



Environmental preferences and jurisdictional distribution of juvenile loggerheads in the eastern North Pacific



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While the basin-scale movements of North Pacific loggerheads are well documented, habitat use remains poorly understood for juveniles in the eastern North Pacific (ENP), including the exclusive economic zones (EEZs) of Mexico and the United States (U.S.). These areas represent developmental habitats where turtles encounter dynamic environmental conditions, fisheries threats, and management frameworks. Here, we used satellite telemetry data from 53 juvenile loggerheads (2023–2025) to characterize seasonal environmental preferences using sea surface temperature (SST) and chlorophyll-a (chl-a). Juveniles occupied waters with a mean SST of 17.4 °C (10–90th percentile: 15.4–19.9 °C) and mean chl-a concentrations of 0.14 mg/m³ (10–90th percentile: 0.07–0.22 mg/m³). These thresholds were applied to 2014–2025 oceanographic data, representing warm ocean conditions in the ENP, to summarize inferred seasonal patterns of suitable loggerhead habitat across jurisdictions. Suitable habitat shifted seasonally, with 2–31% of the U.S. EEZ and 1–13% of the Mexican EEZ containing suitable habitat annually. Overall, 86% of habitat occurred in areas beyond national jurisdiction, compared to 6% within the U.S. EEZ and 8% in the Mexican EEZ. These findings highlight the transboundary nature of juvenile loggerhead habitat in the ENP and the importance of high seas frameworks for conserving this endangered population in a changing ocean.

North Pacific loggerhead sea turtles (*Caretta caretta*) are a highly migratory and transboundary species, undertaking one of the longest transoceanic migrations of any marine animal. Hatchlings originate exclusively from nesting beaches in Japan and spend years, or even decades, foraging across the central North Pacific (CNP)^{1–4}. While many juveniles may remain oceanic throughout their entire juvenile phase, others move eastward towards waters off North America^{5–7}. Some may enter the exclusive economic zones (EEZs) of Mexico and the United States (U.S.), utilizing a well-documented perennial foraging hotspot off the Baja California Peninsula^{8–10} as well as ephemeral habitats off southern California during warm periods^{11,12}. These habitats represent critical developmental areas¹³, yet a detailed characterization of juvenile habitat use in the eastern North Pacific

(ENP), particularly while transitioning into and within jurisdictional waters, has been constrained by limited data.

Assessing relationships between animal movements and environmental variables is a common approach for identifying critical habitat and informing the spatial management of marine species^{14–17}. Sea turtle habitat selection is shaped by physiological constraints and prey availability; as ectotherms, loggerheads exhibit strong thermal sensitivity, with sea surface temperature (SST) a well-established environmental driver constraining turtle movement, habitat selection, and migratory pathways^{18–20}. In the North Pacific, juvenile loggerhead movements are closely associated with the 18 °C-isotherm, corresponding to the Transition Zone Chlorophyll Front, a region of elevated productivity with oceanographic processes that aggregate prey^{21–23}. Chlorophyll-a (chl-a) concentrations serve as a common

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proxy for prey availability, which also drives spatial and temporal variation in turtle habitat use. Together, SST and chl-a have been widely used to characterize suitable habitat for juvenile loggerheads^{1,2,4,21,24,25}, as well as to inform dynamic management approaches aimed at reducing fisheries bycatch^{16,26–29}.

Notably, climate-driven changes in the North Pacific, including multi-decadal warming, marine heatwaves, El Niño Southern Oscillation events, and shifts in productivity, are altering the location and extent of suitable habitat for pelagic species^{30–34}. These changes may drive migratory species to new areas in search of preferred thermal and foraging conditions^{35,36}, potentially driving habitat redistribution across geopolitical boundaries³⁷. Over the past decade, such environmental drivers have already led to a notable northward expansion of North Pacific juvenile loggerheads, with eastward-moving individuals entering the California Current at higher latitudes, where they may face new mortality risks³⁸. Therefore, improving understanding of juvenile loggerhead habitat preferences in the ENP, including habitat use across jurisdictions, is critical not only for current conservation and management strategies, but also to inform proactive approaches in the face of a changing climate.

Fisheries bycatch is the most significant source of human-related mortality for North Pacific loggerheads, occurring across multiple gear types and varying spatially as turtles move across habitats^{39–42}. During trans-Pacific migrations, turtles are routinely exposed to fishing effort from multiple international longline fleets⁴³, and interactions with drift gillnets and pelagic longlines have historically contributed to population-level declines^{43,44}. While areas beyond national jurisdiction (ABNJ) provide critical habitat for many highly migratory marine species of conservation and commercial concern⁴⁵, implementing effective management measures in these spaces has long been challenging due to a fragmented, sector-specific governance system with limited coordination^{46–49}. Conservation is often treated as a secondary priority, and as such, existing ocean governance in ABNJ has largely failed to adequately protect high-seas biodiversity and ecosystems^{50–53}.

While gear modifications, seasonal closures, and increased observer coverage have reduced bycatch in some high seas fisheries^{16,43,54–58}, fisheries operating within U.S. and Mexican waters also pose a significant threat. In Baja California, bycatch remains a particularly severe source of mortality for large juveniles, with small-scale coastal fisheries operating in this region estimated to kill a minimum of 1000 loggerheads annually^{7,59}. High bycatch

rates in longline and gillnet fisheries, combined with heavy fishing effort in areas of high loggerhead use, have resulted in some of the highest documented stranding rates worldwide. This is particularly intense in the southern Gulf of Ulloa, where strandings are heavily concentrated and strongly correlated with fishing seasons^{7,40}. Notably, because this life stage represents a period of high potential reproductive value, heavy bycatch-driven mortality can have disproportionate population-level consequences⁶⁰. It has been suggested that mortality from small-scale fisheries in this region alone can impede population-level recovery for North Pacific loggerheads³⁹. Thus, robust understanding of juvenile habitat use, across both pelagic and coastal regions, is essential for informing spatial management aimed at supporting population recovery.

