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Beyond boundaries: governance considerations for climate-driven habitat shifts of highly migratory marine species across jurisdictions

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The mobile nature of migratory marine animals across jurisdictional boundaries can challenge the management of biodiversity, particularly under global environmental change. While projections of climate-driven habitat change can reveal whether marine species are predicted to gain or lose habitat in the future, geopolitical boundaries and differing governance regimes may influence animals' abilities to thrive in new areas. Broad geographic movements and diverse governance approaches elicit the need for strong international collaboration to holistically manage and conserve these shared migratory species. In this study, we use data from the Tagging of Pacific Predators program to demonstrate the feasibility of using climate-driven habitat projections to assess species' jurisdictional redistribution. Focusing on four species (shortfin mako shark, California sea lion, northern elephant seal, and sooty shearwater), we calculate the projected change in core habitat across jurisdictional boundaries throughout the century and highlight associated management implications. Using climate-driven habitat projections from the period of 2001 to 2010, and an RCP 8.5 climate scenario, we found that all four species are projected to face up to a 2.5-10% change in core habitat across jurisdictions in the Northeast Pacific, with the greatest gains of core habitat redistribution within the United States exclusive economic zone and in areas beyond national jurisdiction. Overall, our study demonstrates how efforts to understand the impacts of climate change on species' habitat use should be expanded to consider how resulting shifts may provoke new management challenges in a legally bounded, yet physically borderless ocean. We discuss governance implications for transboundary habitat redistribution as highly migratory marine species potentially shift across legal jurisdictions, including new ocean areas beyond national judications, considerations which are applicable within and beyond this Pacific case study. Our study also highlights data needs and management strategies to inform high-level conservation strategies, as well as recommendations for using updated tagging data and climate models to build upon this approach in future work.

Climate change is rapidly altering our ocean and shifting the distribution of animals within it[1–4]. Marine species' movements and home ranges reflect their preferences for specific oceanographic and ecological conditions, which change as ocean temperatures rise[3,5]. The world's ocean is expected to experience substantial environmental change even under modest projected carbon emission scenarios. Average sea surface temperatures have steadily increased by 0.11°C per decade since the 1970s[6], and many species have already moved deeper or expanded poleward to stay within preferred

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environmental conditions[7–11]. Marine species are undergoing shifts in spatial distributions at alarmingly fast rates, which can have widespread and severe ecological implications as community structures and food webs change[5,8,12,13]. These redistributions also pose a significant challenge for human society, which may impact economic prosperity, food security, and the well-being of coastal communities around the globe[14–16].

Proactively mitigating the effects of climate change on marine species requires a robust understanding of how a changing climate will impact species core habitat. Projections of climate-driven habitat shifts provide insights on whether species will gain or lose core habitat based on species-specific environmental preferences and geographic barriers[2,17,18], however, geopolitical boundaries and differing governance regimes may influence species persistence within shifted areas[9]. Species will likely move across borders in the coming decades[9,19,20], becoming exposed to new regulations and threats with direct geopolitical and economic implications (*sensu*[21,22]). Notably, this may introduce governance challenges as species move into new jurisdictional spaces[19] and exit former ones[23]. Climate-change-induced habitat shifts can push species into governance situations where countries and regions are unprepared, driving biodiversity loss, creating geopolitical conflicts, and accelerating political issues[19]. Such changes may also push species into areas beyond national jurisdiction, where international bodies and agreements, such as regional fisheries management organizations, remain generally unprepared to sustainably manage the shifting movements of humans and marine species.

The transboundary nature of migratory species can further complicate management given their habitat use across multiple geopolitical boundaries. Complex movements that include broad spatial distributions within exclusive economic zones (EEZ; 200 nautical miles from shore) of multiple nations as well as areas beyond national jurisdictions (ABNJ)[21] underscore the need for robust international coordination to help sustainably manage biodiversity, particular in the face of global change. However, developing and implementing coordinated policies among countries can be difficult due to differing national priorities, complex legal infrastructure, and power imbalances[24]. Further, while multiple management bodies (e.g., regional fisheries management organizations) and multilateral environmental agreements (e.g., the Convention on Migratory Species) do exist with specific conservation measures for migratory marine species, coordinated international cooperation and compliance across the entire migratory range of these highly mobile animals, including areas within and beyond jurisdictions, remains a challenge[25]. Given that these species inhabit different areas during various life-stages, properly protecting species across these ecologically interconnected regions remains crucial for ensuring population survival[26].

