Fisheries Research 288 (2025) 107447

Contents lists available at ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres

In hot water: How marine heatwaves are transforming the recreational albacore fishery in the eastern North Pacific☆

Ian Blixt[a,*], Barbara Muhling[b,c]

[a] School of Biological Sciences, Victoria University of Wellington, Wellington, New Zealand
[b] Institute of Marine Sciences, University of California Santa Cruz, Santa Cruz, CA, USA
[c] Fisheries Resources Division, NOAA Southwest Fisheries Science Center, San Diego, CA, USA

ARTICLE INFO

Handled by A.E. Punt

Keywords:
Albacore
Recreational fishery
Marine heatwaves

ABSTRACT

Albacore tuna (*Thunnus alalunga*: Scombridae) are a socioeconomically important species globally. A portion of albacore in the North Pacific stock recruit to the California Current Large Marine Ecosystem as juveniles, where they undertake seasonal inshore-offshore migrations. A series of marine heatwaves starting in 2014–2016 produced unprecedented oceanographic conditions in the northern California Current Large Marine Ecosystem, during which time recreational albacore landings in Washington State increased by 950.2 %. Fishing effort in this fishery increased by 1109.7 % during the same time period. We used Generalized Additive Mixed Models to show that a thermal habitat compression index was strongly associated with this increase in landings. During marine heatwaves albacore thermal habitat likely became more available closer to shore, and recreational fishers appeared to opportunistically increase fishing intensity to target them. In contrast, the catch per unit of effort (fish per trip) in this fishery was hyperstable, and less responsive to environmental drivers. While our results show that landings rose sharply during a recent period of ocean warming, effort from smaller private fishing vessels has been increasing since 2012, suggesting that social drivers of effort and participation are also important in this fishery. Given the complex behaviours of both albacore and fishing fleets, their response to future climate change will be more complicated than a simple function of sea surface temperature. However, this emergent fishery may represent an increasingly important source of supplemental revenue in coastal communities where other historically important fisheries are declining.

1. Introduction

Increases in ocean temperatures driven by marine heatwaves and anthropogenic climate change are influencing marine ecosystems globally (IPCC et al.,2023). These shifts in climatic and oceanographic patterns are causing the redistribution of some species, particularly highly migratory species of fish, whose spatial distributions are strongly defined by oceanographic conditions (Bell et al., 2020; Pinsky and Mantua, 2014). Many highly migratory species are the focus of socioeconomically important fisheries, meaning that as the distributions of these species shift, their availability to fisheries may change (Link et al., 2011; Townhill et al., 2019).

Albacore tuna (*Thunnus alalunga*, Bonnaterre 1788) are an economically valuable and highly migratory species that supports fisheries throughout their global range (Nikolic et al., 2017). The majority of commercial landings are in the Pacific Ocean, where two distinct albacore stocks exist (Vaux et al., 2021). Adult fish in the North Pacific stock spawn in the central and western North Pacific, and some juveniles undertake a trans-Pacific migration to the California Current Large Marine Ecosystem (CCLME) (Childers et al., 2011; Chust et al., 2019; Muhling et al., 2022). These juvenile fish, mostly aged 2–4 years old, are important predators in the CCLME, and support regionally and nationally important fisheries along the US West Coast (Frawley et al., 2021; Nickels et al., 2023).

The migratory behaviour of juvenile albacore is highly complex. Tagging records show that fish can undertake long-distance seasonal migrations between the northern CCLME and the central North Pacific, and the latitude at which they enter the CCLME is variable on annual to

☆ Alternative Title 1: Marine Heatwaves Drive Increased Recreational Landings of Albacore in the Eastern North Pacific.
Alternative Title 2: Marine Heatwaves Associated With Shifts in the Recreational Albacore Fishing in the Northern California Current

* Correspondence to: Victoria University of Wellington, Kelburn Parade, Kelburn, Wellington 6012, New Zealand.
E-mail address: Ian.blixt@vuw.ac.nz (I. Blixt).

https://doi.org/10.1016/j.fishres.2025.107447
Received 6 January 2025; Received in revised form 19 June 2025; Accepted 19 June 2025
Available online 25 June 2025

decadal scales (Childers et al., 2011; Chust et al., 2019; Laurs and Lynn, 1975; Muhling et al., 2022). However, favourable habitat for juvenile albacore is broadly predictable from sea surface temperature (SST) and surface chlorophyll-a concentration (CHL). Catch and telemetry data indicate that juveniles occur in waters where surface temperatures are between 11 and 22 °C, with peak abundances around 15–19 °C (Alverson, 1961; Muhling et al., 2019). Juvenile albacore are also known to concentrate along fronts where warmer, oligotrophic water abuts cooler, nutrient-rich coastal upwelling plumes that aggregate prey (Nieto et al., 2017; Xu et al., 2017). Since the 1980's, the main fishing grounds for albacore have shifted northward from the California coast to offshore of Oregon and Washington State (Frawley et al., 2021; Muhling et al., 2019; Squire, 1983). Although the eastern North Pacific has experienced substantial warming during this time, the precise drivers of this shift are not clear.

An intense marine heatwave in 2014–2016 resulted in unprecedented oceanographic conditions throughout the CCLME (Bond et al., 2015; Jacox et al., 2016). This was primarily caused by anomalous atmospheric conditions and resulted in a warm and highly stratified upper water column in the region (Fig. 1; Jacox et al., 2016; Zaba and Rudnick, 2016). The spatiotemporal distributions of some highly mobile marine species changed in response to these conditions, including albacore and important albacore prey species (Auth et al., 2018; Smith et al., 2023; Farchadi et al., 2024). During this heatwave, albacore were reported as far north as southern Alaska (Cavole et al., 2016). Several marine heatwaves impacted the CCLME in subsequent years, including 2019 and 2020 (Farchadi et al., 2024). As well as resulting in strong positive temperature anomalies, marine heatwaves were associated with compression of cooler upwelled water against the Washington–Oregon coast, sometimes reducing its area by > 60 % (Harvey et al., 2021; Schroeder et al., 2022). This led to an inshore redistribution of some species (e.g. humpback whales *Megaptera novaeangliae*, Santora et al., 2020), with consequences for fisheries and protected species management.