Long-term satellite tracking of North Pacific loggerheads has improved knowledge of turtle movements across the central Pacific^{1–5,16,22,23,61,62}, yet comparatively less is known about the subset of juveniles that move into jurisdictional waters off North America. The Sea Turtle Research Experiment on the Thermal Corridor Hypothesis (STRETCH) initiative (www.loggerheadstretch.org) began to address this knowledge gap by intentionally releasing cohorts of juvenile turtles in the previously under-sampled ENP. Originally designed to experimentally test the “thermal corridor hypothesis,” assessing how warm ocean conditions facilitate eastward shifts from the CNP⁵, the turtle telemetry dataset from STRETCH has now enabled new insights into fine-scale habitat preferences, seasonal movements, and cross-jurisdictional behavior of juvenile loggerheads that recruit into the ENP. Early results from this program have documented multiple turtles migrating into U.S. and Mexican waters, offering an empirical window into recruitment pathways that have been relatively understudied (Fig. 1). Given the conservation concern of endangered North Pacific loggerheads, as well as the ongoing fisheries threats and high bycatch mortality across this region, a deeper understanding of habitat use of juveniles across the ENP remains critical. While only a fraction of the North Pacific population may currently move into U.S. and Mexican waters, anticipated climate-driven shifts in ocean conditions may increase the proportion of turtles entering these habitats in coming decades. Therefore, insights into transboundary habitat use afforded by this novel dataset can help inform proactive management, guide dynamic conservation strategies, and ensure the persistence of North Pacific loggerheads in a changing climate.

In this study, we use satellite telemetry data from STRETCH to characterize potentially suitable habitat of North Pacific juvenile loggerheads in

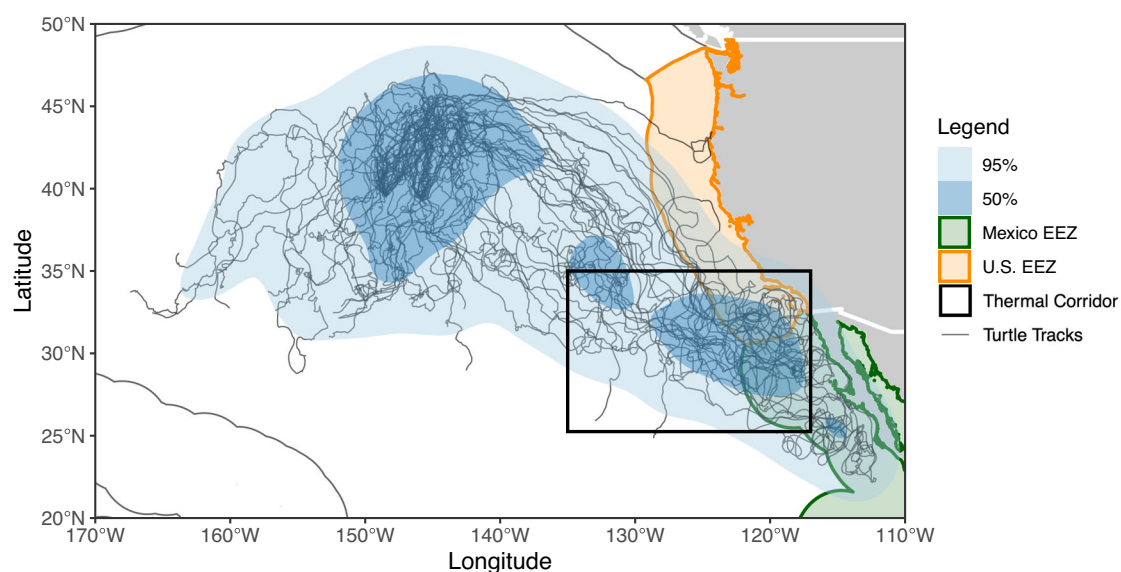


Fig. 1 | Spatial distribution of satellite-tracked juvenile North Pacific loggerheads in the eastern North Pacific. Satellite tracks of STRETCH juvenile sea turtles from cohorts 1 and 2 in the ENP ($n = 53$). Kernel density estimates are shown in blue, with the light blue area representing the 95% utilization distribution and the dark blue

area representing the 50% utilization distribution. The black rectangle indicates the area of the thermal corridor⁵. The exclusive economic zones of the United States and Mexico are colored orange and green, respectively.

the ENP. Using tracking data from 2023–2025, we characterize turtle movements in relation to two key environmental drivers, SST and chl-a, to define seasonal environmental envelopes representing conditions most frequently associated with juvenile movements. These thresholds are applied to long-term climatological data to map the spatial and seasonal distribution of potentially suitable juvenile loggerhead habitat across the U.S. EEZ, Mexico EEZ, and in ABNJ. By integrating fine-scale telemetry

data from cohorts of juveniles intentionally released in the ENP, this study provides a novel opportunity to assess juvenile loggerhead habitat across geopolitical boundaries, examine seasonal shifts, and evaluate cross-jurisdiction habitat distribution.