As climate change continues to alter the distribution of shared species between countries, identifying specific cases where species' transboundary movements may shift is critical for informing where proactive, sustainable co-management initiatives may be most needed. This present study seeks to highlight how we can expand efforts to better understand the impacts of climate change on species' habitat use by considering the governance implications of potential habitat redistributions across jurisdictions. This is illustrated through a case study example using data from Tagging of Pacific Predators (TOPP) program, a collection of biologging data collected from across the North Pacific used to identify habitat hotspots[27]. Hazen et al. [2]. Expanded upon these efforts, coupling species-specific habitat models from the TOPP dataset with climate change projections developed at the Geophysical Fluid Dynamics Laboratory of the National Oceanic and Atmospheric Administration under RCP 8.5[28] to assess how species movements may change throughout the 21st century.

Here, we build upon that work to consider where in geopolitical space these habitat changes are predicted to occur by evaluating changes in the proportion of core habitat within and beyond national jurisdictions for a subset of species in the northeast Pacific (Fig. 1), including shortfin mako shark (*Isurus oxyrinchus*), California sea lion (*Zalophus californianus*), northern elephant seal (*Mirounga angustirostris*), and sooty shearwater (*Ardenna grisea*). Importantly, given several limitations associated with the underlying dataset, our study does not intend to provide a robust modeling analysis for the Pacific predators case study, but rather illustrate an approach that can be used in future work to assess how the management responsibility for transboundary species may change. We then discuss governance considerations given the potential transboundary redistribution of highly migratory species, as well as highlight opportunities for improving data and management needs.

Results

The monthly overlap between projected species core habitats and jurisdictional areas in the northeast Pacific Ocean, including areas beyond and within national jurisdictions, were assessed for the four focal species from 2001 to 2100 at a monthly, 1° resolution using habitat suitability predictions and core habitat thresholds outputs generated in Hazen et al. [2]. The climate-driven habitat projections were geographically constrained to the species-specific domains of the original tagging data, study areas that included varying Pacific coast portions of the EEZs of the United States (including the western continental region, Alaska, Hawaii, and Johnston Atoll), Canada, and Mexico (Fig. 1). All species except California sea lions had core habitats within both areas of national jurisdiction and ABNJ during both the first and last decade of the century (Fig. 2). The core habitat of California sea lions was narrowest in scope and found to remain exclusively within the EEZs of the continental U.S. and Mexico; however, this data is likely not representative as the tagging efforts were limited to two breeding colonies (see Block et al. [27]). On the other hand, sooty shearwaters had the broadest spatial distribution and were the only species that included core habitat within the U.S. EEZs of Alaska and Johnston Atoll.

Deviations from the average monthly proportion of core habitat within jurisdictional waters up to 2100 varied among species. Five-year averages of deviations across jurisdictional areas varied ±10% from the beginning to the end of the century (Fig. 3). Northern elephant seals experienced the greatest increase in the proportion of core habitat within ABNJ by 2100, while also decreasing their proportion of core habitat in Mexico and the U.S. Sooty shearwaters exhibited an opposite trend, where proportions of core habitat decreased in ABNJ by the end of the century, while increasing in Mexico and the U.S. Mako sharks experienced a modest decrease in core habitat within ABNJ and Mexico, but increased within U.S. waters. Changes in the