Future environmental changes in the North Pacific have high potential to impact both commercial and recreational fisheries for albacore throughout the CCLME (Christian and Holmes, 2016; Farchadi et al., 2024; Smith et al., 2023). Climate projections suggest that the CCLME will experience continued warming, as well as potentially enhanced upwelling in the northern part of the system (Pozo Buil et al., 2021; Bograd et al., 2023). In response, juvenile albacore habitat may shift poleward and potentially shoreward, based on historical associations with temperature and surface chlorophyll (Christian and Holmes, 2016; Smith et al., 2023). Although the effects of climate change on recreational fisheries are less documented than on commercial fisheries, there is increasing recognition of the importance of understanding these changes (Holder et al., 2020; Kerr et al., 2009). While recreational fisheries will be impacted by many of the same factors as commercial fisheries, such as changing fish distributions, their socioeconomic dynamics may be distinct (Townhill et al., 2019). Recreational fishers have different motivations for fishing, and may be governed by different regulations to commercial fishers, resulting in differing potential fishing portfolios. The characteristics of recreational and commercial fishing vessels are also often different in terms of vessel size and seaworthiness, impacting their potential range from home ports. As movement behaviours of albacore are complex (Chust et al., 2019; Muhling et al., 2022), anticipating their responses to future climate change is challenging. Examining historical variability, including marine heatwaves, is thus a useful first step (e.g., Farchadi et al., 2024).

The objectives of this study were to examine changes in landings of albacore off Washington by the recreational fishery since the mid-2000s, and to determine if these changes were predictable based on characteristics of the ocean environment. Our results provide valuable information on the potential social, economic, and ecological importance of the Washington recreational albacore fishery during a recent period of unprecedented warming, and into the future.

2. Methods

2.1. Data acquisition

Albacore recreational fishery data were sourced from the Recreational Fisheries Information Network (RecFIN), a US West Coast recreational fisheries database (Recreational Fisheries Information Network, www.recfin.org, accessed 09/15/2024). RecFIN data used in this analysis were originally recorded by the Washington Department of Fish and Wildlife (WDFW) Ocean Sampling Program, before being collated and uploaded to RecFIN (WDFW, 2017). Data are collected using a two-stage design (stage 1: randomly selected days, stage 2: randomly selected boats on a given day), with daily estimates expanded over days within

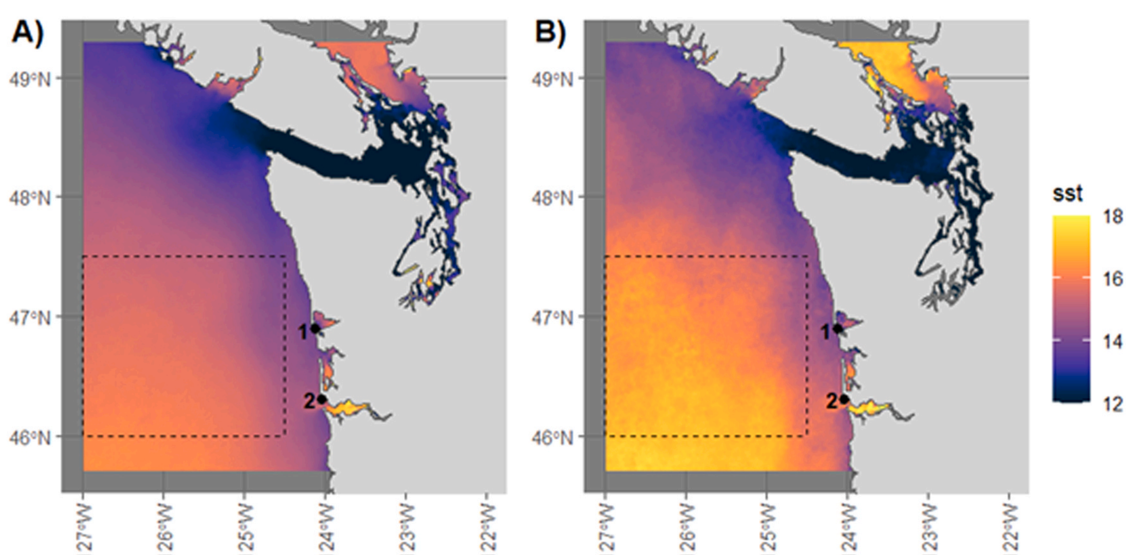

Fig. 1. Sea surface temperature (SST, °C) off the Washington coast. A) mean monthly SST for the albacore season (June – October) during the study period (2003–2021). B) mean monthly SST during the albacore season in 2014, at the beginning of the 2014–2016 marine heatwave. The dashed rectangle represents the estimated fishing grounds for the recreational albacore fishery in Washington state. Points 1 and 2 represent Westport and ilwaco, respectively, which are the two main ports used in the fishery.

strata to produce weekly, monthly and annual estimates of catch and effort (WDFW, 2017). Landings and effort data are from landing surveys conducted on shore and thus may underestimate the total fishery. Albacore have neither a bag limit nor a minimum-size restriction in Washington State. Discards are therefore assumed to be rare. Because total mortality equalled total landings in every study year, we treat total landings as closely approximate to total fishing mortality in this fishery. The data downloaded from RecFIN includes total recreational landings in number of albacore caught, and fishing effort in number of angler trips. The effort variable, angler trips, reflects the total number of individual anglers fishing on a given day, regardless of how many boats were involved. Angler trips are distinguished between those on party/charter boats, and private/rental boats. Party/charter boats are part of the Commercial Passenger Fishing Vessel (CPFV) fleet, which are commercial vessels that take paying customers fishing. Private/rental boats are private fishers who fish from their own boat, or a rental boat. Fishing effort for both was summed into one effort variable. There are also data available for albacore caught by salmon fishers, but as these were never greater than 4 % of the total fishery in any given year, and typically much less, they were excluded from our analysis. We modelled total landings and effort-standardised CPUE separately. Total landings quantify the fishery's overall growth, while CPUE provides a clearer measure of the underlying availability of albacore independent of effort.

Landings and effort data were not precisely geolocated, but the landing survey recorded the region—northern (2.0 %), central (71.3 %), or southern (26.7 %) Washington—where each catch was landed. However, central and southern Washington contain the two largest ports on Washington's Pacific coast, Westport and Ilwaco. These ports are where most tuna fishers depart from, and are near enough to each other that fishers launching at either of these ports may fish the same fishing grounds. Therefore, a combined fishing area was estimated that includes waters seaward of both central and southern Washington out to 127°W (Fig. 1).

RecFIN has recreational albacore fishery landings and effort data available for Oregon as well. However, the Oregon data were not included in the analysis for two reasons; 1) The Washington fishery is not regulated and has no limit on total number of landings, while the Oregon fishery has a landings limit of 25 albacore per day per fisher; 2) Oregon landings data are not geolocated. In Washington the fishing area can be reasonably estimated, given that the large majority of landings are recorded in central and southern Washington, but the same is not true in Oregon. Thus, the fishing area would include waters adjacent to the entire Oregon coastline, a much larger area than the Washington fishing grounds. As a result, we did not attempt to model Oregon landings or CPUE.