Results

Environmental conditions of turtle habitat

Tracked juvenile loggerheads occupied areas with a mean SST of 17.4 °C (median = 17.2 °C), with the overall 10–90th percentile environmental envelope ranging from 15.4–19.9 °C (Table 1). Seasonally, mean SST of turtle-occupied locations was lowest in January–March (16.3 °C) and highest in July–September (18.6 °C). Chl-a concentrations in areas used by turtles averaged 0.14 mg/m³ (median = 0.13 mg/m³), with a 10–90th percentile range of 0.07–0.22 mg/m³. Quarterly chl-a means were highest in October–December (0.15 mg/m³) and lowest in April–June (0.11 mg/m³).

Seasonal distribution of environmentally suitable habitat

The spatial distribution of potentially suitable juvenile loggerhead habitat, defined by meeting both SST and chl-a conditions, showed pronounced seasonal structure across the ENP (Fig. 2). From January–March, environmentally suitable grid cells were largely confined to a narrow, zonal band ranging from 26 to 36°N. This latitudinal band remained spatially restricted around a similar latitude in April–June, while shifting poleward to ~38–45°N and expanding longitudinally along the boundary of the U.S. EEZ during July–September. By October–December, the northern boundary of this area retreated slightly southward.

Distribution of suitable habitat within and across national jurisdictions

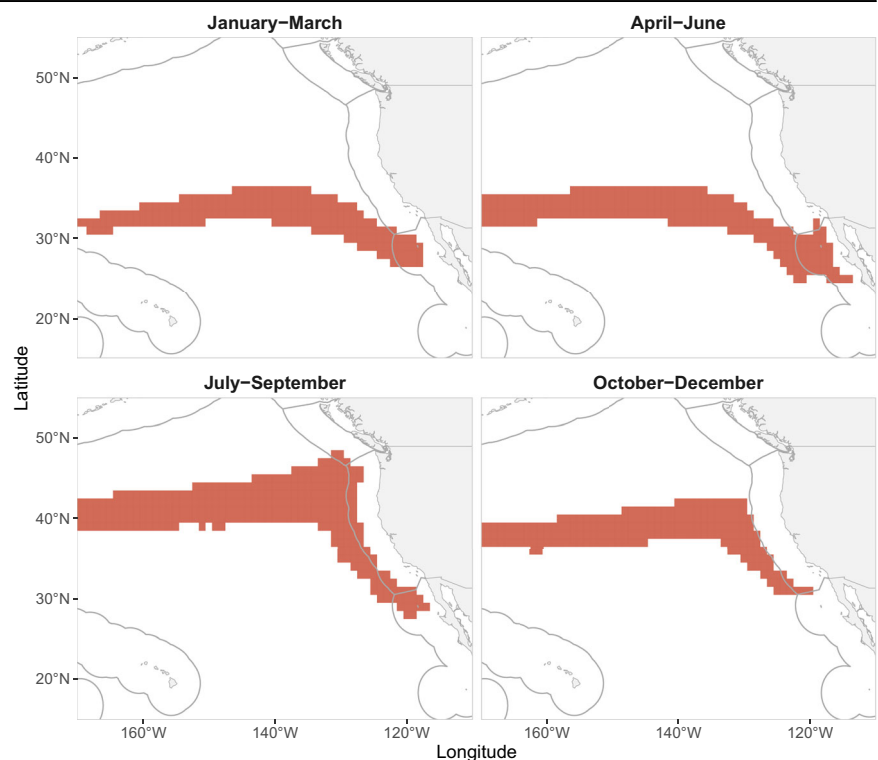
The percentage of the U.S. and Mexico's Pacific EEZs containing environmentally suitable habitat varied seasonally (Fig. 3A). Coverage in U.S. waters averaged 12% annually, ranging from 2% (January–March) to 31% (July–September). Extent of suitable habitat within Mexico's EEZ averaged 7%, ranging from 1% (October–December) to 13% (April–June). When considered relative to the full spatial extent of environmentally suitable habitat, the majority occurred in ABNJ across all seasons (Fig. 3B). Areas

Table 1 | Summary statistics for sea surface temperature (°C) and chlorophyll-a (mg/m³) in areas used by tagged juvenile loggerheads

Sea surface temperature (°C)					
	N	Mean	Median	Min–Max	10–90%
Quarterly					
Jan–Mar	47	16.3	16.3	13.0–19.4	15.0–17.8
Apr–Jun	23	17.6	17.5	13.4–22.4	16.1–19.3
Jul–Sept	53	18.6	18.2	13.4–31.0	16.3–21.2
Oct–Dec	50	16.8	16.8	11.1–25.1	15.1–18.6
Overall	53	17.4	17.2	11.1–31.0	15.4–19.9
Chlorophyll-a (mg/m ³)					
	N	Mean	Median	Min–Max	10–90%
Quarterly					
Jan–Mar	47	0.14	0.13	0.06–12.58	0.08–0.18
Apr–Jun	23	0.11	0.08	0.04–12.02	0.06–0.41
Jul–Sept	53	0.13	0.12	0.05–12.59	0.08–0.21
Oct–Dec	50	0.15	0.14	0.08–11.22	0.10–0.22
Overall	53	0.14	0.13	0.04–12.59	0.07–0.22

Results presented as overall average and quarterly averages. Values shown include mean, median, range (minimum–maximum), and 10–90th percentile ranges. N represents the number of individual turtles contributing data to each calculation; sample size varies among quarters due to differences in tag duration.

Fig. 2 | Seasonal distribution of potentially suitable juvenile loggerhead habitat in the eastern North Pacific. Seasonal distribution of potentially suitable juvenile loggerhead habitat in the ENP, based on sea surface temperature (SST) and chlorophyll-a (chl-a) preferences. Maps show seasonal patterns for January–March, April–June, July–September, and October–December. Red shaded areas indicate environmentally suitable habitat, while country EEZ boundaries are outlined in gray.