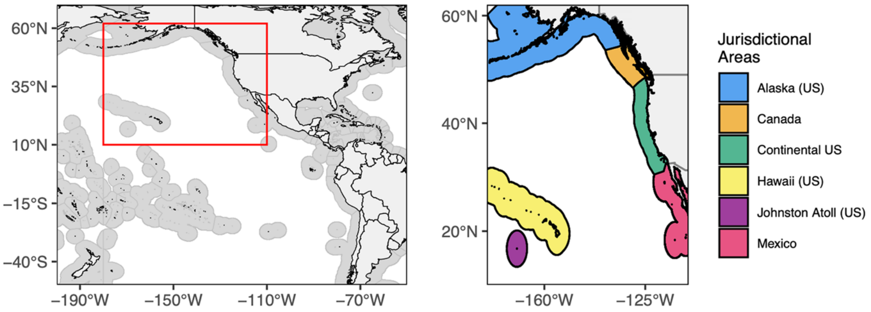

Fig. 1 | Study area (left) with relevant exclusive economic zones (EEZs) that were assessed (right). The United States (U.S.) EEZ was separated into Alaska, Pacific-adjacent continental U.S. states, Hawaii, and Johnston Atoll. Note that the climate-driven habitat projections were geographically using species-specific bounding boxes (see Methods); thus, extent of model projections varied by species and does not necessarily include entire EEZs. Refer to Fig. 2 for extent of individual bounding boxes.

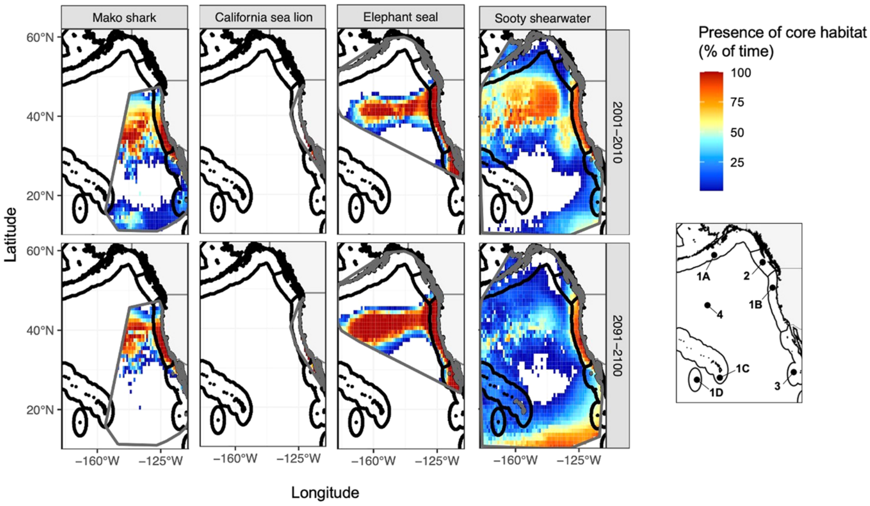

Fig. 2 | Percent (%) of time area/pixels (1° resolution) represent core habitat during the historical period (2001–2010; first row) and end of the century (2091-2100; second row) across species. The gray line represents the individual bounding boxes constructed around the original tagging data, and black lines represent jurisdictional areas (1 = United States (A = Alaska; B = Continental US; C = Hawaii; D = Johnston Atoll); 2 = Canada; 3 = Mexico; 4 = Areas beyond national jurisdiction). A zoomed-in version of the California sea lion can be found in the Supplementary Materials (Fig. S2).