In addition to the Ocean Sampling Program data available in RecFIN, vessel-submitted logbook records are available for both the Oregon and Washington CPFV fleets. These consist of geolocated catch data from July to September from 2005 to 2023. We used these data to examine potential changes in fishing grounds by calculating the mean longitude of all logbook catch locations within 46 – 47.8 °N (72 vessels total). We then compared longitudinal shifts in fishing effort to total recorded landings and environmental predictors (see below). Spatial catch and effort data were not available for the private vessel fleet.

Remotely sensed oceanographic data were obtained from the National Oceanic and Atmospheric Administration Global Earth Ocean – Integrated Data Environment Unified Access Framework Environmental Research Division's Data Access Program server (NOAA GEO-IDE UAF ERDDAP Server, hereafter ERDDAP, accessed 09/15/2023). Data were extracted from the ERDDAP server using the R package rerddapXtracto (Mendelssohn, 2022). We extracted satellite observations from the Aqua-Moderate Resolution Imaging Spectroradiometer (Aqua MODIS) for SST and surface CHL at 0.0417° resolution. Level 3 observations from Aqua MODIS are available from mid-2002 to present. All data were extracted at monthly resolution. Data were extracted within the estimated fishing grounds seaward of central and southern Washington (Fig. 1), and then averaged spatially.

Oceanographic indices were retrieved from NOAA's California Current System Integrated Ecosystem Assessment indicators (CCIEA, www.integratedecosystemassessment.noaa.gov, accessed 09/15/2023). We included the Pacific Decadal Oscillation (PDO), North Pacific Gyre Oscillation index (NPGO), Oceanic Niño Index (ONI), and Habitat Compression Index (HCI). These indices were selected because of their links to CCLME physical conditions and ecosystem processes, which are important in describing albacore distribution and migration (Childers et al., 2011; Muhling et al., 2019; Nikolic et al., 2017). The PDO describes changes in SST across the North Pacific, and is a composite indicator that correlates with changes in precipitation, stream flow, and ecosystem variability (Wen et al., 2008). The NPGO is the 2nd dominant mode of sea surface height variability in the Northeast Pacific, and is correlated with changes in salinity, nutrients, and CHL in the CCLME (Di Lorenzo et al., 2008). The ONI is a 3-month mean of SST anomalies in the North Pacific, and is a common index for tracking El Niño-Southern Oscillation conditions. The HCI represents the availability of cool-water thermal habitat in the coastal CCLME (Schroeder et al., 2022). It is pre-calculated by the CCIEA for four latitudinal regions of the CCLME, and we used the northernmost index (43.5–48 °N) that best overlaps with the estimated albacore fishing grounds. High values of the HCI represent a large area of cool water next to the coast, while low values are associated with inshore intrusions of warmer waters, i.e., greater habitat compression. During the 2014–2016 marine heatwave warm water expanded shoreward in the northern CCLME, compressing the area of cooled upwelled water (Fig. 1).

Higher overall abundances of juvenile albacore in the CCLME resulting from years of strong recruitment to the population could theoretically result in higher landings. The fish caught in the Washington State recreational fishery are typically 2–4 years old (Childers et al., 2011). We summed the modelled biomass estimates of 2-, 3-, and 4-year-old juvenile albacore in the North Pacific stock, from the International Scientific Committee for Tuna and Tuna-Like Species in the North Pacific Ocean (hereafter ICS) stock-assessment model, to create a single juvenile albacore index (Albacore Working Group, 2023). The stock assessment model outputs were available from 1994 to 2021. For simplicity, we refer to this index as recruitment (REC).

2.2. Data quality control and processing

After collation, the data were inspected and exploratory analyses were conducted. None of the predictor variables were strongly collinear. However, HCI and SST were highly correlated within month. Some RecFIN data were reported on a weekly basis, while the rest was reported on a monthly basis. Thus, these data were aggregated by month to create a uniform temporal resolution. Given that Aqua-MODIS data became available in 2003, and the ISC stock assessment model covers up until 2021, the study period was defined as 2003–2021. Note that the statistical analysis and figures are strictly constrained to the study period, but fisheries data is available from 1990 to 2024, which is used to summarize trends in the fishery.

Aqua-MODIS SST had 2 outliers (0° C) in September and October 2011. These outliers were removed and filled with values via linear interpolation. Only months where albacore landings were reported were included in the analysis. The final dataset included 8 predictor variables with 64 observations each, with each observation representing a year-month when albacore landings were reported (Table 1). Nominal catch per unit of effort (CPUE) was calculated by dividing landings by effort, and represents the mean number of fish caught on each angler trip. Catch, in total number of landings, and CPUE are the two response variables in the final dataset. Catch had a strong positive skew, while CPUE had a positive skew as well, but not as strong as catch.

Table 1
Environmental predictors considered for inclusion in generalized additive models predicting catch and CPUE. '*' Denotes predictors not included in final models.

Variable	Units	Source	Method	Description
CATCH	#retained fish	RecFIN	WDFW survey	Total number of recreational albacore landings.
EFFORT *	#Angler trips	RecFIN	WDFW survey	Recreational fishing effort in number of angler trips.
CPUE	#landings / effort	RecFIN	Derived	Catch Per Unit of Effort. Number of fish caught per angler trip.
SST	°C	ERDDAP	Aqua MODIS, OISST	Sea surface temperature, monthly composite.
CHL *	mg m^{-3}	ERDDAP	Aqua MODIS	Chlorophyll-a density, monthly composite.
PDO *	Normalized	CCIEA	Wen et al.	Pacific Decadal Oscillation
ONI *	°C	CCIEA		Oceanic Niño Index
NPGO *	Normalized	CCIEA	Di Lorenzo et al. (2008)	North Pacific Gyre Oscillation
HCI	Percent	CCIEA	Schroeder et al. (2022)	Habitat Compression Index, measure of cool-water habitat inshore
REC	#fish	ISC Stock Assessment	Derived, Stock Assessment Model	Recruitment index of 2–4-year-old albacore in the fishery.

2.3. Generalized additive mixed models

Relationships between total recreational albacore landings (hereafter catch), CPUE, and the stated predictor variables were examined using Generalized Additive Models (GAM). GAMs are Generalized Linear Models (GLM) that use smoothing splines to allow non-linear relationships between covariates and response variables (Hastie and Tibshirani, 1986). All analyses were completed in R version 4.2.3 using the "mgcv" package (R Core Team, 2023; Wood, 2010).

Two models were built, one for each response variable, catch and CPUE. The initial models included all variables listed in Table 1. Each model contained the same predictor variables for comparability of results to ensure that they had the same null hypotheses (Whittingham et al., 2006). If a variable had to be removed from one model, it was removed from both models. We used a Gamma distribution with a log link for both models. The validity of this approach was confirmed by examination of model residuals.