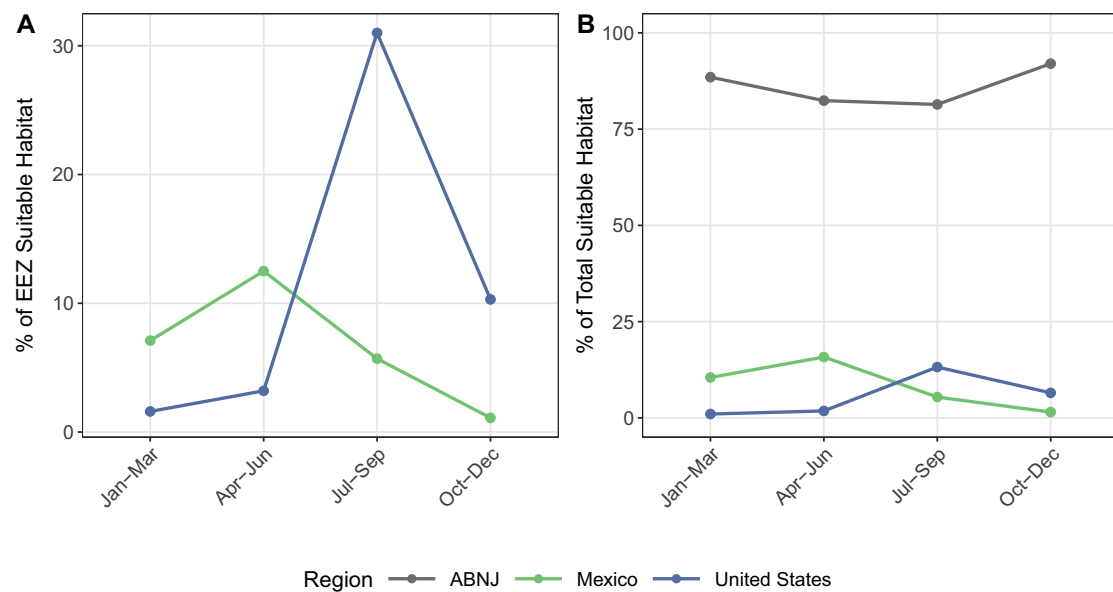


Fig. 3 | Seasonal distribution of environmentally suitable habitat for juvenile loggerheads in the ENP across jurisdictions. A Percentage of the United States' and Mexico's Pacific-facing EEZs containing environmental conditions suitable for

juvenile loggerheads based on preferred sea surface temperature and chlorophyll-a conditions. **B** Proportional distribution of total suitable habitat across the U.S. EEZ, Mexico EEZ, and ABNJ.

were overwhelmingly concentrated in ABNJ waters across all quarters (annual average of 86%) compared to the U.S. (6%) and Mexico (8%). Distribution of suitable habitat was highest for ABNJ in October–December (96%), for Mexico in April–June (15%), and for the U.S. in July–September (10%). Values were lowest in ABNJ in July–September (81%), in the U.S. in January–March (1%), and in Mexico in October–December (2%).

Discussion

Our results provide a characterization of potentially suitable juvenile North Pacific loggerhead habitat across jurisdictions, revealing both seasonal shifts in environmental conditions and a strong presence within ABNJ. We found juvenile loggerheads in the ENP to occupy a range of environmental conditions. Spatial patterns show clear seasonal shifts as suitable habitat disperses eastward toward the U.S. and Mexico. Our analyses indicate that the majority of suitable habitat occurs in ABNJ, underscoring the importance of high seas waters in supporting juvenile loggerheads across the North Pacific, while smaller, seasonally shifting portions of suitable habitat extend into U.S. and Mexican EEZs. Notably, this pattern likely reflects the larger spatial extent of oceanic habitats and thermal constraints that have historically limited coastal recruitment, rather than reduced suitability of these near-shore environments. Together, these findings highlight the importance of open-ocean habitats for juvenile development, as well as the need for coordinated, transboundary management to support the conservation of this highly migratory species. Below, we summarize seasonal and transboundary habitat patterns identified in this study, highlight the governance and conservation implications that they present, and consider adaptive management needs in a changing climate.

The thermal and productivity ranges identified in this study are consistent with existing studies of loggerhead habitat use. Mean SST (17.4 °C) and chl-a (0.14 mg/m³) values fall within the range of values reported for juveniles in the central and western North Pacific, including mean values of 17.6 °C SST and 0.16 mg/m³ chl-a reported by Briscoe et al.²¹, average SSTs of 18–23 °C observed by Abecassis et al.¹, and suitable habitat spanning 14.45–19.95 °C SST and 0.11–0.31 mg/m³ chl-a identified by Kobayashi et al.². These values also align with well-established evidence that loggerheads exhibit strong fidelity to the Transition Zone Chlorophyll Front near the 18 °C isotherm^{22,23}. Seasonally, the distribution of environmentally suitable juvenile loggerhead habitat followed predictable patterns, moving northward during the summer as SSTs rise and the Transition Zone

Chlorophyll Front shifts poleward, then contracting southward as the front retreats during cooler winter months^{22,63}.