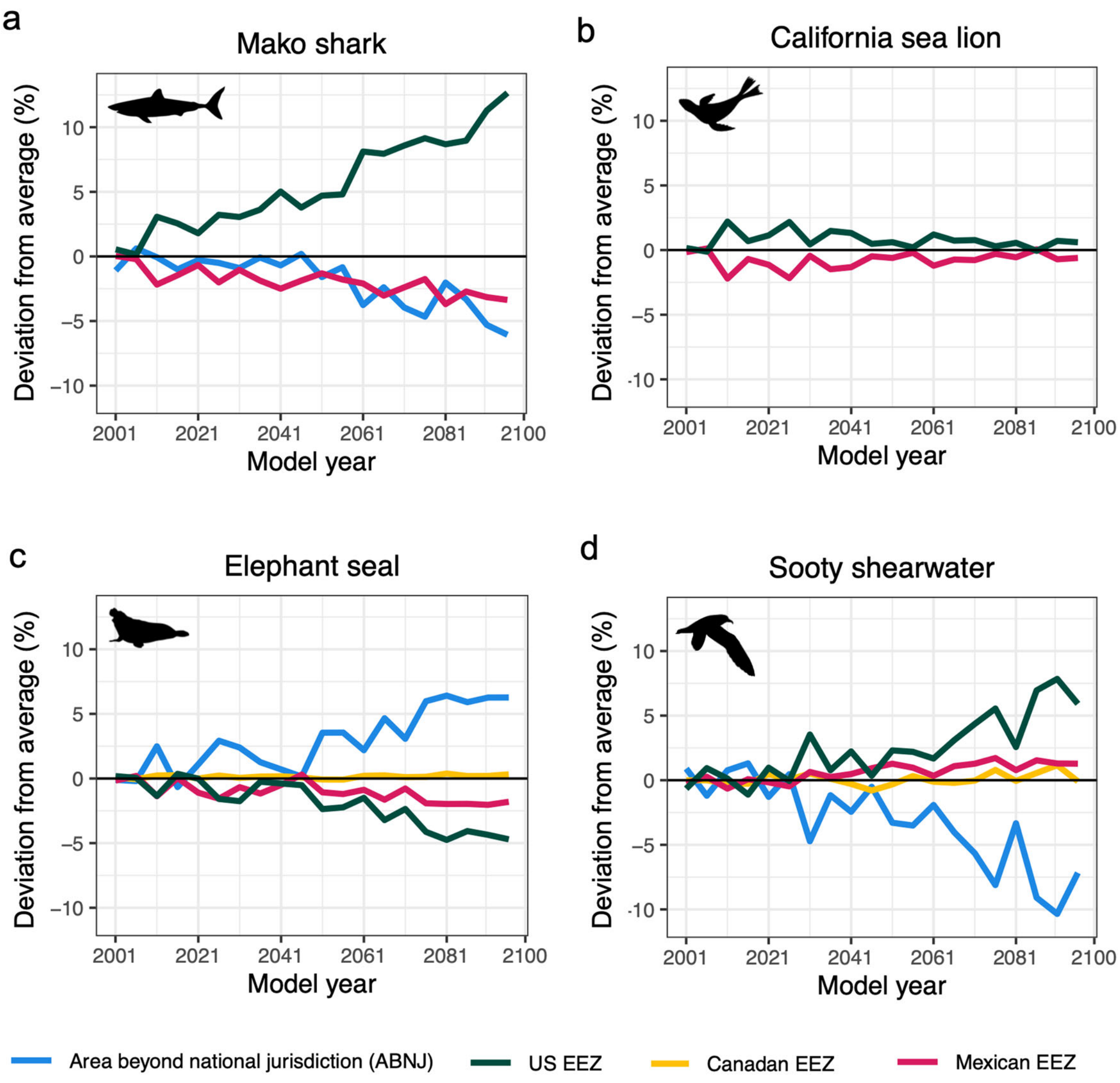

Fig. 3 | Predicted changes in the deviation from the average proportion of core habitat (%) within each jurisdictional area from 2001 to 2100, represented as a 5-year time series for each species. a Shortfin mako shark; **b** California sea lion; **c** northern elephant seal; **d** sooty shearwater. Colors represent jurisdictional waters that include areas beyond national jurisdiction (ABNJ) and the exclusive economic zones (EEZs) of Mexico, Canada, and the United States (US). The United States EEZ includes the Pacific coast of the continental states, Hawaii, Alaska, and the Johnston Atoll. Five-year standard deviations and results at the yearly and monthly levels can be found in the Supplemental Materials (Fig. S1).

proportion of projected core habitat of California sea lions between the U.S. and Mexico were negligible. Only two species (elephant seal and sooty shearwater) had core habitat in Canada, but there was little change in relative proportion over time. Results at the yearly and monthly levels can be found in the Supplemental Materials (Fig. S1).

Discussion

As climate-driven habitat shifts introduce new governance challenges throughout the ocean[29], assessing projected species distributions across geopolitical boundaries can aid in identifying high-level conservation challenges and provide focus areas for management. This study used existing data to demonstrate the feasibility of spatially assessing habitat redistribution as it relates to national jurisdictions, to discern if animals' core habitat shift within or beyond these geopolitical borders. We apply this method specifically to a case study using projections of climate-driven habitat change for select species in the Northeast Pacific under an RCP 8.5 climate scenario. All four species evaluated are projected to face up to a 2.5-10% change in core habitat across jurisdictions throughout the century, with the greatest gains projected within the U.S. EEZ as well as in ABNJ. Recognizing various limitations associated with the underlying dataset, our study aims to provide an example of an analytical approach that can be used in future work with updated projections of species distribution shifts. Understanding where such climate-driven shifts may occur in relation to jurisdictional boundaries can help inform international resource management and identify where proactive, climate-smart management actions, both nationally and internationally, may be needed. Below, we provide a high-level assessment of governance considerations given potential climate-driven redistribution of highly migratory marine species across jurisdictions, applicable within and beyond the Pacific case study. We then discuss data needs, management considerations, and recommendations for building upon this approach in future work.