GAMs are extensions of the GLM framework and are susceptible to standard collinearity issues, as well as concurvity (Kovács, 2022; Marra and Wood, 2011). A high degree of concurvity implies that the effect of a predictor variable can be approximated by a combination of the others, and can only be assessed after a GAM has been built (Kovács, 2024). Concurvity ranges from 0 to 1, and we selected 0.8 as the threshold for unacceptably high concurvity.

Both initial models displayed a high degree of concurvity (> 0.8), likely from overparameterization. Variables with the highest values were removed to reduce total concurvity in the models. Variables were removed individually, the models were rerun, and concurvity was reassessed. Ultimately, PDO, NPGO, REC, and ONI were removed to yield final models with concurvity below 0.8. Given the seasonal nature of the fishery, month was modelled as its own smooth term (Childers et al., 2011).

Thus, the final models included CHL, HCI, and month as predictor variables. This selection reduced model concurvity to acceptable levels. However, in the original GAMs, there was significant lag-1 autocorrelation in the model residuals. Thus, we refit the models as Generalized Additive Mixed Models (GAMMs) with an AR(1) error structure nested within year. All smooth terms were estimated with thin-plate regression splines. The number of knots for CHL and HCI was left at the default of $k = 10$ and produced biologically reasonable partial responses at this value. Month was limited to $k = 4$ to reflect the seasonal cycle and avoid over-fitting. Model fit was assessed using simulated randomised-quantile residuals (250 simulations) in the DHARMa package (v0.4.7, Hartig, 2024). We also examined normalised Pearson residuals from the linear mixed effects component for any remaining autocorrelation (lag-1 ACF < 0.05 in all cases). Out-of-sample testing of model performance was completed using rolling-origin one-month-ahead cross-validation. In both series, root-mean-square error (RMSE) equalled mean absolute error (MAE), indicating that forecast errors were uniform in magnitude and not driven by rare outliers (Table S1).

3. Results

3.1. Fishery summary

During the first ten years of the data available from RecFIN, 1990–1999, mean total recreational albacore landings off Washington (hereafter landings) was 6723 fish annually (Fig. 2). This value is used as the historical baseline for comparison. Landings increased during the early 2000's, then sharply increased between 2012 and 2016, with each year from 2012 to 2015 representing a new record number of landings at that time. Mean landings from 2014 to 2016 was 63,886 fish annually. Recreational albacore landings in Washington state thus increased by 950.2 % during the 2014–2016 marine heatwave relative to the historical baseline. A similar increase was observed again during a second marine heatwave in 2019, with 87,209 albacore landings observed, a 1197.2 % increase from the 1990's.

CPUE did not follow the same trend as landings or effort (Fig. 2). From 1990–1999, mean CPUE was 16.2 fish per angler annually. During the 2014–2016 marine heatwave, mean CPUE rose to 24.1 fish per angler annually, an increase of 48.5 %. This is a much smaller increase than the 950.2 % rise in landings (Fig. 2). Thus, the substantial increase in landings during the 2014–2016 marine heatwave corresponded with relatively little change in CPUE. The recreational albacore fishery was also highly seasonal, with the majority of landings occurring in August and September, with lower landings in July and October (Fig. 2). During the 2014–2016 marine heatwave, the number of fish per angler increased during June, but overall landings in June remained low.

Fishing effort, in number of angler trips, followed a similar trend to landings. From 1990–1999, there were an average of 919 angler trips annually targeting albacore, of which only 6.6 % were private fishers, with the remainder paying passengers in the CPFV fleet (Fig. 3). Effort increased substantially during the study period, reaching a mean of 11,117 angler trips annually during the 2014–2016 marine heatwave, of which 74.0 % were private fishers (Fig. 3). Thus, fishing effort increased by 1109.7 %, over three orders of magnitude, during the 2014–2016 marine heatwave, and the majority of this increase was from private fishers. There was a particularly sharp increase (229 %) in number of angler trips on private boats from 2011 to 2012, and again from 2018 to 2019 increasing by 101 % (Fig. 3).

3.2. Model results

The catch model demonstrated a good fit with a high degree of explanatory power ($R^2 = 0.411$), while the CPUE model showed much lower explanatory power ($R^2 = 0.111$; Table 2, Figure S2). REC and SST were selected out of the catch model, and also contributed little explanatory power to the CPUE model, and were thus removed from both models. Month provided the greatest explanatory power across both models ($F = 92.695$, $p < 0.001$), supplemented by a highly significant HCI effect in the catch model ($F = 8.350$, $p < 0.001$; Table 2).

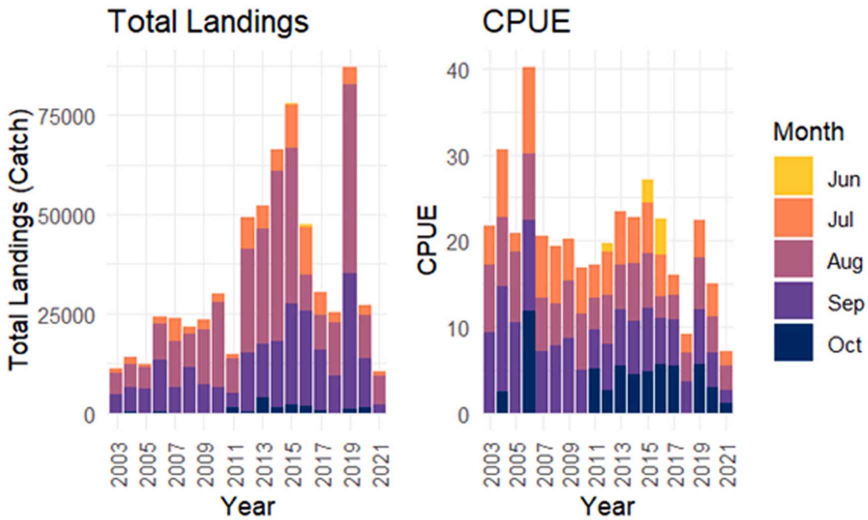

Fig. 2. Total number of albacore landed in Washington by the recreational fishery, and catch per unit effort (CPUE) per year.

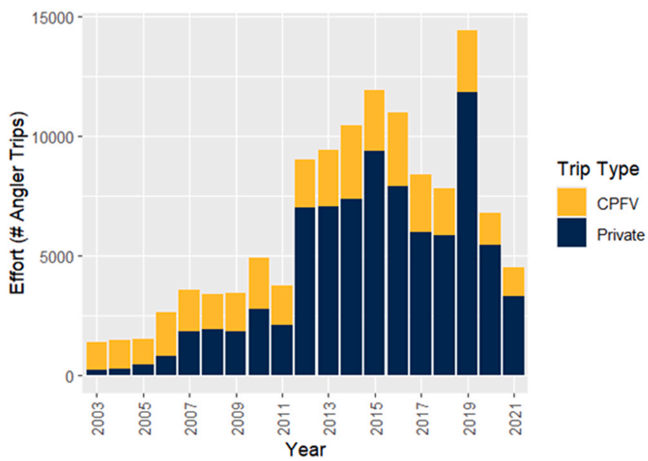

Fig. 3. Fishing effort in number of angler trips, by vessel type (private and Commercial Passenger Fishing Vessel, CPFV), from 1994 to 2021. An angler trip is defined as a single fishing trip made by one individual, regardless of the number of people on the same vessel.

