a qualitative data analysis software, to code short answer responses (Supplement C).

Respondents were asked to identify their primary role when conducting climate-related activities: a user, provider, or both. The climate services referenced in this study were adapted from Nordgren et al. (2016). We provided a definition and an example of each climate service with a clickable link for survey respondents to reference while taking the survey. Key terms with definitions were also provided for climate, climate adaptation, climate preparedness activities, climate services provider, climate services user, and mitigation.

We asked respondents to indicate the value of each climate service and asked the primary role (i.e., user, provider, or both) they held when engaging with a particular climate service. Survey items included challenges faced when conducting climate preparedness activities and how these challenges could be addressed. A section of the survey included items concerning the respondent's engagement in each stage of the climate adaptation cycle: activities started, in progress, or completed. Another question asked about how relevant 19 different geographic domains are to a respondent's climate-related activities. Finally, respondents were asked to report climate services that they like or dislike and how those they dislike could be improved. The supplementary information section includes a copy of the short-form survey (Supplement A) and climate services definitions with a linked example (Supplement B).

Survey Validation and Content Validity

Pilot survey invitations were sent to 21 environmental professionals in different sectors who work in proximity to or with tribal communities and those who do not. Ten completed the survey, and 6 provided additional feedback on ways to improve the survey. The University of Washington Institutional Review Board (IRB) initially received exempt status. However, the

IRB application was submitted a second time to address extra security measures in response to an uncontrolled instrument distribution, including bot activity and unintentional human responses. Therefore, data from the initial survey release were not used in the analysis. In the second approval process, the survey approved by IRB included a short intake form to validate participants' names and employers and a short descriptive statement concerning how the respondent learned about the survey. The short form also included two screening questions to ensure that the age criterion was met and that respondents had a climate service user or climate service provider experience. Individual survey links were then emailed to vetted individuals.

Results

There were 252 individuals who shared interest in taking the survey, of which 157 individuals completed and submitted the short form. Among the 157 responses, 24% indicated a primary role as a user of climate services (*n* = 37), 8% indicated a role as a provider (*n* = 12), 43% indicated roles as both user and provider (*n* = 68), and 25% of respondents indicated they were neither a user nor provider (*n* = 40). Individuals who indicated not having a role as a user or provider did not receive a link to the survey. Individual survey links were sent to 117 individuals, and 53 completed the survey. Of the 53 who completed the survey, two additional individuals were not users or providers, and their data were removed from those analyzed, leaving 51 participants' data for analysis.

Demographics

Of the 51 respondents meeting all the study criteria, 30% (*n* = 15) indicated a primary role as a user of climate services, 17% (*n* = 8) indicated a role as a provider, 55% (*n* = 28) indicated a role as both user and provider, and 4% (*n* = 2) indicated they were neither users nor providers.

Participants were asked if they were members of a Tribal entity or Alaska Native community. The responses indicated that 31% (*n* = 16) responded yes, 61% (*n* = 31) responded no, and 8% (*n* = 4) preferred not to answer. When asked about years of experience, 11 reported 0 to 2 years, 11 reported 3 to 5 years, 19 reported 6 to 10 years, 4 reported 11 to 15, 4 reported 16 to 20 years, and 2 reported 21 years or more. Participants were presented with 12 categories of different types of employers. Most respondents were employed by federally recognized tribal governments (41%, *n* = 21, Table 1), followed by individuals working for non-tribally chartered colleges or universities (18%, *n* = 9; Table 1). The region of residence for respondents spanned the contiguous United States and Alaska, but the largest regional representation was from the Midwest (25%, *n* = 13), followed by the Northwest (22%, *n* = 11; Table 2).

We focused our assessment on responses from staff of tribal entities (*n* = 30; i.e., federally recognized tribal government, state-recognized tribal government, non-profit organization that is tribally focused, and tribal college/university), which includes users (*n* = 14), and users and providers (*n* = 14). We also received responses from staff of non-tribal entities (*n* = 20), i.e., non-profit organizations not primarily focused on indigenous communities, non-tribally chartered college or university, local government, state government, the federal government, charitable/philanthropic foundation, and private sector. These groups included users (*n* = 1), providers (*n* = 6), and some who were both users and providers (*n* = 13).

The Roles of User and Provider in Climate Services Engagement

Among the staff of tribal entities, 47% (*n* = 14) identified primarily as users of climate services, 7% (*n* = 2) identified as providers, and 47% (*n* = 14) as both users and providers. Among staff of non-tribal entities, 5% (*n* = 1) identified primarily as a user, 29% (*n* = 6) identified as providers, and 67% (*n* = 14) as both users and providers of climate services.

Users of tribal entities had both user and provider roles for almost two-thirds of the 28 climate services while holding a provider role for only four climate services (i.e., youth outreach and education, curriculum, case study, and talking points, Figure 1). In almost equal numbers, users, and providers of tribal entities held the user or both user and provider roles while engaging with a climate service. Users and providers of tribal entities held a provider role for 18 of 28 climate services.

Where do People Learn About Climate Services?

We asked participants where they first learned about new climate services. The staff of tribal entities shared that they learned about climate services primarily from their community (i.e., project collaborators, colleagues) and through speaking with others in the field. One respondent described, “The best way to hear about these [climate services] in our community (place) is by word of mouth or fliers [sic] posted around local establishments” (P43, User of tribal entity). The second highest mentioned that sources for learning about climate services were federal agencies, followed by tribal networks. The staff of non-tribal entities most often learned about climate services from federal entities, followed by their communities, then from colleges and universities, and lastly via tribal networks. The staff of tribal entities and non-tribal entities responded that they learned about climate services from various agencies (e.g., tribal or federal) and networks through various formats, with emails and newsletters receiving the most significant mention. For example, a participant who listed more than one source of learning explained, “Various listservs from state, federal, and inter-Tribal organizations, partners I work with often, or from webinars” (P21, Provider of tribal entity). Only a few staff members of non-tribal entities mentioned that they learned about climate services from the private sector or charitable or philanthropic foundations.

Climate Services of Value

Participants were asked which climate services are most valuable to their work using a 5-point scale from not valuable to extremely valuable. More than half of users of tribal entities ranked grants as extremely valuable (78%, *n* = 11; Figure 2). Climate services that include engagement with peers that allow for peer learning and shared experiences were ranked next as extremely valuable and very valuable. These experiences included conferences (57%, *n* = 8) and workshops (50%, *n* = 7) ranked as both extremely valuable. Most participants ranked training as very valuable (50%, *n* = 7; Figure 2). Blogs were ranked the lowest as slightly valuable (54%, *n* = 7), followed by pledge/political activism and conflict mediation. Almost half of the climate services received a very valuable or extremely valuable ranking. Most participants ranked six climate services as extremely valuable and very valuable (> 75%, e.g., grants, conferences, workshops, scientific report/data source, training, and tools). Users and providers of tribal entities ranked grants and networks highest. Climate services that provide in-person interactions or shared experiences (i.e., workshops and conferences) ranked lower for users and providers of tribal entities. Youth, outreach, and education were ranked high by users and providers and ranked low by users of tribal entities.

Status of Completed Climate Adaptation and Mitigation Stages

When asked about the stages of climate adaptation planning and mitigation completed (nine stages were offered), participants identified as users of climate services from tribal entities (*n* = 14) marked more stages in progress than completed in the adaptation planning cycle. More participants gave reports of a combination of "Not planned" and "Planned but not started" for almost all stages except for "Raise awareness" and "Monitoring." A "Not planned" status was the most frequent response for “Adaptation plan implementation” and “Update adaptation plan using new information or priorities.”

Among providers (*n* = 6) and users and providers (*n* = 13) of tribal entities, there were more climate services indicated as provided for the earlier phases of the adaptation cycle (i.e., Raise awareness, Vulnerability assessment, and Identify risk, and plan, assess climate adaptation options; Figure 3B, 3C). A high percentage of users and providers indicated a “Not provided” status for the later phases, most notably for “Climate mitigation.” Providers indicated equal instances of climate services that are “Not provided,” “Planned but not provided,” and “Provided” for “Climate mitigation” (Figure 3C). Both users, and users and providers, of tribal entities explained that more climate services were provided for in the earlier phases than the later phases of the adaptation cycle (Figure 3A, 3B, 3C).

Geographic Domains Relevant to Climate Preparedness Activities

Survey respondents were presented with 19 different geographic domains and asked to rate each domain’s relevance to their climate preparedness activities. Geographies relevant to the decision-making needs of indigenous groups were marked as highly relevant (e.g., usual and accustomed area, trust lands, reservation-federal) by users and users and providers of tribal entities (Figure 4). Providers of non-tribal entities ranked city/metropolitan, state, and county as highly relevant and very relevant. In contrast, users and providers of non-tribal entities ranked city/metropolitan, state, and county with lower ranks and ranked traditional territories, usual and accustomed area, and ancestral territories higher than providers did. Across all users and providers of tribal and non-tribal entities, reservation-federal was consistently ranked either third or fourth highest or extremely relevant. Watersheds were also ranked consistently mid to high with extremely and very relevant. Both staff of tribal and non-tribal users and providers ranked

Hydrologic Unit Code the lowest, with the fewest respondents indicating it as extremely relevant. Additional geographies submitted by respondents were specific to their geographic area of interest or tied to land and water governance (e.g., “The coastal redwoods of Northern California,” from P27 (User tribal entity), “Indian burial grounds, bayous, oyster reefs,” from P19 (User and provider of tribal entity), and “Tribal Fee Simple Lands,” from P39, User tribal entity).