Governance considerations for transboundary habitat redistributions

In this case study, we found that the core habitat of all four species is projected to shift across jurisdictions throughout the end of the century, adding to a growing body of literature suggesting that climate-driven habitat redistributions may shift species across geopolitical boundaries[19,30,31]. Collaborative management approaches that transcend national borders will be key to allow for flexible, yet coordinated governance strategies as species needs change[25]. The Convention on the Conservation of Migratory Species of Wild Animals (CMS) is the primary international legal instrument focused on the protection of migratory species and their habitats. It provides a global framework to enable the adoption of global or regional agreements relevant to HMS (e.g., Agreement of Conservation of Albatrosses and Petrels, Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and contiguous Atlantic Area), as well as less formal memorandums of understanding (e.g., Pacific Islands Cetaceans, Indian Ocean and Southeast Asia Marine Turtles)[25]. Such bilateral and multilateral environmental agreements can aid in the conservation of migratory species through area-based conservation measures such as marine protected areas (MPAs). However, the effectiveness of these approaches hinge on the careful design of spatial networks that adequately capture enough ecologically interconnected areas used by migratory marine species[26]. Establishing connective spatial management partnerships that transcend national borders and consider these linkages[32], such as the Eastern Tropical Pacific Marine Corridor, a voluntary transboundary network of MPAs created by Ecuador, Costa Rica, Colombia and Panama[33], or and the Baja to Bering Initiative, which seeks to establish a network of MPAs within the neighboring EEZs of Canada, Mexico, and the U.S[34], are key for the effective conservation of these highly mobile species.

While regional MPA networks are becoming more common[32], many are geographically limited within the political boundaries of a country[35]. High seas MPAs are sparse; examples include the South Orkney Islands South Shelf MPA and Ross Sea MPA, implemented through the Convention on the Conservation of Antarctica Marine Living Resources, as well as the OSPAR MPA network established by the Convention for the Protection of the Marine Environment of the North-East Atlantic[36]. Notably, the presence of potential core habitat for many species within ABNJ through the end of the century (Fig. 2), and the projected increase in this proportion for some (Fig. 3), also highlight the need for increased international collaboration around the conservation and sustainable use of marine biodiversity within international waters. Adopting conservation measures for marine migratory species while they are in ABNJ has long been a challenge[37], however these spaces continue to be a significant habitat for highly migratory animals[21]. For example, some migratory marine species can spend up to three-quarters of their annual cycle in ABNJ[21]. Both northern elephant seals and sooty shearwaters are estimated to spend over 65% of the year within the Pacific high seas[21], and mako sharks move into the high seas waters of the central subtropical gyre[21,38], where they may face threats from direct and indirect interactions with multiple types of fishing gear[39–42]. Our results suggest the ABNJ may continue to be an important habitat for the four Pacific predators we assessed, highlighting the need to bolster marine management within the high seas.

The new United Nations Agreement under the UN Convention on the Law of the Sea for the conservation and sustainable use of marine biodiversity of areas beyond national jurisdiction (BBNJ) can help support the capacity for more holistic and effective ocean governance initiatives in international waters. After almost 20 years of informal and formal discussions, the treaty was successfully adopted in June 2023. Notably, one of the four key focus areas within the BBNJ treaty includes area-based management measures and tools, providing a legal foundation for establishing international MPAs that may overcome democratic and scientific challenges associated with implementation through existing regional treaties[36]. The BBNJ treaty could help address some regulatory and governance gaps in ABNJ by expanding opportunities to establish MPAs, including ecologically connected networks for migratory marine species, as well as implementing other area-based management tools for fishing, shipping, and other ocean activities, to protect core habitat as well as densely used migratory corridors. Further, the BBNJ treaty also provides an opportunity to establish an ocean governance framework that guides the international community in collaboratively tackling the challenges of global change by operationalizing climate-resilient principles. This can include advancing capacities for countries to consider adaptive strategies for managing biodiversity that address the impacts of climate change and the complications that may arise with shifting stocks.