Table 2
Results for each model, with R^2 and deviance explained values. For each variable, effective degrees of freedom (edf), F-statistics and p-values coded by significance (e.g. *) are provided.

Catch GAMM R^2: 0.411			
	edf	F-statistic	p-value
HCI	2.23	8.350	< 0.001 ***
CHL	1.00	0.104	0.749
Month	2.96	92.695	< 0.001 ***
CPUE GAMM R^2: 0.111			
	edf	F-statistic	p-value
HCI	1.00	0.639	0.427
CHL	1.00	2.975	0.089
Month	2.37	6.208	0.002*

These results indicate that the fishery is highly seasonal, and that habitat compression (low HCI) is important for predicting total landings (Fig. 4, Figure S3). Out-of-sample testing of model performance showed moderate skill. In both series, root-mean-square error (RMSE) equalled mean absolute error (MAE), indicating that forecast errors were uniform in magnitude and not driven by rare outliers (Table S1). The CPUE model had a positive bias of + 1.5 units (28 %), indicating moderate but systematic over-prediction, while the catch model had a bias of -2.8×10^{3} (30 %), showing consistent under-prediction. The one-step-ahead forecasts tracked the observed month-to-month fluctuations well, supporting the model's ability to capture short-term variability, with Pearson correlations of 0.56 and 0.80 for the CPUE and catch models, respectively (Table S1).

During marine heat waves, HCI decreased sharply (Figure S4), and this reduction was significantly associated with increased annual landings (Fig. 4; Table 2). The negative relationship between HCI and catch, combined with the strong explanatory power of the catch model, suggest that during the study period, marine heat waves and shoreward habitat compression created favourable conditions for the fishery. That is, albacore catches were higher when cool, productive habitat was most compressed against the coast, possibly increasing albacore availability to nearshore fishers. Logbook records from the CPFV fishery show that albacore catch was greatest in years with low HCI, corresponding to an inshore shift in centres of fishing effort, near to the boundary between oligotrophic offshore waters and productive nearshore waters (Fig. 5). On average across the fishing season (July to October), every 10 % rise in the Habitat Compression Index pushed the fleet's center of longitude 0.026° farther west. The mean longitude of recorded CPFV trips ranged from 125.71 °W, or 126.9 km from the nearest land, in July 2008–124.8 °W, or 57.6 km from land in October 2014.

4. Discussion

4.1. Main results

Our research joins a growing body of evidence highlighting the responses of fisheries to marine heatwaves and changing oceanographic conditions. Projected oceanographic conditions will lead to winners and losers among fisheries globally, as they respond to the varied impacts of climate change (Bell et al., 2020; Link et al., 2011; Pinsky and Mantua, 2014). Some highly migratory species are shifting poleward, which has caused shifts in commercial fishing fleets (Bell et al., 2020; Nikolic et al., 2017; Pinsky and Mantua, 2014). This is already documented in the US West Coast commercial albacore fleet, which has mostly shifted from southern California to Oregon and Washington since the 1980's (Frawley et al., 2021; Smith et al., 2023). However, recreational fishers are not likely to undertake large-scale shifts, especially those fishing from privately-owned vessels (Alvarez et al., 2014; Beaudreau and Whitney, 2016). Here, we report that recreational fishers in Washington

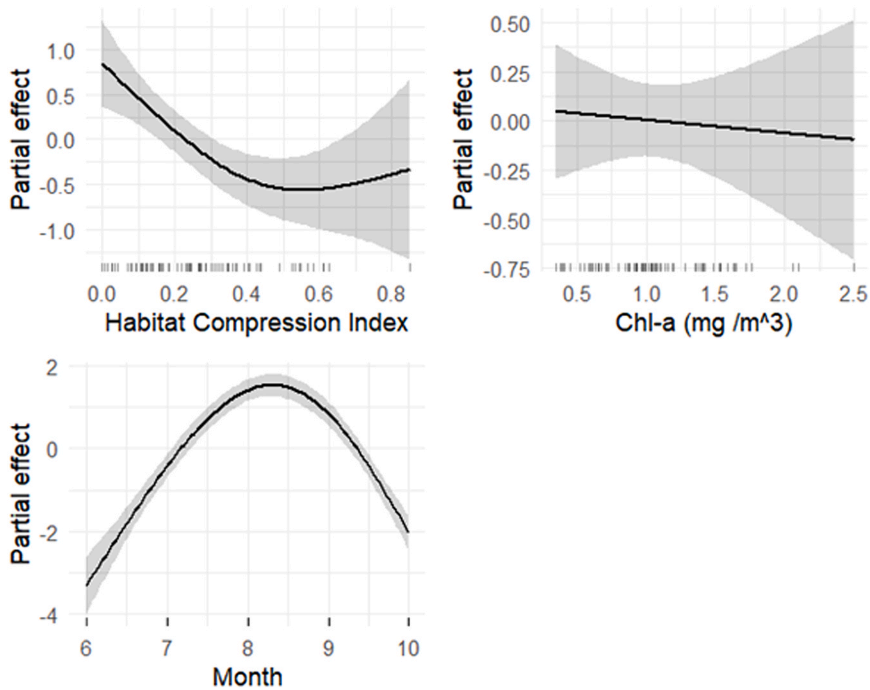

Fig. 4. Partial response plots from the catch generalized additive model predicting albacore landings from 2003 to 2021, for habitat compression index (top left), CHL (top right), and month (bottom left).

State are instead opportunistically increasing fishing intensity to target a highly migratory species, which may be becoming more available due to anomalous ocean conditions.

Fluctuations in the recreational albacore fishery off Washington State have not been examined in depth since the 1980's, when total recreational albacore landings fluctuated between 1500–5,000 annually (Holts, 1985; Squire, 1983). Our results describe an increase to approximately 64,000–87,000 total annual landings during the 2014–2016 and 2019 marine heatwaves, respectively (Fig. 2). These results show over an order of magnitude increase in the fishery since it was last reported on in the primary literature. These results establish that Washington State's recreational albacore fishery, measured in both landings and effort, has undergone a dramatic increase during recent marine heatwaves when warm water compressed the cool upwelling band along the Washington coast. Although we did not use Oregon landings records in our analyses, we note that catch and effort in the Oregon-based recreational albacore fishery has also increased through time, although not as markedly as in Washington (Noordman, 2024).