Spatially, our results reinforce evidence that habitats across jurisdictions in the ENP provide seasonally suitable habitat for juvenile loggerheads. Within U.S. waters, suitable habitat was most extensive during July–September, coinciding with limited, but recurrent, observations of juvenile loggerheads along the southern California coast, where stranding and bycatch records show peak occurrence during summer and warm fall months¹². While loggerheads have been recorded further north along the North American coast, stranding and observational sightings are rare and typically associated with anomalously warm ocean conditions^{64–67}. The episodic, temperature-driven presence of loggerheads in U.S. waters¹¹ has been closely linked to periods of increased overlap with fisheries, motivating the development of dynamic management strategies^{54,55,68}. In contrast, suitable habitat within the Mexican EEZ, particularly off Baja California, was more extensive and persistent across seasons, consistent with long-term documentation of this region as a core juvenile loggerhead foraging area^{5–8,39,62,69}. The seasonal progression of suitable habitat observed in this study, including a summer and early fall extension into U.S. waters followed by a southward contraction towards Mexico in winter and spring, aligns with spatial patterns of modeled habitat hotspots reported by Abecassis et al.¹. Together, these patterns support that juvenile loggerheads experience seasonally structured use of U.S. and Mexican habitats in the ENP, with Baja California serving as a more consistently year-round suitable area whereas U.S. waters may be accessed more intermittently.

Importantly, the patterns identified in this study reflect environmental conditions averaged over a recent period (2014–2025) of unusually persistent ocean warming and recurrent marine heatwaves in the North Pacific^{70–74}, as well as several El Niño and La Niña events. As such, our findings may not fully capture the environmental variability that has historically influenced eastward recruitment of marine species across the East Pacific barrier^{5,75–77}. Studies suggest that most juvenile loggerheads remain within the CNP for extended periods, with only an annually varying subset moving into the ENP^{5,13}. Interannual climate variability, such as SST anomalies and circulation changes associated with El Niño Southern Oscillation and the Pacific Decadal Oscillation, has been shown to influence the strength and location of oceanographic barriers and accessibility of different habitats for North Pacific loggerheads^{5,12,78}. The “thermal corridor hypothesis” proposes that access to coastal habitats may be episodic,

occurring primarily during anomalously warm conditions that allow transient thermal connectivity across the ENP⁷. Viewed in this context, our findings likely capture the seasonal extent of suitable habitat under contemporary, warm-biased conditions.

This warm-biased decade provides a valuable window into how a climate-sensitive sentinel species may be responding to changing ocean conditions. Recent multi-decadal analyses show that juvenile loggerhead pelagic foraging habitat in the North Pacific Transition Zone has shifted hundreds of kilometers northward over the past few decades, presumably in response to ocean warming and declining productivity, reflecting a broad redistribution of suitable habitat²¹. While our results should be interpreted with appropriate caution, given that the environmental conditions underlying our analyses may differ from those experienced by loggerheads in earlier decades, they may also capture an emerging ecological state in which historically episodic thermal corridors become more frequent. As such, the pathways identified here may offer critical insight into a shifting migratory landscape for juvenile loggerheads in a rapidly changing North Pacific. Although not included in the present analyses due to limited data availability at the time of analysis, initial observations from the 2025 STRETCH cohort suggest a return to cooler oceanographic conditions that may limit sea turtle connectivity and recruitment to coastal areas (www.loggerheadstretch.org).

A substantial proportion of potential juvenile North Pacific loggerhead habitat in the ENP occurs in ABNJ (Fig. 3), areas that remain among the most challenging spaces for conservation. While the UN Convention on the Law of the Sea established broad obligations for protection of the marine environment, high seas governance remains fragmented and difficult, largely sector-specific with limited coordination and weak conservation mandates^{46–48,79}. This patchwork approach has struggled to address growing human pressures and the conservation needs of highly migratory species in ABNJ^{53,80–83}. Most existing international agreements lack explicit mechanisms for establishing spatial management measures, such as marine protected areas (MPAs), in ABNJ⁸⁴. Traditional management frameworks are largely jurisdiction-based, poorly aligning with mobile species that freely move across geopolitical boundaries^{45,85–88}. Fisheries governance in ABNJ has relied primarily on regional fisheries management organizations (RFMOs), where bycatch mitigation remains constrained due to low observer coverage, fragmented data collection, and limited adoption of ecosystem-based approaches^{89–91}. Collectively, these challenges constrain the capacity of existing ocean governance mechanisms in ABNJ to effectively protect non-target species, such as sea turtles, and to implement flexible management approaches that are spatially and temporally dynamic.

The recent adoption of the UN Agreement on the Conservation and Sustainable Use of Marine Biodiversity of Areas Beyond National Jurisdiction (BBNJ Treaty) provides a timely opportunity to address these governance gaps. Following decades of negotiation, the treaty entered into force in January 2026, establishing a new legal framework for implementing MPAs in international waters. By complementing existing management efforts by RFMOs and other global conservation agreements, such as the Convention on Migratory Species, the BBNJ Treaty could enable more integrated and ecosystem-based governance for migratory species conservation in ABNJ³⁷. Importantly, the treaty creates a mechanism through which information on species' habitat use, habitat connectivity, and seasonality can directly inform spatial conservation planning in the high seas. In this context, our results provide a useful starting point for identifying broad areas of potential juvenile loggerhead habitat in the ENP, offering a foundation for more detailed analyses that can help identify where and when area-based management in ABNJ aimed at sea turtle conservation may be most effective.