The BBNJ treaty can also complement existing conservation agreements relevant to the management of migratory species. While the CMS does emphasize the role of transboundary conservation measures, it has focused primarily on areas within national jurisdictions. The BBNJ treaty has the potential to strengthen existing efforts of the CMS, providing the legal framework to expand capacity to implement area-based management tools in international waters, extending or creating new ecologically connected networks of MPAs through critical habitats[43]. Provisions around environmental impact assessments can increase transparency of activities and contribute to reducing impacts on migratory species in international waters, while mechanisms for shared research, capacity building, and technology transfer offer opportunities for mutual benefit and learning between the two treaties[43–45]. The BBNJ treaty can also strengthen existing marine management efforts implemented by regional fisheries management organizations (RFMOs). Several RFMOs exist with mandates and resolutions that include managing the impact of fishing on vulnerable marine species, including the Western and Central Pacific Fisheries Commission and Inter-American Tropical Tuna Commission. Although these regulations can be hard to monitor and enforce[46–48], the BBNJ treaty may present a timely opportunity to mobilize greater political willingness and increase capacity within RFMOs to address these issues[49]. The BBNJ treaty can also provide a common and consistent framework that supports an ecosystem-based approach to marine management across sectors, strengthening mechanisms already established by RFMOs and the CMS, promoting coherence and coordination, as well as help to fill geographical gaps in coverage.

Planning ahead: data needs and management strategies

Planning for climate-ready marine management and conservation will require reliable projections and assessments of shifting human and species movements[19]. Investing in techniques that improve tracking human[50,51] and biodiversity activities[52,53], such as machine learning, high-resolution satellite data, or new biologging tools, can highlight priority areas for focused biodiversity conservation efforts and improved enforcement of fisheries management strategies. Enhanced real-time tracking of marine biodiversity that provides needed information on species distribution and habitat use can aid in site-based biodiversity conservation and policy[54,55]. Equally as important is the need to increase monitoring of human activity at-sea, leveraging automatic tools such as onboard automated identification systems (AIS) or using innovative remote-sensing strategies[52], to anticipate overlaps between human activity and species habitat use.

Notably, efforts to estimate human and species footprints can be hindered by data biases in sampling efforts as well as barriers in information sharing. Transboundary conservation approaches can support the international exchange of knowledge, technical expertise and conservation funding[56]. Bilateral agreements (e.g., Joint Norwegian-Russian Fisheries Commission[57]) or international online platforms (e.g., Migratory Connectivity in the Oceans consortium; www.mico.eco) where data can be shared using open science principles[58] can be built into ocean governance strategies and improve public availability of data. Data accessibility is particularly critical in the case of highly migratory marine species, given that international coordination is essential for adequately managing species throughout their range[55].

Further, MPAs are traditionally created with the assumption that biodiversity distribution and abundance remain static throughout time and space, thus these strategies may not be equipped to adequately respond to climate-driven shifts in shifting distributions[59]. Climate-smart principles, such as utilizing a network of static, adaptive, and dynamic conservation tools to more effectively and rapidly respond to shifts in species distributions and threats, as well as building climate change objectives into management targets and indicators, should become more deeply integrated into spatial management initiatives[60,61]. In addition, marine spatial planning, a framework that considers the spatial and temporal distribution of ocean activities, should also be multi-sectoral, moving away from single-sector management to integrated approaches that account for a wide range of human activities across space and time[62]. Further, management plans, which are not typically developed for spatial management measures beyond MPAs, could be useful for designing and monitoring area-based management strategies seeking to protect species on the move. Such tools could allow policy and management frameworks to adapt more quickly to meet the changing needs of species as they undergo climate-driven habitat shifts.