Preferred Climate Services and for What Reasons?

We asked respondents why they liked a particular climate service. Short answer responses were grouped into five categories: accessibility, community engagement, targeted or curated data, examples of climate service providers, and examples of climate services engaged. Participants identified as users and providers of tribal entities commented twice as often as users of tribal entities concerning specific climate service providers and services they like. Users of tribal entities commented more often about targeted and curated climate services, while users and providers had no comments on these services. There were few comments on community engagement and accessible climate services from either group. More non-tribal users and providers than providers of non-tribal entities commented on specific examples of climate services that they preferred, such as community engagement, accessible climate services, and targeted and curated data.

Various providers of climate services were listed. For example, one participant wrote, “GLIFWC [Great Lakes Indian Fish & Wildlife Commission], ITEP [Institute for Tribal Environmental Professionals], [and] NC CASC [North Central Climate Adaptation Science Center]: These organizations seem to be more forward-thinking and wanting to prepare for the impacts of climate change in the future. They also seem to put out more information more often and regularly reach out and engage" (P39, User of tribal entity). Another participant responded with "ITEP (Institute for Tribal Environmental Professionals) trainings; tribe-to-tribe info sharing/learning" (P28, User and provider of tribal entity), and another stated, "ITEP [Institute for Tribal Environmental Professionals]; ARCUS [Arctic Research Consortium of the U.S.], ALASKA CASC [Alaska Climate Adaptation Science Center]" (P10, User and provider of tribal entity). A third respondent, P48 (Provider of non-tribal entity) mentioned, "NOAA Regional Climate Services—have trusted information, know the states and tribes, know what's available, trained climate scientists."

Some respondents provided examples of specific climate services with which they engage. Among all respondents, two of the most mentioned climate services were tools and workshops. Among participants from tribal entities, tools and webinars came up often in responses, followed by conferences and networks. Users of tribal entities commented on relevant climate services that are regionally scaled (i.e., fact sheets, planning guide). One of these participants expressed, "We don't have an internal list of climate data and tools. We do have experts to work with and often do meet with them. It depends on a case-by-case basis as tribes need" (P29, User of tribal entity). For participants of non-tribal entities, tools and workshops appeared most often in their responses, followed by fact sheets and applied research. Other reasons included accessibility of climate services described as non-technical, clear, open-source, and a good summary. Target or curated climate services were described as context-specific or regionally scaled data. A survey response that mentioned working with experts on a case-by-case basis, was coded as targeted or curated.

Climate services that include a form of community engagement were also favored. These were described as offering trust and relationship building through interpersonal interactions. For example, "Workshops. I appreciate the hands-on application, and I feel it helps practitioners from different fields and organizations a chance to interact in constructive ways" (P41, User and provider of non-tribal entity). Another example of interpersonal interactions was, "Localized factsheets help in providing context for the impacts and changes that occur in an area. The in-person engagements have helped with gaining more trust in Tribal Nations and organizations" (P18, User and provider of non-tribal entity).

Why Climate Services are Disliked and for What Reasons?

Participants were asked to explain why they did not like particular climate services. Most responses were in three categories: data, lack of interaction or communication, and specific examples of climate services disliked. Users of tribal entities and users and providers of tribal entities commented with equal frequency on data-specific items as reasons for disliking a climate service. Users and providers offered a few more comments on specific climate services they did not like compared to the other respondents. Among those associated with non-tribal entities, providers had fewer submitted comments than other respondents. Across all participants, there were fewer comments on lack of interaction and communication as a reason for disliking a climate service.

Regarding climate services data, participants described a dislike for data that were too broad, having too much information, not curated, limited in geography, inaccessible, and having more jargon than desired. One respondent commented on limited geography, "Any that aren't applicable to our area. Alaska is as unique as the climate-sensitive issues we face, and often resources are geared toward the lower-48 states" (P43, User of tribal entity). Another participant shared, "Some online tools — they tend to be general across all Tribes, so the data isn't specific enough to be used in any planning efforts" (P32, User tribal entity). A comment concerning too much information was, “Sometimes the EPA data can be confusing and simply not helpful. While having all the background data is great, sometimes I just want a simple, climate-for-dummies answer” (P30, User and provider of tribal entity). Another comment on limited geography was,

> Climate Explorer, because it only allows searching by city and county. Some tribes’ lands overlap multiple counties, and relationships between tribal and county governments may be strained, making using county data problematic. FEMA floodplain mapping online because it only includes riverine floodplains, not areas that are subject to other types of flooding, which are common in the west. It’s also limited to the data FEMA has now, which is typically very minimal on tribal lands. (Yet FEMA is promoting this product to tribes at conferences.)” (P16, User and provider of non-tribal entity).

Respondents explored various examples of disliked climate services. Some services were described as missing pertinent information, requiring fees to access publications, and lacking clear directions on the best use of a tool. Two responses reflected these impediments; one respondent commented, “It doesn’t feel like there’s a clear best practice or best tool for estimating emissions from land-use change and/or carbon sequestration by forests and working lands” (P12, User tribal entity). Another participant shared, “Planning guides — while they have been useful when we were in the planning phase, not many of these planning guides focus on implementation” (P1, User and provider of non-tribal entity). A preference for in-person interaction when engaging with climate services was also shared. One respondent preferred face-to-face interactions and expressed, “Online planning. I really think people need to be face to face discussing the issues that are most relevant to them and how they will move forwards together” (P31, Provider of non-tribal entity).

Suggested Improvements for Climate Services

Participants were asked about climate services that they disliked and also about how these climate services could be improved. Various responses were received and grouped into five categories, data improvements, relationships and communication, capacity building, and examples of specific climate services to be improved. Both participants of tribal and non-tribal entities commented frequently on specific data improvements, while users of tribal entities and users and providers of non-tribal entities submitted more comments on data specifics to be improved than users and providers of tribal entities and providers of non-tribal entities. In addition, users and providers of tribal and non-tribal entities offered more comments than users or providers within their respective groups on suggested improvements. Some comments on data-specific items included, “The long, complicated data can be great, but also having a simple overview for policy-makers would be best” (P30, User and provider of tribal entity). Comments on specific climate services included, “WQX- simplify the process for uploading data; GIS — make it a one-stop-shop for our data” (P10, User and provider of tribal entity). Finally, P32 (User tribal entity) highlighted a need for scalable and regionally relevant data:

> There is a need for the expansion of climate services into remote and regional areas of Alaska, as climate services tend to be tailored for use in the lower 48 states. In some cases, general tools that are supposed to meet the needs of multiple tribes, are not specific enough for planning efforts.

One respondent gave a few examples of improvements to be made:

> It would help to have clear procedures for requesting climate projections from CASCs and RISAs, and also understand if and when there may be costs for these projections. All federal agencies mapping climate projections and natural hazards should ensure their

systems are searchable based on tribal boundaries (using the most up-to-date tribal boundary maps). This should be considered part of the federal government's trust responsibility. FEMA should comprehensively improve the data it has related to how flooding occurs and flood possibilities on tribal lands. (Tribes should not be expected to individually find the funding for this and should not have to get matching funds for this work (P16, User and provider of non-tribal entity).

A comment on relationships and communication emphasized, "Ensure that all voices from the Tribal Nations are considered throughout the working process. The climate service provider should assist but not lead in decision-making for these communities" (P18, User and provider of non-tribal entity).

Challenges Faced When Conducting Climate Preparedness Activities

When asked about how challenging specific activities are when conducting climate preparedness activities, participants were asked to rank 18 different challenges on a 5-point scale from not challenging to extremely challenging. Among users of tribal entities, a large majority of the participants ranked "Lack of staff time" (71%, n = 10) and "Funding" (46%, n = 6) as the most extremely challenging to their climate preparedness activities (Figure 5). These responses were followed by "Integrating into policy" (36%, n = 4) primarily as extremely challenging and "Implementing actions" (46%, n=6) primarily as very challenging (Figure 5). The top three challenges for users and providers of tribal entities included "Integrating into the policy" (64%, n = 9), "Lack of staff time" (57%, n = 8), and "Funding" (50%, n = 7), were extremely challenging to their climate preparedness activities. A small number of providers of non-tribal entities (n = 6) mentioned that "Integrating into policy", "Lack of staff time", and "Funding" were all extremely challenging to conducting climate preparedness activities. Users and providers of non-tribal entities (n = 13) rated "Funding" as extremely challenging (n = 5). Other responses that indicated high levels of challenge were a "Lack of staff time" and "Implementing actions," both ranked as very challenging (n = 7). For non-tribal providers and users and providers, the least challenging activities were "Legal issues," while "Learning from others" and "Obtaining reports/data" were the least challenging for both users and providers of tribal entities.