Once the seasonal signal was accounted for, the habitat-compression index (HCI) was the most important factor in explaining total landings. During marine heatwaves, HCI decreased sharply and this reduction was significantly associated with increased annual landings. A low HCI means that cooler inshore upwelled waters are more compressed against the coast. Albacore are strongly associated with thermal fronts, particularly where warm offshore waters meet cool inshore waters (Alverson, 1961; Childers et al., 2011; Xu et al., 2017). They have been observed moving onto the cool sides of fronts to forage, and then retreating to the warm side to digest their prey (Snyder et al., 2017). These findings suggest that during periods with less cool-water thermal habitat present inshore, the coastal front also moves inshore, and albacore become more accessible to nearshore fishers. During times of high HCI, frontal features may also have been stronger, further concentrating albacore where recreational fishers could target them. Consequently, the fishers, who are typically on smaller vessels with limited range and less tolerance for adverse weather, could more easily access the albacore, leading to increased landings. Because the recruitment index was excluded from the final models, it is most likely that the increased accessibility of the albacore, not overall juvenile abundance, resulted in a sharp increase in landings as the recreational fishers opportunistically increased fishing intensity.

Although years of high albacore landings were associated with marine heatwave conditions, fishing effort began rising sharply in 2012, prior to the first major marine heatwave in 2014. This appears to be primarily driven by an increase in the participation of private vessels, rather than CPFVs (Fig. 3). Private recreational fishing vessels are typically smaller than CPFVs, and may thus be limited in their ability to target albacore when they are distributed further offshore. However, a trend towards larger, more powerful private vessels was noted as early as 2014 (Industrial Economics Inc. 2014). The observed increase in albacore landings is thus likely a product of both enhanced accessibility of albacore during marine heatwave years, as well as an expansion of the private vessel fleet due to social factors such as albacore fishing becoming more popular.

4.2. CPUE hyperstability

The CPUE model had low explanatory power relative to the catch model (Table 2). Between the 1990s baseline and the 2014–2016 marine heatwave, annual landings rose by $\approx$ 950 %, whereas mean CPUE increased by 49 % (Fig. 2). However, recent interannual variability in CPUE tracked variability in catch. For example, both catch and CPUE were relatively high in 2019, and lower in 2021 (Fig. 2). (Fig. 2). When CPUE is relatively unresponsive to changes in the regional abundance of the target fishery species, it is called hyperstable (Cabanellas-Reboredo et al., 2017; Ward et al., 2013). Here, regional abundance refers to the availability of albacore on fishing grounds accessible to the Washington recreational fleet. The hyperstability in CPUE is evidenced by the high degree of covariance between the catch (total landings) and effort (number of angler trips) variables, which had a correlation coefficient score of 0.95 during the study period. This produced a CPUE that changed far less than the order-of-magnitude surge in total landings.

In recreational fisheries, CPUE hyperstability is often caused by experienced or well-equipped fishers' ability to catch their daily limit of fish regardless of the population size of the target species. In Washington

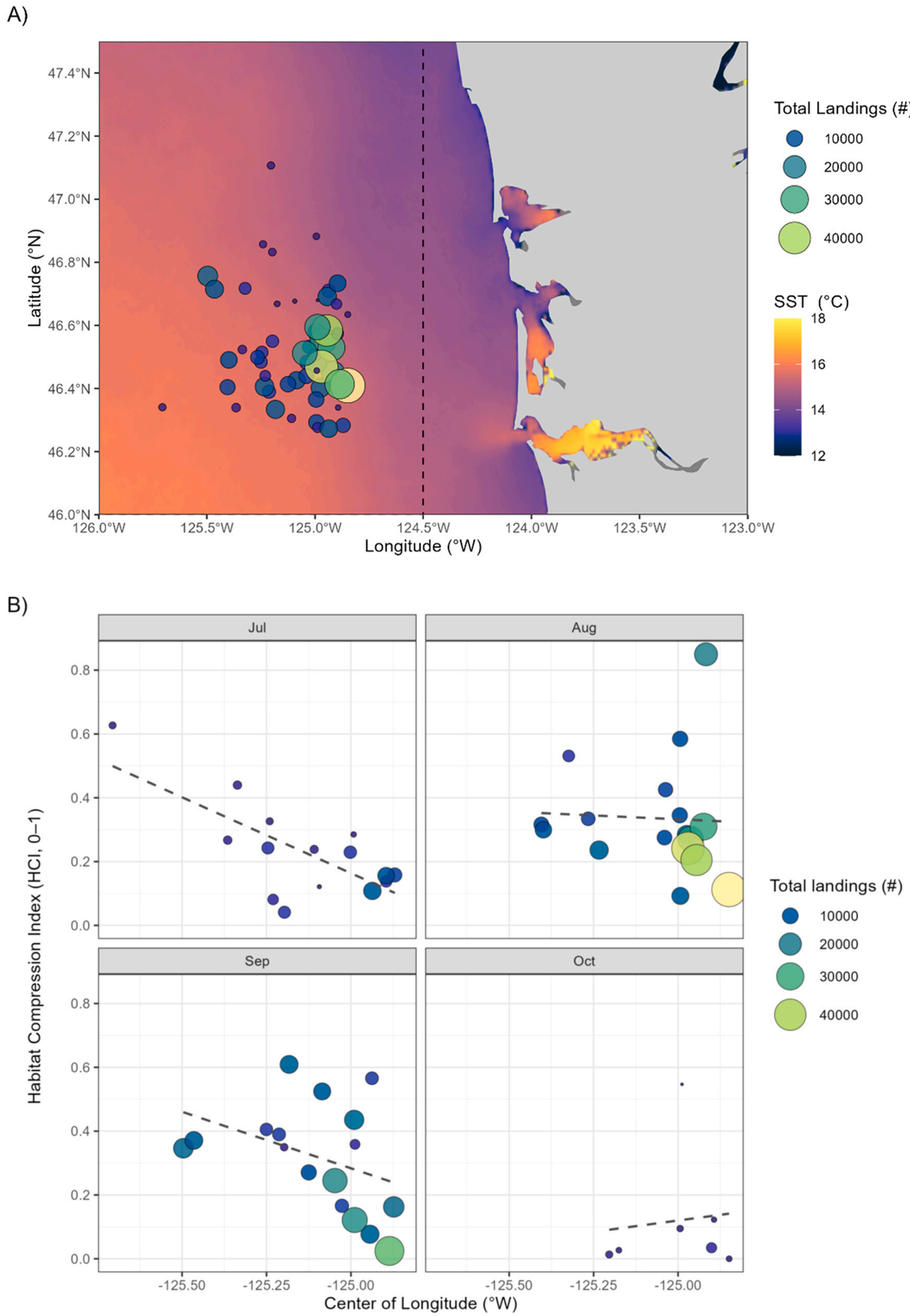

Fig. 5. Spatial distribution of fishing effort, landings, and habitat compression off Washington state. (A) Mean latitude and longitude of fishing effort for commercial passenger fishing vessels (CPFVs), scaled by total landings (2003 – 2021, Jul–Oct), plotted over mean sea-surface temperature during the study period. Bubble size and fill indicate the number of albacore landed during the corresponding month-year. the black dashed line at 124.5° w marks the eastern boundary of the main recreational fishing grounds. (B) Habitat compression index (HCI) versus CPFV mean longitude for the same month-year observations, faceted by month (Jul–Oct). bubble size and colour again denote total landings. The dashed black lines are regression lines displaying the relationship between HCI and center of longitude.