Limitations and considerations for future work

Species distribution models, such as the methods underlining the data used in this study, are useful approaches that can identify species' shifts under climate change and inform conservation planning. While our results suggest that climate-driven habitat redistribution may not necessarily push study species into completely new jurisdictional spaces or exit former ones, a similar methodology could be used with other species and in other locales to identify instances where species' exposure to nationally instituted management regimes does significantly change. By assessing the specific movements of a few select species in a few locales, along with the policy implications of these movements, generic guidance could be developed to foster the sort of international collaboration that is needed to sustainable manage and conserve these species in a changing climate. Notably, while we chose to assess Hazen et al. [2]. Climate-driven habitat projections given its large, cross-taxa repository of tagging data for Pacific predators, model projections should be cautiously interpreted given several limitations with this existing dataset. This study only used a single global climate model and a single RCP[63] which limits our ability to look at variability. We acknowledge that the RCP 8.5 climate scenario represents the extreme case, while RCP 4.5 is described by the Intergovernmental Panel on Climate Change as a more moderate projection. Applying an ensemble modeling approach across multiple climate emission scenarios can help address model uncertainly in future work[64]. Further, the projections used in this study includes sea surface temperature and chlorophyll, but not the direct prey species of the predators examined, which should better represent drivers of habitat shift. Future models could be improved by using additional biotic and abiotic input variables. Further, the results of this study may be influenced by the track length and the North American coastal deployments of many of the tagged animals in the dataset[27]. Our results depend on data from specific populations and life history stages as studied by the TOPP program[27] and are not necessarily applicable across all populations. It is also important to highlight that these models project potential suitable habitat based on oceanographic variables[2], but do not necessarily imply shifts in species distributions per se. Thus, results should be cautiously interpreted with this limitation in mind.

Despite these limitations, our analysis provides a methodological approach for using climate-driven habitat projections to assess species' jurisdictional redistribution and highlights potential governance implications to consider. Research could apply this approach using habitat projections that incorporate newer tagging data and updated climate models as well as consider differences in habitat use based on life history stage, such as those related to reproduction. Future work can also be conducted to distinguish and expand on management considerations associated with highly migratory marine species which are commercially exploited, versus those that are predominately species of conservation concern. In additional, vulnerability can vary significantly based on life history stage, thus understanding species behavior across redistributed areas of core habitat is a key component in assessing changes in species risk.

Importantly, not at all ocean spaces pose the same level of threat for marine species, thus truly understanding governance challenges and opportunities from an international collaboration standpoint requires a deeper understanding of individual species-level risks and country-level policies. Species-specific protection priorities may differ significantly depending on the life history of individual taxa, as well as habitat specificity and scale[65–69]. Such considerations highlight the need to understand specific population-level life history characteristics and regional geopolitical nuances more deeply. This study uses data from this Pacific case study to illustrate an analytical approach for further research, rather than intending to provide a detailed and robust modeling or policy analysis. Future efforts should build off this work to assess threats and policies at both the species and country-level, consider international and regional organizations and agreements across a range of individual species, and use updated, state-of-the-art climate models and species predictions to identify more specific gaps and opportunities for climate-ready conservation and policy priorities.

Conclusion

Our results contribute to a growing body of literature that seeks to understand how to better manage highly migratory marine species in a changing climate. We demonstrate the feasibility of using climate-driven habitat projections to assess changes across geopolitical boundaries and discuss how resulting shifts may provoke new management challenges. Within our Pacific case study, we found that climate change may redistribute species core habitat across jurisdictional borders of Northeast Pacific nations by the end of the century, with the greatest gains projected within the U.S. and in ABNJ. Governance strategies that rely on man-made boundaries are likely to be less effective for these highly migratory species, underscoring the importance of strong international cooperation to ensure the sustainable management of migratory marine species in changing climate. Future research unpacking risk exposure, adaptive capacity, and vulnerability at the species, country, and international level is needed to better identify discrete areas for increased conservation attention and collaborative management efforts.