Respondents were prompted to share additional challenges not covered in the survey. Four categories of challenges were coded from these short answers: data needs, capacity building, relationships, and timing. The codes for data needs were specific to data replication, richness, simplicity, and tailoring to decision-making. Challenges related to capacity building included organizational support and monetary support for infrastructure. The temporal dimension of challenges referenced by respondents was limited staff time, the need for real-time solutions, events such as a global pandemic that has hindered or delayed relationship building, and climate-related activities. Relationship-building challenges were also discussed regarding the need to develop more frequent interactions.

Of the four types of challenges identified from responses, challenges related to developing capacity were mentioned more than the others. Several comments from users of tribal entities suggested that staff and leadership support is key to climate-related activities. One participant mentioned, "Getting everyone (from team members to Council) to think about climate change planning. Strategic future planning is needed to make decisions, and key players are not invested" (P39, User of tribal entity), and another stated, "Interest from managers on up" (P47, User of tribal entity). A response on leveraging funds to expand capacity was, "Lack of opportunity for funds to benefit regions opposed to specific areas" (P5, User and provider of tribal entity). Another response explained that "Most challenges are capacity-related" (P33, User tribal entity). One response emphasized the intricacies of timing with all climate-related activities, especially with human interactions:

> Timing — since everything is based on interacting with other humans, sometimes timing for implementation of a project/initiative is not right — either politically or legally, there exist barriers, lack of community support – or not enough resources (staff time, financial). Hence, I'm calling one or more of these factors combining to become "bad timing" (P22, User tribal entity).

Another response that touched on multiple themes was:

> Much of our climate adaptation planning work has been done during COVID, which has made it extremely difficult to conduct outreach with our Tribal communities. In addition, lack of internet access and transportation challenges (shortened ferry season in winter, lots of winter storms causing flight cancellations) has made it difficult to travel to communities even when they are open to outside visitors during COVID" (P14, User and provider of tribal entity).

P1 (User and provider of non-tribal entity) responded with,

> Some of the challenges are linked above – for example, the lack of funding and staff time are usually the two main reasons why implementing actions and monitoring, and evaluation projects don't happen. So, despite all the planning, there's little support to actually do the work in the plans.

Respondents were asked to list specific climate services or data that could help overcome some challenges. Examples included improving capacity building with technical assistance, including providing WiFi in rural tribal communities and supporting tribes' economic development. In addition, some respondents expressed the need to increase funding for staff capacity, support community-led implementation, and provide funding directly to tribes instead of to collaborative partners. The staff of tribal entities commented on the ways that capacity building could address challenges, while the staff of non-tribal entities had half as many comments on capacity building. The tribal and non-tribal entities' staff expressed an equal number of comments on data-specific needs.

Other Topics Relevant to Climate Services Shared by Respondents

At the end of the survey, there was an opportunity for respondents to share topics not covered in the survey. Some of the topics raised centered increased tribal visibility and funding for mitigation action. Other topics mentioned include relationship building, a need to enhance climate services, and other data needs. One comment on visibility reflected that "As a state-recognized tribe, we are often excluded from engagement and inclusion as larger funding pools are processed by local and state government, and they are not mandated to consult with state tribes" (P15, User and provider of tribal entity). While another comment regarding visibility suggested that "not enough people know that our tribe is here" (P19, User and provider of tribal entity). A few comments on mitigation action described that "Place X is continually working towards being a green community member with the upcoming implementation of fleet electrification, Tribal Independent Power Producer, and various sustainable economic development projects" (P43, User tribal entity). Finally, one comment focused on visibility, enhancing climate services, funding, and data needs:

> The survey touched on our problems but, just to emphasize, we are remote and must rely on internet media for most of our access to resources and services. We are very funding limited so do not have sufficient staff to fully engage in needed climate related planning and adaptation. Also, because of finding limitations, it is very difficult for us to keep up

with the climate-related literature published in the leading science journals (P45, User and provider of tribal entity).

Discussion

The survey results show that the climate service needs of tribes are met in some ways at specific stages of climate adaptation that are currently in progress, with a few stages complete, including vulnerability assessments and climate mitigation. Providers of climate services shared that a large portion of the climate services that they provide are aimed at earlier phases of the adaptation cycle; thus, the outcome aligns with the lower activity of users in the later stages of the adaptation cycle. Consistent with other studies (e.g., Nordgren et al., 2016), a notable gap in services was found in the responses by providers of non-tribal entities pointing to climate services that are not provided, particularly in the later stages of the adaptation cycle. Completing some of these stages may be directly linked to the activities ranked as challenging by users and providers. Users of tribal entities mentioned that lack of staff time and integrating into policy were extremely challenging, this may be addressed by institutional support and policy change and should be explored further.

The number of climate services shared by survey respondents and the different combinations of providers from federal agencies, regional environmental networks, and tribal networks suggests that indigenous communities and organizations have access to numerous decision support tools. This suggestion does not imply that all climate services are usable and relevant; indeed, many respondents described particular services and tools that could be improved, such as accessibility, relevance, and data content. Climate services that were ranked as extremely valuable across the user community among tribal entities, such as grants, conferences, and workshops, offer opportunities for providers to engage in these types of climate services further with tribal networks. Interestingly, the data also show that the user and providers of climate services rank the value of climate services differently. This difference supports the need for user-driven provision of climate services to meet the highly contextual needs of place, region, and role when engaging with a particular climate service.

The findings also suggest that the user-provider interface will continue as vital, as exemplified by mentions of tailored climate services and specific data needs in the short answer responses. For example, users of tribal entities shared that extremely relevant geographies are linked to tribal decision-making (e.g., usual and accustomed area, trust land), and some participants provided additional geographies when prompted after ranking how relevant geographic domains are to their climate-related activities. Comments made regarding place-specific needs and scalable climate services from local to regional show communities' variable and specific data needs. Not surprisingly, providers of non-tribal entities shared city, state, and county as geographies of extreme relevance.

In our assessment of survey responses, most notably short answer responses, three primary needs emerged from the experiences and perspectives shared by survey respondents. These three themes are capacity building, data, and relationships. The results show specific data needs that have not been met for decision-making among indigenous communities and Tribal Nations and that challenges faced when engaging with climate services primarily point to capacity building. A third central piece is relationships or partnerships that ultimately influence the usability and effectiveness of climate services. Climate services, if strictly approached as demand-driven with a focus on products, may miss some critical aspects of the demand-relevant and process side of climate services production (Findlater et al., 2021). However, aside from the production of climate services, the process side appears to be more critical, in which case relationships are the focus, and other components of relationship building, such as science translation, communication, and co-production, are critical to usable and practical climate services.

While the questions presented in the survey did not explicitly ask about specific data needs, the references made to specific data needs in the short answers suggest that it is a primary issue to be further explored. The data-specific needs shared by survey respondents include data replication, data richness, and different aspects of data accessibility, including tailored data specific to user needs. Data needs such as these have been referred to as intrinsic factors because they relate to the information and how it is produced (Simpson et al., 2016). Specific data needs may be a given in any capacity of climate-related work. An outstanding response among those regarding data was the need for scalable and regional climate services, where certain regions are distinctly underrepresented. This focus may be due to regional provider networks that offer some of the local and regional data needs. In short answer responses, regional providers of climate services were frequently mentioned along with other national climate science providers. Regarding other data needs, gaps pointed to fine-scale relevant data and data that can be scalable for regional and system-wide decision-making. Another area of improvement expressed by respondents is a preference for easily navigable websites with enhanced features to search for data and clear directions on how to apply or use a resource on a website. Other examples of needed data were guidance materials, including climate adaptation projects, community or group protocols for data sharing, and guidance on navigating the nuances of tribal, state, and federal land governance.

The results suggest that capacity-building services are among the most valued and that lack of capacity is a significant barrier to indigenous community climate preparedness. Capacity building, in this sense, is related to the usability of climate services within the range of a community or user's actual capacity to engage with various climate services (i.e., institutional support, staff support, funding; Dilling & Lemos, 2011). When improved, the general capacity building could go a long way toward supporting climate-related activities. Survey respondents stressed the need for funding climate adaptation and mitigation action, organizational and institutional support, and infrastructure needs, such as reliable internet and improved road systems. Funding to build staff capacity was another topic that was often cited. Lack of staffing capacity and funding are widely cited as barriers to climate adaptation efforts (Moser et al., 2018; Nordgren et al., 2016). Another issue raised by respondents was funding for non-federally recognized tribes, as most funding for climate adaptation activities originates from federal programs. A proposal by Moss et al. (2019) to establish a nonfederal "climate assessment consortium" to involve multiple actors in focusing on often overlooked processes of climate services could be a program that brings visibility to communities that do not qualify for federal funding. Long-term institutionalized funding for climate services not constrained to short timelines has also been suggested (Brasseur & Gallardo, 2016).