state the recreational albacore fishery is unregulated, meaning that the fishers have no regulatory or legally enforceable limit to the number of albacore that they can catch. However, the hyperstable CPUE suggests that the fishers may have a practical upper limit to the number of albacore that they can land. Notably, juvenile albacore in the CCLME typically have fork lengths of 66–94 cm, and weights between 7 and 11 kg (Childers et al., 2011; Dudley et al., 2021; Muhling et al., 2022). Thus, a mean CPUE of 24.1 albacore per angler per trip during the 2014–2016 period corresponds to a relatively large total mass and volume of fish, which may be limited by vessel hold capacity as well as the ability of anglers to store their catch once home.

In addition, anecdotal evidence suggests that recreational fishers in this fishery conduct their own oceanographic analyses on online platforms with tuna fishing indexes, and share catch information on social media platforms (Phill Dionne, WDFW, pers. comms.). They then opportunistically increase fishing intensity when albacore are present in large numbers and are accessible, i.e. when the fishing is good. This behaviour is well documented in the US west coast commercial albacore fishery (Alverson, 1961; Laurs et al., 1984; Nieto et al., 2017; Watson et al., 2018; Xu et al., 2017). While this behaviour can maximize efficiency for fishers, it does present a statistical challenge in describing trends in CPUE in this fishery and likely explains why the CPUE model had poor explanatory power.

Alternatively, other anecdotal evidence suggests that private boat seaworthiness and offshore fishing capabilities increased during the study period, from 1993 to 2021 (Phill Dionne, WDFW, pers. comms., Industrial Economics Incorporated, 2014). This may be increasing fisher's ability to fish offshore safely, and could explain some of the sharp rise in fishing intensity in this recreational fishery. However, it is difficult to measure boat seaworthiness and offshore capacity without conducting a bespoke survey, which is outside the scope of the work presented here. There are no publicly available data series that we are aware of that cover the recreational albacore fleet during the study period.

4.3. Future projections

Ocean temperature is one of the main drivers of albacore distributions globally, including in the CCLME, and is important in describing albacore movements and migration (Alverson, 1961; Childers et al., 2011; Chust et al., 2019; Erauskin-Extramiana et al., 2019; Laurs et al., 1984; Muhling et al., 2019; Snyder, 2016). Projections of oceanographic conditions indicate that the waters of the northern CCLME will become warmer in future, and potentially more habitable for albacore (Christian and Holmes, 2016; Smith et al., 2023). Moreover, important albacore prey species (e.g. northern anchovy *Engraulis mordax*, Pacific sardine *Sardinops sagax*) are expected to expand northward as well, and upper water column stratification and eddy kinetic energy may intensify, which may increase overall prey availability (Auth et al., 2018; Muhling et al., 2019; Nickels et al., 2023; Smith et al., 2023). Wind-driven upwelling may also intensify in the northern CCLME (Pozo Buil et al., 2021), potentially strengthening the thermal fronts that albacore tend to aggregate around (Xu et al., 2017). Thus, the observed inshore shift in albacore distribution, and resulting higher availability off the coast of Washington, may continue in the northern CCLME (Christian and Holmes, 2016; Smith et al., 2023).

Although warming in the northern CCLME may expand available habitat for albacore, it is not yet clear how temperature will interact with other variables, such as dissolved oxygen, to determine overall habitat suitability. The northern CCLME is projected to become more oxygen depleted in future, which may impact metabolic and energetic processes in pelagic animals, with subsequent effects on CCLME food webs (Pozo Buil et al., 2021). Change to both biotic and abiotic conditions throughout the North Pacific may also shift the location and timing of albacore inshore-offshore migrations (Field et al., 2006; Koehn et al., 2016; Sydeman et al., 2013). Thus, given the complexity and variability of albacore behaviour and migrations, their response to future oceanographic conditions in the region is challenging to predict and not simply a function of water temperature (Muhling et al., 2022; Phillips et al., 2014). While our results demonstrate that albacore can respond rapidly to oceanographic changes in the eastern North Pacific, it is unclear whether future conditions in the region will lead to similarly high albacore inshore availability and landings. This is reflected in the high degree of variability in the magnitude and distribution of albacore fisheries historically, relative to other US West Coast fisheries (Childers et al., 2011; Phillips et al., 2014).

4.4. Socioeconomic implications

In 2006, recreational fishers in Washington State spent $904.8 million USD on fishing equipment and trip-related items (WDFW, 2008). Historically, the most socio-economically important recreational fisheries in Washington State are salmon fisheries (Holts, 1985). US West Coast salmon fisheries are suffering under current climate conditions, with increased SST, river temperatures, and pollution associated with increases in pre-spawning mortality in adult salmon (Atlas et al., 2021; Barnett et al., 2020; Feist et al., 2017; Howard and von Biela, 2023; Waldman and Quinn, 2022). When this is considered in the context of the dramatic increase in fishing effort in the recreational albacore fishery, our results show that recreational fishers are shifting to a warmer water fish species as their accessibility increases, and historically important fisheries decline. Thus, recreational albacore fishing may become an increasingly important source of supplemental revenue for Washington coastal communities that have historically been reliant on salmon fisheries.

Participation in the Washington recreational albacore fishery requires a fishing license but is otherwise unregulated. Our results show that private boats routinely land several hundred kilograms of albacore per trip, and annual catches have peaked at $>$ 75000 fish (~525–825 metric tons; Fig. 3). However, with North Pacific albacore biomass exceeding 1 million metric tons in 2019–2021 annually, this fishery removes only 0.05–0.08 % of the stock each year at most (Albacore Working Group, 2023). Commercial landings of albacore into Washington from the US surface fleet have ranged between 2300 and 10,800 metric tons during our study period (acific Fisheries Information Network PacFIN retrieval dated May 1st, 2025). Assuming that a recreationally caught albacore weighs approximately 10 kg (Chen et al., 2012), recreational catch has ranged between 1.0 % (2003) and 20.2 % (2019) of commercial landings, with a mean of 5.5 %. At current population levels, any increased mortality from recreational landings thus appears unlikely to have stock-wide impacts at current exploitation levels.