Methods

Species selection

The study region of Block et al. [27] and Hazen et al. [2] encompassed the entire northeast Pacific Ocean (10°N to 60°N, 110°W to 180°W), predicting changes in habitat suitability of fifteen species on a broader, basin-wide scale. As our analysis required a finer-scale geographical comparison (e.g., comparing across ocean governance boundaries such as EEZs), we limited our analyses to species whose habitats we felt confident that the Hazen et al. [2]. Models reproduced well within smaller, coastal areas. First, to avoid unrealistic model extrapolation beyond a species' observed movements, we geographically constrained Hazen et al. [2]. Climate-driven habitat projections to the domains of the original tagging data, using species-specific bounding boxes from Welch et al. [20]. These areas were created by drawing a minimum bounding polygon around each of the species' original tagging data from Block et al. [27]. Next, the original tagging data (deployments occurring during 2000-2009) for each species was visually compared to habitat projections during a similar period (2001–2010) to check if habitat hotspots were correctly replicated. This was assessed by looking for strong overlap between model-predicted core habitat hotspots and areas of aggregated raw tagging data.

Model outputs from four species overlapped nearly identically with the raw tagging data and were deemed sufficient for further analysis. These species included shortfin mako shark (*Isurus oxyrinchus*), California sea lion (*Zalophus californianus*), northern elephant seal (*Mirounga angustirostris*), and sooty shearwater (*Ardenna grisea*). Importantly, many species-specific tagging information in the TOPP dataset are impacted by biological life history traits such as age, sex, or annual cycles. Our results reported herein, utilizing models from Hazen et al. [2], are based on specific geographies or life history stages and are not necessarily generalizable to entire populations (e.g. future modelers could sort data sets by sex, maturity and or ontogeny to see how they are influenced). See Block et al. [27]. For dataset details.

Predicted core habitats

We assessed the predicted core habitat for these four species from 2001 to 2100 at a monthly, 1° resolution throughout their species-specific bounding box domain using habitat suitability predictions and core habitat thresholds outputs generated in the original models from Hazen et al. [2], which used variables of sea surface temperature and chlorophyll. We recognize that not all habitats are used similarly by species. Still, identifying core habitat allows an *a priori* selection of the most important habitats for assessment. Species-specific core habitat was determined by calculating the top quantile of model outputs each month from 2001 to 2010 (a time period classified as the "historical period"). These monthly values were averaged together over the 10 years, calculating a core habitat threshold for each month, with values above this top quantile threshold considered core habitat. For each year over the entire model output (2001–2100), individual grid cells were re-coded to indicate the presence (1) or absence (0) of core habitat based on this threshold. The total monthly core habitat area was calculated by summing across the entire bounding box domain for each year-month combination.

Overlap with jurisdictional areas

We calculated the monthly overlap between species core habitats and jurisdictional areas in the northeast Pacific Ocean, including areas beyond and within national jurisdictions. Areas within national jurisdiction included Pacific coast portions of the EEZs of the United States (including the western continental region, Alaska, Hawaii, and Johnston Atoll), Canada, and Mexico. First, for each species, the shapefiles of these regions were cropped to the individual bounding box. Next, each month-year threshold raster output was overlaid with each shapefile. The total number of grid cells containing a "1" within each jurisdictional area was counted. This value represented the "size" of the species' core habitat during a given month-year combination within each jurisdictional area. It was divided by the size of the total core habitat (e.g., the total number of grid cells across all jurisdictional spaces within the bounding box) and multiplied by 100 to calculate the percentage of core habitat within each jurisdictional area. This process was repeated for each jurisdictional area and each year-month model combination across all four species.

Deviations from the average monthly proportion of core habitat within each jurisdictional area over time was calculated for each species. First, the percent of total core habitat within each jurisdictional area during the historical period (e.g., 2001–2010) was calculated by averaging results across this 10-year period for each month. Then, for each year-month combination from 2001 to 2100, the percentage of core habitat within each jurisdictional area was subtracted from the percentage during the averaged historical period at its corresponding monthly period. This deviation from the average monthly proportion of core habitat within each EEZ was averaged within 5-year bins.

Data availability

The modeling data underlining this research are from Hazen et al. [2]. The spatial analysis of this data (in terms of proportion within and beyond national jurisdictions) are available from the corresponding author upon reasonable request.

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Author contributions

B.S. led the study design and data analysis. E.H., H.W., N.L. and L.C assisted in conceptualizing research aims and data consultation. B.S. wrote the manuscript, with edits and revisions from E.H., H.W., N.L., B.B, D.C., S.S., and L.C.

Competing interests

L.C. serves on the journals' editorial board.

Additional information

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