The data from this study also show a need for ongoing improvements in climate information products and support staff to establish relationships across the user and provider communities. Climate services identified as highly valuable offered an opportunity for co-learning, interpersonal interactions, and shared experiences. Relationships and collaborative partnerships were often mentioned in short answer responses, indicating their importance in any climate-related activity. The staff of tribal entities shared that they primarily source climate services from the community, including colleagues, collaborators, tribe-to-tribe, and through climate services that offer interactions with peers, experts, and others. These climate services are certainly areas to redirect communication and provide opportunities for improving the process of climate services. Some of the challenges that impede climate preparedness activities were the lack of interactions with persons to develop relationships and gain more trust. Interpersonal interactions are key, as higher levels of interactions across users and providers have increased usability and the use of climate services (Kirchhoff et al., 2013). As co-production of knowledge has gained traction (Bremer & Meisch, 2017; Brugger et al., 2016), so have boundary staff and boundary organizations in the climate services field. These are certainly avenues for further developing relationships to help alleviate the burdens of decision-makers identifying or connecting with collaborators or identifying relevant climate services. A challenge to the relationship building critical for adaptive climate capacity is the urgency of climate action that requires fixed projects and short-term collaborations that undermine the natural and slow progression of building relationships or kinship over time (Whyte, 2020).

Our results suggest that future research should focus on how current models of the user-provider interface among users of tribal entities and providers can be improved to enhance and solidify relationship building. Further insight into how flexible grants can help meet the needs of tribes in all stages of the climate adaptation cycle while also increasing tribal capacity to undertake climate preparedness activities could be essential. One topic we did not explicitly address in the survey is specific climate preparedness activities tied to hazards and disasters (Maldonado et al., 2013) and how to best support tribes implementing climate mitigation action. The survey had few responses from staff employed by federal and state agencies and charitable foundations; the result leaves room for future studies because input from staff in these sectors could likely improve understanding of the gaps, challenges, usability, and effectiveness of climate services.

Table 1 | Participating demographics of survey respondents (n = 51). The two responses for "Other" listed University/Academia and an employer spanning three different sectors (Federal, private, and university).

Primary employer	**Percent**	**Count**
Federally recognized Tribal government	41	21
Non-Tribally chartered college/university	18	9
Nonprofit organization Tribally focused	12	6
Private sector	12	6
Federal government	8	4
Tribal college/university	4	2
Other	4	2
State-recognized Tribal government	2	1

Table 2 | Regional representation of survey respondents (n=51). States in the Midwest (IA, IL, IN, MI, MN, MO, OH, WI); Northwest (ID, OR, WA); Southwest (AZ, CA, NV, UT); South Central (LA, NM, OK, TX): North Central (CO, KS, MT, NE, ND, SD, WY); Northeast (CT, DC, DE, KY, MA, MD, ME, NH, NJ, NY, PA, RI, VA, VT, WV); Southeast (AL, AR, FL, GA, MS, NC, SC, TN).

Region of residence	**Percent**	**Count**
Midwest	25	13
Northwest	22	11
Alaska	14	7
Southwest	14	7
South Central	12	6
North Central	6	3
Northeast	6	3
Southeast	2	1

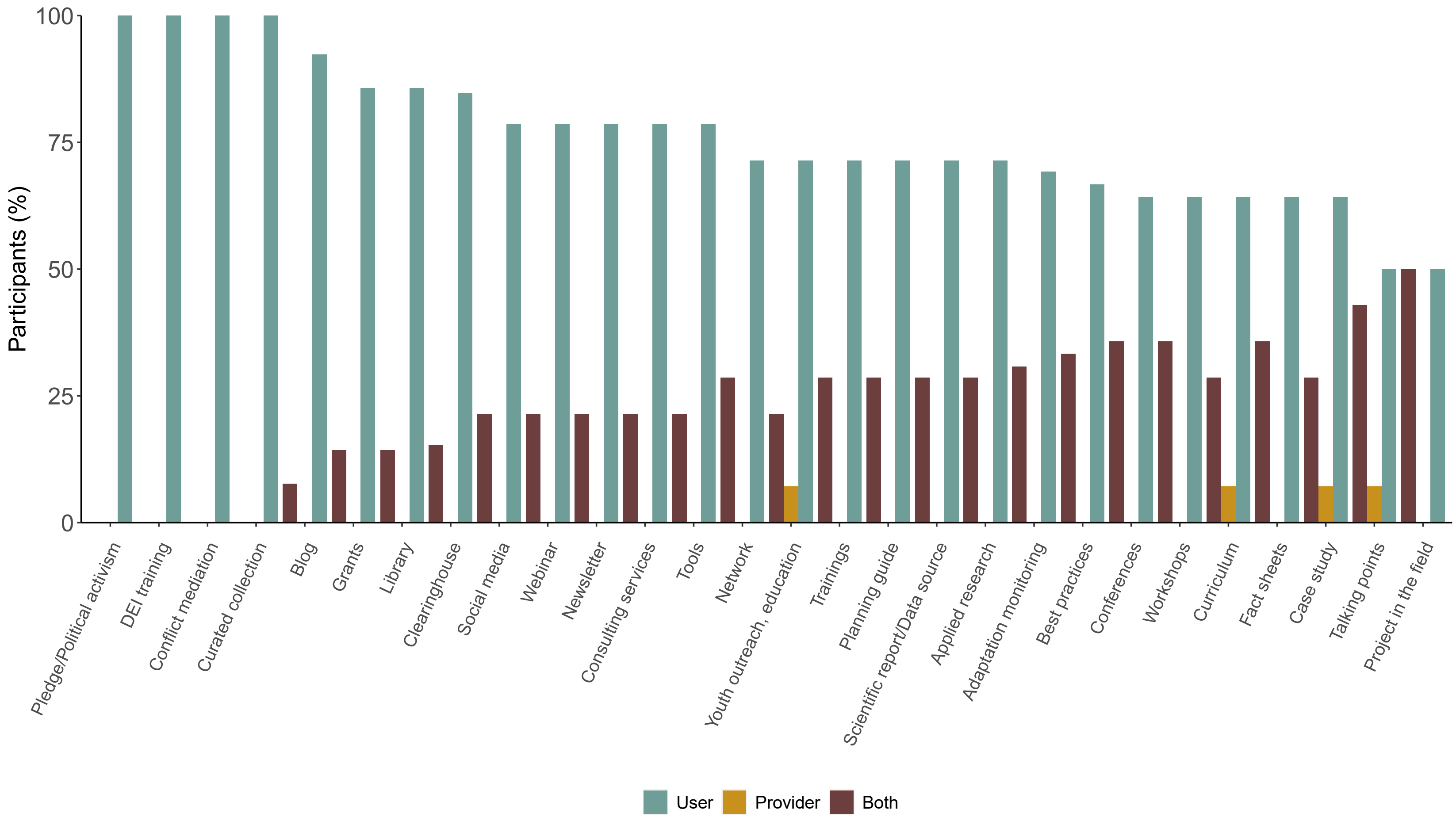

Figure 1 | Primary role held when engaged with each of 28 climate services by users or staff of tribal entities (*n* = 14) in response to, “Indicate the primary role you had when you engaged with (i.e., used or provided) a climate service”.