While the majority of suitable juvenile loggerhead habitat in the ENP occurs in ABNJ, U.S. and Mexican EEZs contain smaller, yet ecologically important and management-relevant, portions of suitable habitat (Fig. 3). Compared to the high seas, governance and enforcement within EEZs tend to be stronger and easier to manage⁹². Coastal states have full sovereign rights and legal authority to regulate activities within their EEZs, and coastal fisheries are generally better managed than those operating in the high

seas⁹³. Management measures aimed at protecting North Pacific loggerheads and reducing fisheries bycatch have been successfully developed within U.S. and Mexican waters. For example, in response to the observed relationship between loggerhead bycatch in California and anomalously warm ocean conditions, the Pacific Loggerhead Conservation Area (LCA) was established off southern California in 2004^{54,55}, implementing time-limited spatial closures of the large-mesh drift gillnets during El Niño conditions in the Southern California Bight. This closure has been activated several times since its designation^{94–98}. More recently, a Temperature Observations to Avoid Loggerhead (TOTAL) tool was developed to provide real-time guidance on loggerhead presence based on SST and support the adaptive implementation of commercial fishery closures within the LCA⁶⁸. Bycatch mitigation measures have also been implemented within U.S. waters of the CNP, where gear modification, observer coverage, and time-area closures have helped mitigate interactions between loggerheads and the Hawaii-based longline fishery^{16,42,56,99,100}. In Mexico, a marine reserve and associated new management measures enacted in 2016 were successful in temporarily reducing loggerhead bycatch in Mexican waters, although risk quickly rebounded once measures were relaxed^{42,101}. Complementary approaches, such as co-management strategies that actively involve fishers and their families, show strong potential for mitigating bycatch in Mexican small-scale fisheries³⁹. Although EEZs represent a smaller fraction of the overall suitable habitat for juvenile loggerheads in the ENP compared to ABNJ, these coastal areas represent bycatch hotspots^{7,102} and contribute disproportionately to the mortality of North Pacific loggerheads^{7,39}. Thus, they remain strategic areas for management interventions with population-level conservation benefits.

Climate change has the potential to significantly alter sea turtle habitat use and migratory pathways, with shifts in oceanographic conditions already influencing juvenile loggerhead distributions in the North Pacific. Multi-decadal analyses suggest that sustained ocean warming and declining productivity have driven a northward shift of suitable pelagic habitat for juvenile loggerheads, with average foraging areas moving 450–600 km northward over the past three decades²¹. Climate-driven habitat redistribution could impact loggerhead connectivity to established coastal developmental habitats and introduce new challenges and risks for both loggerhead populations and associated fisheries^{103–105}. As SSTs rise, the proportion of suitable loggerhead habitat may shift across jurisdictional spaces, following projected patterns of other highly marine migratory species in the North Pacific³⁷. Such habitat redistributions may create governance challenges by exposing loggerheads to differing threats and regulatory frameworks across geopolitical boundaries⁸⁷.

Implementing climate-smart principles is essential for effective management strategies in a rapidly changing ocean. Establishing ecologically connected networks of MPAs that adequately protect critical foraging and developmental waters across both ABNJ and EEZs remains key⁸⁵. However, traditional MPAs are designed with the assumption that species distributions are static, which may limit their effectiveness as climate-driven habitat redistribution drives changes in migratory behavior and habitat use¹⁰⁶. A combination of static, adaptive, and dynamic area-based management tools can provide the flexibility that is needed to respond to shifting species distributions and emerging risks across jurisdictions^{107,108}. Dynamic ocean management approaches, which adjust protections in near real-time based on environmental conditions, offer promising avenues³⁹. For example, TurtleWatch, a North Pacific loggerhead bycatch avoidance tool developed for the Hawaii-based longline fishery, uses loggerhead environmental preferences for specific SST to guide fishers away from high-risk areas^{16,28}. TurtleWatch aims to reduce bycatch while allowing continued fishing; however, its effectiveness depends on fisher uptake and incentives¹⁰⁹. Similar relationships between warmer oceanographic conditions and loggerhead bycatch are used to manage the Pacific LCA^{54,55}. Looking ahead, integrating climate-driven habitat shifts into conservation planning, including emerging international frameworks such as the BBNJ Treaty, will be critical for developing adaptive strategies that protect important foraging areas and migration corridors while also supporting sustainable fisheries^{37,110}. As

climate change alters the North Pacific ecosystem, dynamic, climate-adaptive management approaches that transcend geopolitical boundaries will be increasingly important for protecting this highly migratory species.

Several limitations of this study should be noted. First, our environmental envelope defining potentially suitable habitat was based solely on SST and chl-a, variables selected because of their well-established relationship with sea turtle spatial distribution and behavior^{1,2,4,21,24,25}. Given that this study uses an environmental envelope approach, rather than a statistical occurrence model, we do not quantify the proportion of variability in loggerhead habitat use explained by SST and chl-a alone. Notably, other environmental factors, such as mixed-layer depth¹¹¹, bottom depth^{26,111}, oceanic fronts^{69,112}, and currents¹¹³, may also influence turtle movements and habitat use in the eastern Pacific. Thus, these variables could be incorporated in future work to explain extended use of the southern California Current System by juvenile loggerheads and further refine habitat suitability within the broad areas identified in this study. SST and chl-a can be used as an initial screening layer, while these higher-resolution variables (e.g., depths, fronts, currents) can be used to provide finer-scale characterization of preferred habitat. Further, because our analysis is based on seasonally averaged environmental conditions during a recent period of sustained ocean warming and marine heatwaves^{70–74}, it likely reflects potentially suitable habitat under contemporary, warm-biased conditions. Although these conditions represent a relatively warm recent baseline, they may also provide insight into how suitable habitat could shift as warmer ocean conditions become more prevalent under climate change. Results should be interpreted with this in mind; studies aimed at characterizing a fuller historical range of suitable habitat should incorporate longer timeframes and explicitly consider patterns across different climate regimes, including potential analog-year approaches to estimate historical ranges of suitable habitat in prior years.