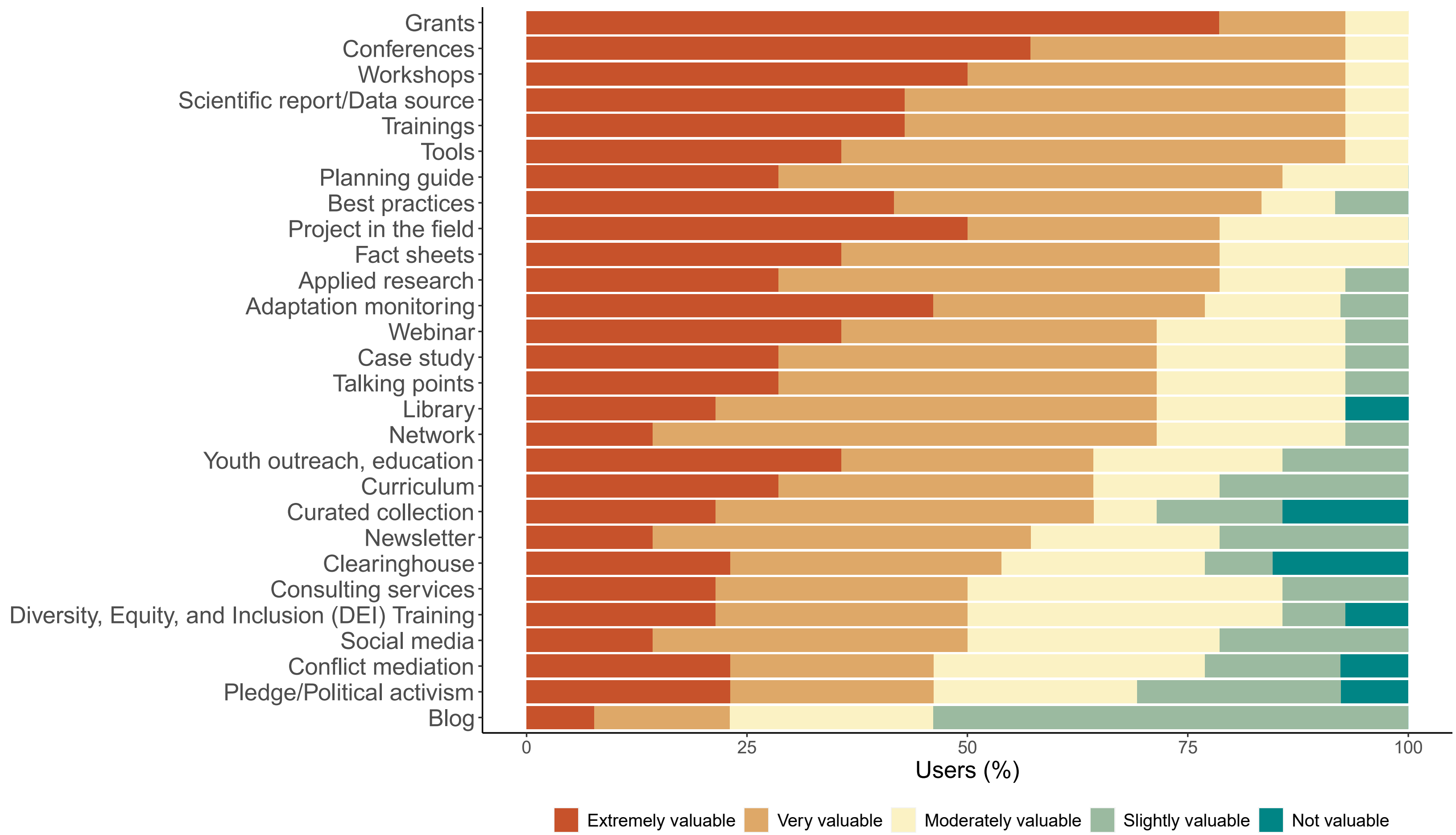

Figure 2 | Percentages of users or staff of tribal entities (*n* = 14) that ranked 28 climate services in the above categories in response to the question, “Which climate services are most valuable to your work?”.

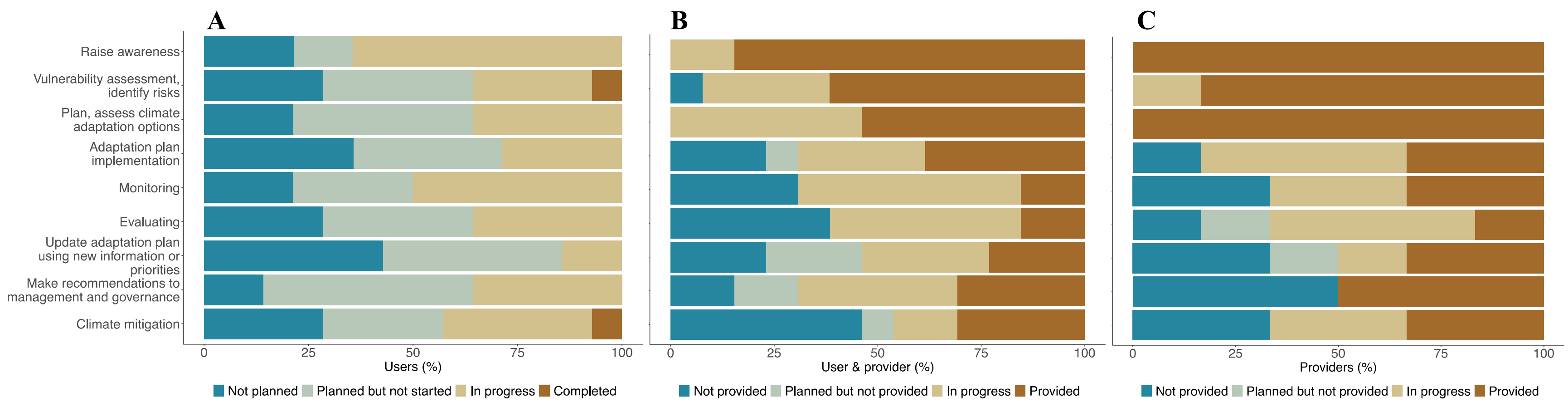

Figure 3 | Stages of climate adaptation planning and mitigation completed by (a) users or staff of tribal entities (n = 14) in response to the question, "What stages of climate adaptation planning/mitigation have you completed?; (b) users and providers or staff of non-tribal entities (n = 13) in response to, "What stages of adaptation planning/mitigation does your place of work provide climate services for?; (c) providers or staff of non-tribal entities (n = 6) in response to, "What stages of adaptation planning/mitigation does your place of work provide climate services for?

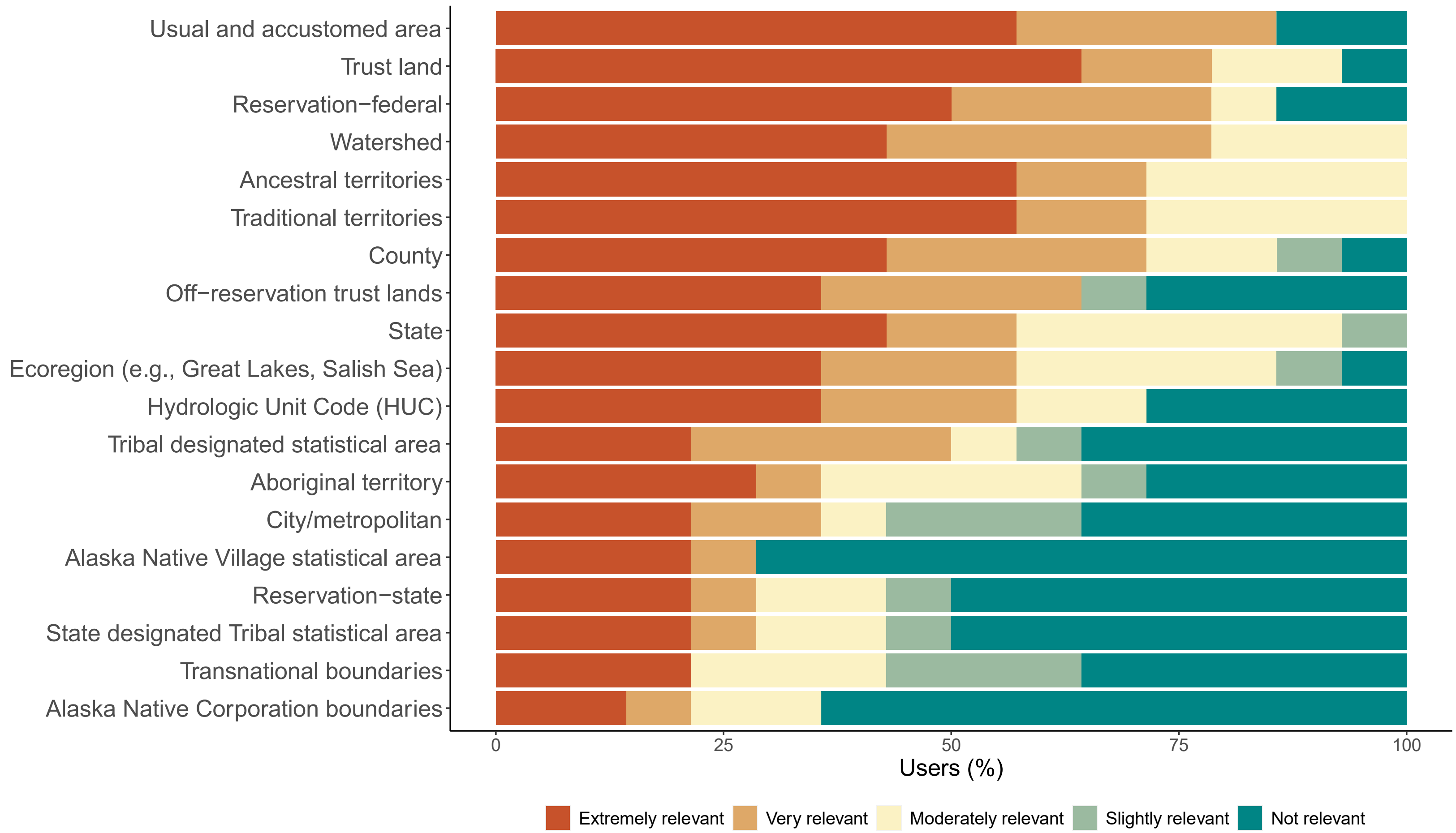

Figure 4 | Percentages of respondents that ranked geographic domains by relevance to climate preparedness activities for users or staff of tribal entities (*n* = 14) in response to the question, “Indicate how relevant each geographic area is to your climate preparedness activities or work”

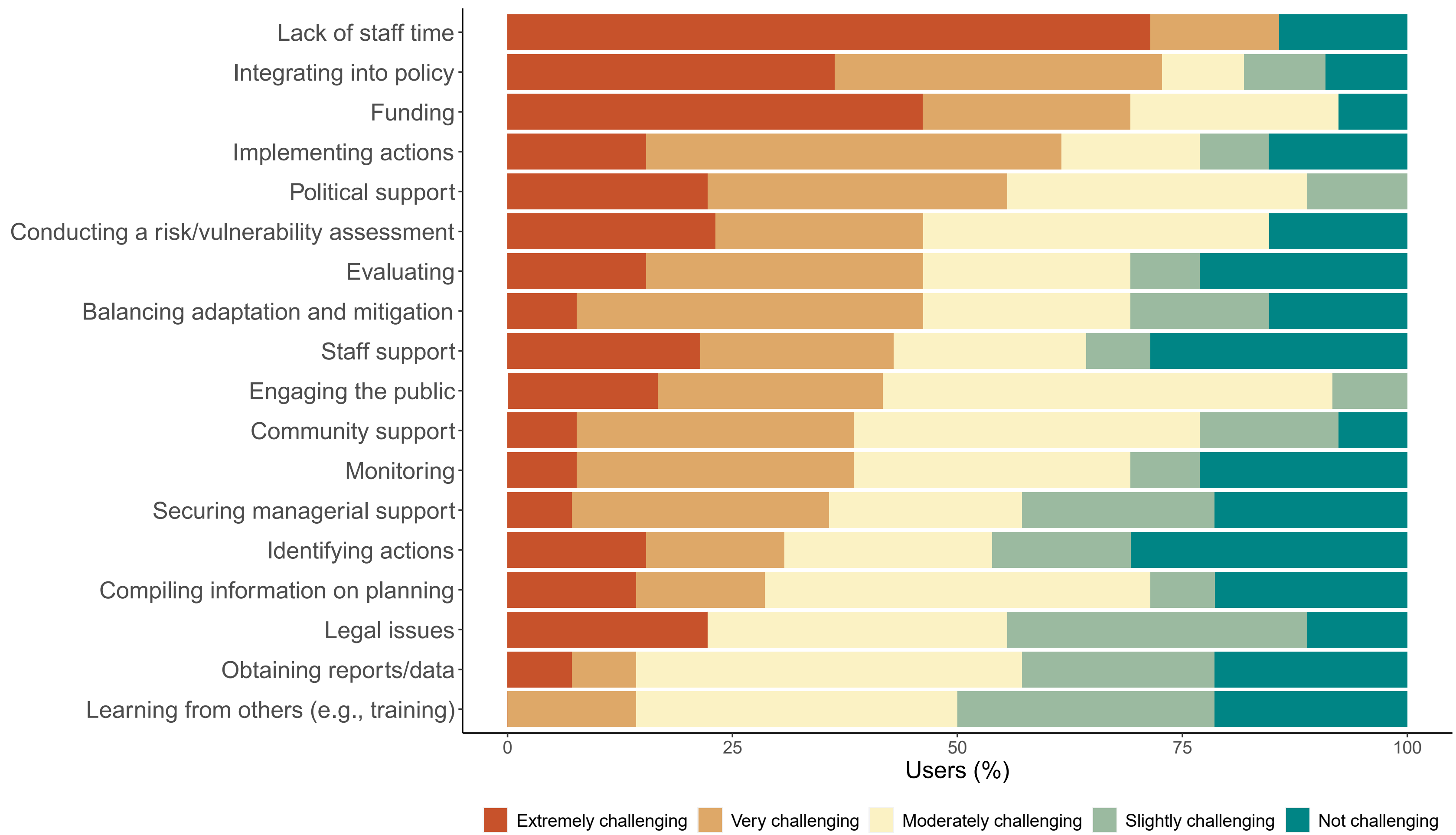

Figure 5 | Percentages of respondents that ranked challenges to a climate preparedness activity in response to the question, "How challenging are each of the following to your climate preparedness activities?" for users or staff of tribal entities ($n = 14$).

Supplemental Materials

Supplement A: Short form to validate potential survey participants and long form full survey

Short Form: Climate Services Survey

SQ1 Are you at least 18 years of age?

- Yes (1)
- No (2)

SQ2 Are you primarily a user or provider of climate services, or both?

Climate services A direct provision of a collection of information service products to specific decision makers. More generally, climate-related resources and tools that include technical expertise, tools, and websites, to name a few.

Climate services provider Supplies climate information and knowledge and participates in the production of demand-driven climate services to be utilized for decision making and climate preparedness activities. Providers may also operate at the local to international levels, and for a private or public entity, or a mixture of both [1]. Providers may also take on the role of a climate service user.

Climate services user Employs climate information and knowledge for decision making [1] and climate preparedness activities. Users may also participate in producing climate service products, taking on the role of both a climate service producer and climate service user.

- User of services (1)
- Provider of services (2)
- Both user and provider of services (3)
- Neither a user or provider (4)

1. Vaughan, C. & Dessai, S. (2014). Climate services for society: origins, institutional arrangements, and design elements for an evaluation framework. Wiley Interdisciplinary Reviews. Climate Change, 5(5), 587–603. https://doi.org/10.1002/wcc.290
Article is viewable on ResearchGate.

Q1
Please enter your full name

____

Q2 *Enter your email address*

____

Q3 *Confirm your email address*

____

Q4 Please list your primary employer

____

Q5 How did you find out about this survey?

____

____

EOS
Thank you for your interest in our study.

Within two business days, you should receive an email from Qualtrics (noreply@qemailserver.com) with "Climate Services Survey" in the subject line. A unique link to the survey that allows one submission will be enclosed. Please check your spam folder if you do not receive an email after 48 hours has passed from the time you submitted this form.

The survey will close on April 18th at 11:59 PM (PT).

If any issues arise, please send a message to kyazzie@uw.edu with "Climate Services Survey" in the subject line.

Climate Services Survey – Long Form Version

Introduction

We are hoping to gain a greater understanding of the state of climate services in Native American communities in the contiguous United States and Alaska. **Survey respondents who complete all questions will receive a $20 digital gift card.**

For the purpose of this survey, "climate services" are climate-related resources and tools (e.g., technical expertise, websites, guides, etc.) that support climate preparedness activities (e.g., climate change mitigation and adaptation). The climate services referenced in this survey are adapted from Nordgren et al. [1].

The goal of the survey is to identify key gaps in the development, accessibility and use of climate services aimed at supporting tribes' climate preparedness efforts. We hope that the outcome of this survey will help increase the effectiveness of tribal climate services and tools.

You do not have to identify with a tribal entity or Alaska Native community in the U.S. to complete this survey. Responses are anonymous. **The survey should take approximately 20 minutes to complete.** You can leave the survey at any time and return to complete it on the same device at a later time. Taking the survey on a personal computer is advised for a viewer-friendly experience. You can complete the survey on a mobile device. Once you complete the survey, you will be redirected to fill out a contact form to receive directions for redeeming your gift card at any one of multiple stores online. **The survey will close on April 18th at 11:59 PM (PT).**

Results from this study will be available as a report and peer-reviewed publication on the NW Climate Adaptation Science Center website (https://nwcasc.uw.edu). The online version of the report will feature data that can be used for purposes that you or others may have. **Results should be available by Summer 2022.**

If you have any questions about this study or if you encounter any issues while taking the survey, please contact Kim Yazzie at kyazzie@uw.edu.

Thank you for your participation!

Kim Yazzie, University of Washington
Kathy Lynn, University of Oregon
Kyle Whyte, University of Michigan
Nikki Cooley, Institute for Tribal Environmental Professionals (ITEP)
Karen Cozzetto, Institute for Tribal Environmental Professionals (ITEP)
Julie Maldonado, Livelihoods Knowledge Exchange Network
Meade Krosby, University of Washington

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1. Nordgren, J., Stults, M., Meerow, S. (2016). Supporting local climate change adaptation: Where we are and where we need to go. *Environmental Science & Policy*, 66, 344-352. https://doi.org/10.1016/j.envsci.2016.05.006
Article is viewable on ResearchGate.

C1

PII **The following key terms appear throughout the survey. You can return to this page at any point in the survey. Where these key terms appear, you may hover over the italicized text in *blue* to see the corresponding definition.**

Key Terms
Climate Average weather for an extended period of time, or expected future trends in weather.
Climate adaptation A response to climate impacts, adjusting to current or expected climate change.
Climate preparedness activities Activities that plan and manage for climate-related impacts,

including climate adaptation and mitigation.
Climate services A direct provision of a collection of information service products to specific decision makers. More generally, climate-related resources and tools that include technical expertise, tools, and websites, to name a few.
Climate services provider Supplies climate information and knowledge, and participates in the production of demand-driven climate services to be utilized for decision making and climate preparedness activities. Providers may also operate at the local to international levels, and for a private or public entity, or a mixture of both [2]. Providers may also take on the role of a climate service user.
Climate services user Employs climate information and knowledge for decision making [2] and climate preparedness activities. Users may also participate in producing climate service products, taking on the role of both a climate service producer and climate service user.
Mitigation Climate action and activities to reduce greenhouse gas emissions.