Second, our analyses defined suitable juvenile loggerhead conditions using the 10–90th percentile range to minimize the influence of outliers and emphasize environmental conditions most consistently used by the turtles. While several of the turtles migrated into U.S. and Mexican waters, most tracking data were collected while turtles were in ABNJ (Fig. 1). This may have limited our ability to fully characterize habitat use in the jurisdictional waters of the California Current System, potentially underrepresenting loggerhead suitable habitat in these more coastal EEZ areas. Coastal and oceanic habitats can differ substantially in environmental conditions; for example, Sandoval-Lugo et al.²⁵ reported that loggerheads in coastal habitats of the Gulf of California occupy foraging areas with mean SST of 27.8–34.4 °C and chl-a concentrations ranging from 0.28–13.14 mg/m³, substantially higher than the ranges observed in our largely oceanic pelagic study area (mean SST of 17.4 °C and mean chl-a of 0.14 mg/m³). Similarly, Eguchi et al.¹² note that loggerheads observed during an aerial survey off southern California in October 2015 were found in warmer waters than turtles in the CNP, likely influenced by marine heatwaves. It is possible that the full extent of highly productive coastal habitats within the U.S. and Mexico EEZs may not be fully captured as suitable habitat in our study. These include known juvenile loggerhead hotspots in the Gulf of Ulloa on the Baja California Peninsula, as well as ephemeral habitats off southern California, which may fall outside the defined percentile range that was largely driven by more offshore, oceanic pelagic habitat use. Future work could evaluate turtle movements and environmental preferences separately across slope, shelf, and coastal habitats, including bays and lagoons, to avoid inadvertently excluding important suitable habitats within jurisdictional waters. In particular, given that the SST- and chl-a-based habitat suitability presented in this study are more representative of broad-scale oceanic conditions, they may underrepresent finer-scale coastal habitats that are more likely to occur within EEZs and thereby contribute to the observed disparity in suitable habitat between ABNJ and EEZs.

In addition, assessments of habitat suitability could be strengthened by incorporating additional behavioral and environmental data. Adding information on dive and foraging behavior, including foraging-site fidelity, could improve interpretations of habitat use and assist in the identification

of habitat hotspots^{1,25}. Further, habitat use may also vary ontogenetically or behaviorally among sea turtles; for example, larger juveniles in the CNP have been shown to experience a broader range of SST compared to smaller individuals¹. As individuals grow, changing energetic demands and prey preferences may also influence habitat selection, potentially leading turtles of different sizes to target areas with differing productivity (e.g., chlorophyll-a concentrations). Finally, coupling information on turtle movements with human-use datasets, including fishing effort, could help identify areas of increased risk. Assessing spatial overlap between sea turtle habitat hotspots and commercially important species, such as Pacific swordfish (*Xiphias gladius*), could inform spatially explicit management strategies to reduce bycatch and support population recovery.

Conclusion

Using high-resolution telemetry from the STRETCH initiative, this study provides a characterization of potential juvenile North Pacific loggerhead habitat across the ENP, revealing strong seasonal structure across both national and international waters. Our results highlight the critical role of ABNJs in supporting juvenile movements and connectivity, while also identifying seasonally suitable habitats in U.S. and Mexican waters that carry important conservation and management implications. By linking turtle movements and environmental conditions, this study offers a framework for identifying broad areas of potentially suitable habitat that can inform spatial, climate-resilient management measures across jurisdictions. While our analysis focused on patterns within the broader ENP context, finer-scale assessments within U.S. and Mexican EEZs, particularly those integrating fisheries effort and bycatch risk, could inform more targeted conservation action. Together, our findings underscore the inherently transboundary nature of juvenile loggerhead habitat in the North Pacific and highlight the need for coordinated, adaptive management approaches that can respond to shifting habitats in a rapidly changing ocean.

Methods

Our study analyzed the tracks of 53 juvenile North Pacific loggerhead sea turtles reared in captivity at the Port of Nagoya Public Aquarium and released at a known-occurrent location as part of the STRETCH initiative. The turtles were approximately two years in age and ranged in size from 33.2 to 45.9 cm straight carapace length (SCL) at time of release. The dataset includes 25 turtles released in July 2023 (mean SCL = 37.5 cm) and 28 turtles released in July 2024 (mean SCL = 39.2 cm). Individual turtles were tracked from the time of release until satellite tags stopped transmitting, spanning July 2023–March 2024 for the 2023 cohort and July 2024–December 2025 for the 2024 cohort. All data processing and analyses were conducted using R (version 2025.9.2.418).

Characterization of seasonal environmental habitat suitability

To characterize the environmental conditions associated with juvenile loggerhead habitat use, daily turtle telemetry locations were paired with remotely sensed oceanographic data from satellite observations. Monthly mean SST (5-km spatial resolution) and chl-a concentrations (4-km spatial resolution) were sourced from the National Oceanic and Atmospheric Administration's Coral Reef Watch Program (NOAA, 2024) and the Copernicus Marine Environmental Monitoring Service's Global Ocean-Colour blended product (CMEMS EU Copernicus Marine Service, 2025), respectively. At each turtle location, SST and chl-a concentrations were extracted on a 1° spatial grid using a nearest-neighbor approach. We defined the environmental envelope as the range of environmental conditions most frequently occupied by turtles during each quarter of the year (January–March; April–June; July–September; October–December). A quarterly scale was chosen to reduce short-term variability in monthly environmental conditions while capturing seasonal variability associated with coastal upwelling and relaxation in the region¹¹⁴. Thus, for each quarter, we calculated the 10–90th percentile range of SST and chl-a values across all turtle locations. This percentile range was selected to characterize the environmental conditions most consistently associated with juvenile loggerhead

habitat use while minimizing the influence of extreme outliers. Given that use of ENP waters often occurs near the margins of known suitable thermal and productivity ranges, broader percentile thresholds were applied to capture a more complete range of conditions under which turtles were observed. These percentile ranges were used to represent environmentally suitable conditions for juvenile loggerheads during each seasonal period. A suite of summary statistics was calculated for SST and chl-a values across all turtle locations and quarters. Chl-a concentrations were log10-transformed for calculations and to define environmental envelope ranges, but back-transformed to their original units (mg/m³) for reporting and interpretation.