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2. Vaughan, C. & Dessai, S. (2014). Climate services for society: origins, institutional arrangements, and design elements for an evaluation framework. *Wiley Interdisciplinary Reviews*. *Climate Change*, 5(5), 587–603. https://doi.org/10.1002/wcc.290
Article is viewable on ResearchGate.

Q1a **Do you identify as a member of a Tribal entity or Alaska Native community?** You do not have to identify with a Tribal entity or Alaska Native community to complete this survey.

O Yes

O No

O I prefer not to answer

Q2b **Please identify your primary employer.** If your employer is not listed, please feel free to enter it under Other.

O Federally recognized Tribal government

O State-recognized Tribal government

O Nonprofit organization that is Tribally focused

O Nonprofit organization that is not primarily Tribally focused

O Tribal college/university

O Non-Tribally chartered college/university

O Local government

O State government

O Federal government

O Charitable/philanthropic foundation

O Private sector

O Other (please specify) ____________________

Q2c **In which region of the U.S. do you currently reside?**
Region

▼ Alaska ... I reside outside of the U.S.

PIII **The rest of the survey will make reference to specific climate services and key terms.** Click here **to view the definitions of climate services with examples of each in a new window. Where these climate services and key terms appear, you may hover over the italicized text in *blue* to see the corresponding definition.**

Q2a **Do you use any of these *climate services* to inform your *climate preparedness activities*?** Click here **to view the definitions of climate services with examples of each in a new window.**

O Yes

O No

O I am not sure

O Other (please explain) ____________________

Q2b **Are you primarily a *user* or *provider* of *climate services*, or both?**

O User of services

O Provider of services

O Both user and provider of services

O Neither a user or provider

Q2c **For how many years have you used or provided *climate services*?** Enter 1 if less than a year.
Year(s)

▼ 0 ... 30

Q3 **Where do you first learn about <u>new</u> *climate services* of interest** (e.g., Tribal collaborators, federal programs, Tribal environmental networks, etc.)**?**

____

Q4a **Which *climate services* are <u>most</u> valuable to your work?** Select N/A if "Not applicable". Click here to view the definitions of climate services with examples of each in a new window. You can also hover over the italicized text in ***blue*** to view its definition.

	Not valuable	Slightly valuable	Moderately valuable	Very valuable	Extremely valuable	N/A
Best practices	O	O	O	O	O	O
Case study	O	O	O	O	O	O
Project in the field	O	O	O	O	O	O
Applied research	O	O	O	O	O	O
Fact sheets	O	O	O	O	O	O
Scientific report/Data source	O	O	O	O	O	O
Talking points	O	O	O	O	O	O
Planning guide	O	O	O	O	O	O
Tools	O	O	O	O	O	O
Adaptation monitoring	O	O	O	O	O	O

Consulting services	O	O	O	O	O	O
Newsletter	O	O	O	O	O	O
Blog	O	O	O	O	O	O
Curriculum	O	O	O	O	O	O
Clearinghouse	O	O	O	O	O	O
Curated collection	O	O	O	O	O	O
Library	O	O	O	O	O	O
Webinar	O	O	O	O	O	O
Trainings	O	O	O	O	O	O
Workshops	O	O	O	O	O	O
Conferences	O	O	O	O	O	O
Youth outreach, education	O	O	O	O	O	O
Network	O	O	O	O	O	O
Social media	O	O	O	O	O	O
Conflict mediation	O	O	O	O	O	O
Diversity, Equity, and Inclusion (DEI) Training	O	O	O	O	O	O

Pledge/Political activism	O	O	O	O	O	O
Grants	O	O	O	O	O	O

Q4b **Indicate the primary role you had when you engaged with (i.e., used or provided) a *climate service*. Were you a climate service *user*, *provider*, or both?** Click here to view the definitions of climate services with examples of each in a new window. You can also hover over the italicized text in ***blue*** to view its definition.

	User	Provider	Both user and provider
Best practices	O	O	O
Case study	O	O	O
Project in the field	O	O	O
Applied research	O	O	O
Fact sheets	O	O	O
Scientific report/Data source	O	O	O
Talking points	O	O	O
Planning guide	O	O	O
Tools	O	O	O
Adaptation monitoring	O	O	O
Consulting services	O	O	O
Newsletter	O	O	O
Blog	O	O	O
Curriculum	O	O	O

Clearinghouse	o	o	o
Curated collection	o	o	o
Library	o	o	o
Webinar	o	o	o
Trainings	o	o	o
Workshops	o	o	o
Conferences	o	o	o
Youth outreach, education	o	o	o
Network	o	o	o
Social media	o	o	o
Conflict mediation	o	o	o
Diversity, Equity, and Inclusion (DEI) Training	o	o	o
Pledge/Political activism	o	o	o
Grants	o	o	o

Q5a **How challenging are each of the following to your *climate preparedness activities*?** Select N/A if "Not applicable" (e.g., not relevant to your role). Feel free to list additional challenges below.

	Not challenging	Slightly challenging	Moderately challenging	Very challenging	Extremely challenging	N/A
Engaging the public	O	O	O	O	O	O
Obtaining reports/data	O	O	O	O	O	O
Conducting a risk/vulnerability assessment	O	O	O	O	O	O
Compiling information on planning	O	O	O	O	O	O
Identifying actions	O	O	O	O	O	O
Balancing adaptation and mitigation	O	O	O	O	O	O
Implementing actions	O	O	O	O	O	O
Integrating into policy	O	O	O	O	O	O
Monitoring	O	O	O	O	O	O
Evaluating	O	O	O	O	O	O
Funding	O	O	O	O	O	O
Lack of staff time	O	O	O	O	O	O
Staff support	O	O	O	O	O	O

Community support	O	O	O	O	O	O
Securing managerial support	O	O	O	O	O	O
Learning from others (e.g., training)	O	O	O	O	O	O
Political support	O	O	O	O	O	O
Legal issues	O	O	O	O	O	O

Q5b
Please list additional challenges not listed above that are relevant to your *climate preparedness activities*.

____

Q5c
Please list any specific *climate services* or data that could help you overcome any of the challenges you selected or listed.

____

Q6a **As a *climate services user* what stage(s) of *climate adaptation* planning and/or *mitigation* have you completed?**

	Not planned	Planned but not started	In progress	Completed
Raise awareness	O	O	O	O
Vulnerability assessment, identify risks	O	O	O	O
Plan, assess climate adaptation options	O	O	O	O
Adaptation plan implementation	O	O	O	O

Monitoring	O	O	O	O
Evaluating	O	O	O	O
Update adaptation plan using new information or priorities	O	O	O	O
Make recommendations to management and governance	O	O	O	O
Climate mitigation	O	O	O	O

Q6b **As a *climate services provider* what stage(s) of *climate adaptation* planning and/or *mitigation* does your place of work provide *climate services* for?**

	Not provided	Planned but not provided	In progress	Provided
Raise awareness	O	O	O	O
Vulnerability assessment, identify risks	O	O	O	O
Plan, assess climate adaptation options	O	O	O	O
Adaptation plan implementation	O	O	O	O
Monitoring	O	O	O	O
Evaluating	O	O	O	O
Update adaptation plan using new information or priorities	O	O	O	O
Make recommendations to management and governance	O	O	O	O
Climate mitigation	O	O	O	O

Q7a **Indicate how <u>relevant</u> each geographic area is to your *climate preparedness activities* or work.** This list is not exhaustive. Feel free to list additional geographic areas below.

	Not relevant	Slightly relevant	Moderately relevant	Very relevant	Extremely relevant
Traditional territories	O	O	O	O	O
Ancestral territories	O	O	O	O	O
Usual and accustomed area	O	O	O	O	O
Trust land	O	O	O	O	O
Aboriginal territory	O	O	O	O	O
Reservation-federal	O	O	O	O	O
Reservation-state	O	O	O	O	O
Off-reservation trust lands	O	O	O	O	O
Tribal designated statistical area	O	O	O	O	O
State designated Tribal statistical area	O	O	O	O	O
Alaska Native Village statistical area	O	O	O	O	O
Alaska Native Corporation boundaries	O	O	O	O	O
County	O	O	O	O	O
City/metropolitan	O	O	O	O	O

State	O	O	O	O	O
Transnational boundaries	O	O	O	O	O
Hydrologic Unit Code (HUC)	O	O	O	O	O
Watershed	O	O	O	O	O
Ecoregion (e.g., Great Lakes, Salish Sea, Gulf prairies)	O	O	O	O	O

Q7b
Please feel free to list additional geographic areas not listed above that are relevant to your work.

____

Q8a **Which *climate services* have you engaged with (i.e., used or provided) that you particularly <u>like</u> and why?** You can provide specific examples and website links. Enter N/A if "Not applicable".

____

Q8b **Which *climate services* have you engaged with (i.e., used or provided) that you particularly <u>don't like</u> and why?** You can provide specific examples and website links. Enter N/A if "Not applicable".

____

Q8c **How could the *climate services* that you <u>don't like</u> be improved?** Enter N/A if "Not applicable".

____

Q9 **If there are any other topics or issues relevant to *climate services* for tribes that this survey did not cover that you would like to share, please feel free to do so here.**

____

Q10
Would you be interested in further exploring topics in this survey through an interview or

group discussion? Please select one form of engagement. Your response will help gauge potential interest.

- O Not interested in any form of engagement at this time
- O Phone interview
- O Virtual interview (video)
- O In-person interview at a conference or workshop
- O Group discussion at a conference or workshop

Q11 **Please select all that apply to you.**

- ☐ I completed this survey on a personal computer
- ☐ I completed this survey on a mobile device (e.g., mobile phone, tablet)
- ☐ I used the link provided to view the definitions of climate services in a new window
- ☐ I used the hover over text feature

End of survey
Thank you for your participation.
On the next page you will be redirected to a separate form with instructions on how to redeem your gift card. The form includes a section on how to be notified of results from this study.

Supplement B: Climate services definitions and examples provided to survey participants.

Climate service	**Definition and example**
Best Practices	A document or compilation of statements and guidelines to recommend research practices that are equitable and just for climate-related activities and research. **Ex.** Guidelines for Considering Traditional Knowledges in Climate Change Initiatives (Climate and Traditional Knowledges Workgroup)
Case Study	A self-labeled document or compilation of documents (or stories) that detail specific climate-resilience activities, including lessons learned in a specific region, sector, or department. **Ex.** Moving Forward Together: Building Tribal Resiliency and Partnerships (US Climate Resilience Toolkit)
Project in the Field	Climate-resilience related project or activity that is place-based (located in a specific location or region) aimed at enhancing the resilience of the location or sector. **Ex.** Project Explorer (Northeast Climate Adaptation Science Center)
Applied Research	Climate-specific studies on topics related to climate adaptation and mitigation, and climate-preparedness. A service to a user of climate services. Research may include use of various datasets and tools for desired analysis and products. These may or may not be peer-reviewed sources. **Ex.** Climate Profile for the Fort McDowell Yavapai Nation (Native Nations Climate Adaptation Program, University of Arizona)
Fact Sheets	Brief compilation (generally 1-2 pages) giving useful information about a particular climate-related issue. **Ex.** Flooding, Storms & Pala (Pala Environmental Department, Pala Band of Mission Indians)

Scientific Report/Data Source	Peer-reviewed report or data source that can be used for climate-resilience related activities. These resources may include long or short-term climate or weather data, downscaled climate data, or peer-reviewed science-based reports with utility for local governments. These include sources that have been published outside of academic journals that have been reviewed by experts in the field. **Ex.** The Status of Tribes and Climate Change Report (Institute of Tribal Environmental Professionals, Tribes & Climate Change Program)
Talking Points	Specific messaging material designed to help local governments communicate internally or externally about why they are or need to be taking action on climate change. **Ex.** Climate Talking Points (EcoAmerica)
Planning Guide	A written resource that provides step by step guidance on how a local government or entity can plan for climate change. This includes creating a new or separate adaptation plan as well as strategies for integrating climate change considerations into existing plans. **Ex.** Dibaginjigaadeg Anishinaabe Ezhitwaad: A Tribal Climate Adaptation Menu (Great Lakes Indian Fish and Wildlife Commission)
Tools	A technical resource such as software or an application that is specifically related to climate-resilience. The tool can be related to climate-resilience related processes, accessing relevant information, or facilitating desired outcomes. **Ex.** Tribal Climate Tool (University of Washington Climate Impacts Group, Northwest Climate Toolbox)
Adaptation Monitoring	Any specific programs administered by an organization aimed at tracking the effectiveness of climate-resilience strategies that have been implemented. **Ex.** Seventh Generation Climate Change Monitoring Plan (Bad River Band of Lake Superior Tribe of Chippewa Indians)

Consulting Services	Climate-related services offered for a fee by the organization. This includes fee-based trainings, specific projects in which the consultant leads the engagement, and other services that require an additional fee for the use of the consultant and their resources. **Ex.** Decision Support Tools (Cascadia Consulting Group)
Newsletter	A regularly administered paper or web-based compilation of climate-related material issued periodically to members of the organization or its distribution list. **Ex.** Tribal Climate Adaptation Newsletter (North Central Climate Adaptation Science Center)
Blog	An online website where a person or an organization records climate-related opinions, links to other sites, resources, etc., on a regular (at least monthly) basis. Generally, a blog will be self-identified on the organization's website. **Ex.** News + Blog (Indigenous Climate Action)
Curriculum	Climate-related materials including syllabus, lesson plans, and support materials needed to teach an external party about climate-related issues. **Ex.** CAMEL: Climate Change Education Project (National Council for Science and the Environment)
Clearinghouse	An online repository of climate-resilience related information, tools, resources, etc. The resources stored in the clearinghouse do not need to be from the organization that hosts the clearinghouse. To be classified as a clearinghouse, as opposed to a library, an organization needs to have a fairly comprehensive aggregation of resources related to a given topic. **Ex.** Tribal Climate Change Guide (Pacific Northwest Tribal Climate Change Project)

Curated Collection	A central location, often online, where a curated collection of resources is collected and published for all to use. In contrast to a clearinghouse, a curated collection's resources are not meant to represent a comprehensive list. A curated collection contains just a few resources identified as some of the most useful ones available. **Ex.** Tribal Vulnerability Assessment Resources (Climate Impacts Group, University of Washington)
Library	An online website or series of pages that provide targeted climate-related resources. This resource is almost always self-labeled and much smaller than an official clearinghouse. **Ex.** Adaptation Library for the Western United States (Adaptation Partners)
Webinar	An online event (or series of events) specifically focused on sharing climate-related success stories, lessons learned, or general information (including information on specific tools, resources, and organizations). **Ex.** Tribal Climate Webinar (North Central Climate Adaptation Science Center)
Trainings	A course format to exchange knowledge or learn technical skills and processes for climate-related planning and analysis. **Ex.** Tribes & Climate Change Program (Institute for Tribal Environmental Professionals)
Workshops	Highly interactive small group engagement and knowledge exchange on climate-related issues and topics. **Ex.** Tribal Climate Camp (Affiliated Tribes of Northwest Indians)
Conferences	Large gathering of individuals to exchange research and discourse on various climate-related topics. **Ex.** National Tribal and Indigenous Climate Conference (Institute for Tribal Environmental Professionals)

Youth Outreach, Education	Resources that provide guidance on conducting outreach and education around climate change adaptation for a community's youth. This includes but is not limited to publications, events, tools, and trainings. **Ex.** Tribal Resilience Resources for Youth (South Central Climate Adaptation Science Center)
Network	A group of individuals that have voluntarily elected to be part of an identified "group" based on similarities in interests, job types, or other pertinent climate-resilience related category. Includes professional societies as well as sector-based and peer-to-peer based groups. **Ex.** Rising Voices (The Rising Voices Center for Indigenous and Earth Sciences)
Social Media	Indicates that the organization has a Facebook page, Twitter account, Tumblr account, or other form of social media with which it engages with and attempts to educate its client base or the broader public. **Ex.** twitter.com/se_casc (Southeast Climate Adaptation Science Center)
Conflict Mediation	A resource, documentation, or mediation expert to address climate-induced inequalities and power imbalances, to identify actionable steps to take, including peace agreements, etc. **Ex.** Case Studies Demonstrating the use of Mediation, Consensus Building and Collaborative Problem Solving (Mediators Beyond Borders)
Diversity, Equity, and Inclusion (DEI) Training	Expertise-led training on how to stop social discrimination in climate-related work, including forms of discrimination such as racism, sexism, ableism, and the exclusion of some people based on income, culture, education, and language. **Ex.** Health Impacts of Climate Change: The Role of JEDI (American Public Health Association)

Pledge/Political Activism	A document that local communities (or key decision-makers) can sign on to confirming their commitment to a key resilience-related issue. The pledge or statement generally aims to draw political attention to an issue. **Ex.** Tell the Senate: Invest in a 100% Clean Future (The Center for American Progress)
Grants	Financial support for climate preparedness activities. **Ex.** Tribal Climate Resilience Program (US Interior Bureau of Indian Affairs)

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Article viewable on ResearchGate.

Supplement C: Coding framework for short answer responses

Inductive coding

- Challenges
  - Capacity building
  - Data needs
  - Examples of climate services
  - Relationships
  - Timing

- To help with challenges
  - Capacity building
  - Data specifics

- Climate services liked
  - Accessible
  - Community engagement
  - Examples of climate services
  - Examples of climate service providers
  - Targeted/curated

- Climate services not liked
  - Data
  - Examples of climate services
  - Lack of interaction

- Climate services improvements on not liked
  - Data improvements
  - Capacity building
  - Improve relationships/communication
  - Examples of specific climate services

- Other topics raised
  - Mitigation
  - Visibility
  - Data other
  - Relationships
  - Enhance climate services

- Source of climate services
  - Community
  - Providers
  - Climate services format
  - Specific climate service providers

- Great quotes

- Additional geographies

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