Potential habitat was identified on a quarterly basis by selecting all 1° grid cells where environmental conditions fell within the defined percentile ranges. Habitat suitability was assessed based on identifying grid cells meeting both SST and chl-a criteria simultaneously, representing areas of overlapping thermal and productivity suitability. To extend habitat suitability estimates beyond the tracking period and characterize longer-term seasonal patterns in potential juvenile loggerhead habitat, the derived quarterly environmental envelope ranges were applied to 2014–2025 SST and chl-a data. This range captures a time period dominated by anomalously warm ocean conditions across the ENP and California Current, beginning with the onset of an unprecedented marine heatwave event in 2014^{115,116}. For each quarter, SST and chl-a values were averaged across all years at a 1° resolution (Figs. S1 and S2) to generate mean quarterly environmental conditions for each grid cell. Grid cells where these mean quarterly SST and chl-a values fell within the corresponding seasonal environmental envelope ranges (as previously calculated using the STRETCH turtles) were classified as environmentally suitable habitat for juvenile loggerheads. Results for areas meeting SST-only or chl-a-only conditions are provided in the Supplemental Materials (Figs. S3 and S4).

Spatial overlap across jurisdictional boundaries

Next, spatial overlap between environmentally suitable juvenile loggerhead habitat and jurisdictional boundaries was assessed using two complementary metrics, describing (1) the extent of suitable habitat within national waters as well as (2) how suitable habitat is distributed across jurisdictions.

First, grid cells classified as environmentally suitable were spatially intersected with the Pacific-side EEZs of the contiguous United States and Mexico, which represent known juvenile North Pacific habitat. The EEZs for Hawaii and Canada were excluded in this analysis given that no turtles in this study traversed through Hawaiian or Canadian waters (Fig. 1). For each country, the proportion of the EEZ containing suitable habitat was calculated as the number of suitable 1° grid cells divided by the total number of 1° grid cells comprising that EEZ. This metric quantified the proportion of each national jurisdiction containing potentially suitable conditions for juvenile loggerheads. Calculations were performed separately for each environmental criterion and each quarter to capture seasonal variability.

Second, the same set of suitable grid cells was used to quantify the distribution of suitable habitat across jurisdictions by calculating the proportion of the total environmental envelope occurring within the U.S. EEZ, Mexico EEZ, and ABNJ. This method follows approaches previously used to assess transboundary habitat distributions (e.g., Santos et al.³⁷). In this study, the ENP spatial extent was outlined as east of 168°W, as this encompassed the full range of turtle movements. All environmentally suitable grid cells within this boundary, extending to the North American coastline, were considered. The number of suitable grid cells within each jurisdiction (ABNJ, U.S. EEZ, and Mexico EEZ) was expressed as a percentage of the total area of suitable habitat. This metric characterizes how the total suitable habitat for juvenile loggerheads is shared among national and international waters, providing a complementary perspective to the proportion of each EEZ occupied by suitable habitat. As with the first metric, estimates were generated separately for each quarter to capture seasonal shifts in jurisdictional allocation of suitable habitat.

Data availability

This study has been conducted using publicly available environmental data from NOAA Coral Reef Watch Program (<https://coralreefwatch.noaa.gov>) and E.U. Copernicus Marine Service Information Global Ocean Colour (<https://doi.org/10.48670/moi-00283>). The datasets presented in this article are not yet readily available because data collection is ongoing but may be available upon request. Requests to access the datasets should be directed to Denise Parker (denise.m.parker@outlook.com) and Larry Crowder (lbcrowder@stanford.edu).

Received: 12 March 2026; Accepted: 17 September 2026;

Published online: 06 October 2026

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Acknowledgements

The authors gratefully acknowledge Jeffrey Seminoff and Cali Turner Tomaszewicz for their valuable contributions to this project. The STRETCH Project was initially conceived by L.B.C., who also secured the funding and serves as lead P.I. Project STRETCH would not have been possible without access to the legacy data on satellite tagging of North Pacific loggerheads provided by G.H.B., D.P., M.R., and J.P.P. STRETCH depends on the dedication and expertise of the many individuals involved in turtle collection, rearing, tagging, and transportation over the past 3 decades, as well as publication and social media. Analysis of the legacy data as well as the STRETCH data in the context of climate variation involved many key team members. This project represents a collective team effort, and all coauthors have played an essential role in its success. The authors gratefully

acknowledge the personnel at Port of Nagoya Public Aquarium and the students and staff of USA Marine Biological Institute, Kochi University, for their generous role in securing and rearing sea turtles for this study. We gratefully thank MOL Mitsui O.S.K Lines, Ltd for ensuring the safe transport and release of all turtles.

Author contributions

B.S.: conceptualization, data curation, formal analysis, methodology, visualization, writing—original draft, writing—review & editing. L.C.: funding acquisition, writing—review & editing. G.B., M.K., M.S., and T.S.: data curation, resources, writing—review & editing. J.P., A.A., P.G., L.I., and D.P.: writing—review & editing. C.L. and N.Y.: resources, writing—review & editing. M.R.: data curation, writing—review & editing. D.B.: conceptualization, methodology, data curation, writing—review & editing.

Competing interests

The authors declare no competing financial interests but the following competing non-financial interest. Author Larry Crowder is an editorial board member of npj Ocean Sustainability. Dr. Crowder was not involved in the journal's review of, or decisions related to, this manuscript. The remaining authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s44183-026-00250-w>.

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