4.5. Future research

As Washington State's recreational albacore fishery grows, further research is needed to understand and quantify its impacts. Specifically, including albacore on Washington's already existing catch-card system for recreational fisheries may become necessary if current trends continue. Similarly, this fishery presents an excellent opportunity for a citizen science project with the aim of creating geolocated catch data from a subset of recreational fishers, to better understand environmental drivers of albacore availability in the northern CCLME. As both the commercial and recreational albacore fisheries contribute substantially to CCLME coastal communities and economies, improved understanding of the effects of recruitment, and other drivers such as eastern North Pacific oceanographic conditions, on these fisheries is important.

A key limitation of this study was the lack of geolocated recreational fishing catch data; RecFIN does not report catch coordinates for recreational fisheries, so we aggregated landings into a broad coastal grid. This coarse resolution obscures fine-scale spatiotemporal variation. We were able to partially address this by use of spatially resolved logbook data for the CPFV fleet, however this fleet has not shown the large increase in landings that the private vessel fleet has. In addition, CPFV vessels are likely to be substantially larger than most private vessels, and thus may be less impacted by the nearshore accessibility of albacore. An additional potential limitation of this study was COVID-19 disruptions in 2020–2021 that likely altered fishing effort and reporting. Model validation revealed a pronounced over-estimate of catch in 2020, suggesting a mismatch in fishery productivity and fishing effort.

5. Conclusion

In this study, we show that recreational albacore landings in Washington State increased dramatically during the 2014–2016 and 2019 marine heatwaves. The increase was related to compression of warm, oligotrophic habitat next to the coast. Fishing effort in this recreational fishery has also increased by over three orders of magnitude since the 1990's, suggesting that fishers are opportunistically increasing fishing intensity when albacore are available. This has also created a hyperstable CPUE, which makes assessing trends in this fishery challenging. Our results, in combination with published literature on the northern CCLME, suggest that the albacore fishery off of Washington State may continue to grow in magnitude and socio-economic importance. This fishery may represent an increasingly important source of supplement income for coastal communities, where other historically important fisheries are declining.

CRediT authorship contribution statement

Ian Blixt: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Barbara Muhling:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Funding

This research was funded in part by a Marsden grant from the Royal Society of NZ, grant number E4034.

Declaration of Competing Interest

The authors have no conflicts of interest to report

Acknowledgements

The authors would like to thank the Washington Department of Fish and Wildlife for making their creel reports publicly available, the WDFW staff who conducted the landings surveys, and to those involved with RecFIN in posting collated data online. Further thanks to Corey Niles and Phillip Dionne of WDFW for their insights in Washington recreational fisheries, and Yuhong Gu for provision of CPFV logbook data. We would also like to thank Dr. Steve Teo and Dr. Sarah Hawkshaw for their useful conversations on the ISC stock assessment model. Thank you also to Dr. Lisa Woods for helpful conversations regarding statistics, and Dr. Desiree Tommasi for fruitful conversation and contacts. Further thanks to Owyn Snodgrass for his review and helpful discussion. Finally, we thank Nicola Nelson's lab group at Te Herenga Waka – Victoria University of Wellington for providing very helpful comments and edits to this manuscript.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fishres.2025.107447.

Data availability

Data will be made available on request.

References

Albacore Working Group. (2023). Stock Assessment of Albacore Tuna in the North Pacific Ocean in 2023. Available at https://isc.fra.go.jp/pdf/ISC23/ISC23_ANNEX08-Stock_Assessment_Report_for_Albacore_Tuna_in_the_North_Pacific_Ocean_Updated_FINAL.pdf.

Alvarez, S., Larkin, S.L., Whitehead, J.C., Haab, T., 2014. A revealed preference approach to valuing non-market recreational fishing losses from the deepwater horizon oil spill. J. Environ. Manag. 145, 199–209. https://doi.org/10.1016/j.jenvman.2014.06.031.

Alverson, D.L., 1961. Ocean temperatures and their relation to albacore tuna (Thunnus germo) distribution in waters off the coast of oregon, Washington and British Columbia. J. Fish. Res. Board Can. 18 (6), 1145–1152. https://doi.org/10.1139/f61-068.

Atlas, W.I., Seitz, K.M., Jorgenson, J.W.N., Millard-Martin, B., Housty, W.G., Ramos-Espinoza, D., Burnett, N.J., Reid, M., Moore, J.W., 2021. Thermal sensitivity and flow-mediated migratory delays drive climate risk for coastal sockeye salmon. Facets 6 (1), 71–89. https://doi.org/10.1139/FACETS-2020-0027.

Auth, T.D., Daly, E.A., Brodeur, R.D., Fisher, J.L., 2018. Phenological and distributional shifts in ichthyoplankton associated with recent warming in the northeast Pacific Ocean. Glob. Change Biol. 24 (1), 259–272. https://doi.org/10.1111/gcb.13872.

Barnett, H.K., Quinn, T.P., Bhuthimethee, M., Winton, J.R., 2020. Increased prespawning mortality threatens an integrated natural- and hatchery-origin sockeye salmon population in the lake Washington basin. Fish. Res. 227. https://doi.org/10.1016/j.fishres.2020.105527.

Beaudreau, A.H., Whitney, E.J., 2016. Historical patterns and drivers of spatial changes in recreational fishing activity in puget sound, Washington. PLoS ONE 11 (4). https://doi.org/10.1371/journal.pone.0152190.

Bell, R.J., Odell, J., Kirchner, G., Lomonico, S., 2020. Actions to promote and achieve Climate-Ready fisheries: summary of current practice. Mar. Coast. Fish. 12 (3), 166–190. https://doi.org/10.1002/mcf2.10112.

Bograd, S.J., Jacox, M.G., Hazen, E.L., Lovecchio, E., Montes, I., Pozo Buil, M., Shannon, L.J., Sydeman, W.J., Rykaczewski, R.R., 2023. Climate change impacts on eastern boundary upwelling systems. Annu. Rev. Mar. Sci. 15 (1), 303–328. https://doi.org/10.1146/annurev-marine-032122-021945.

Bond, N.A., Cronin, M.F., Freeland, H., Mantua, N., 2015. Causes and impacts of the 2014 warm anomaly in the NE pacific. Geophys. Res. Lett. 42 (9), 3414–3420. https://doi.org/10.1002/2015GL063306.

Cabanellas-Reboredo, M., Palmer, M., Alós, J., Morales-Nin, B., 2017. Estimating harvest and its uncertainty in heterogeneous recreational fisheries. Fish. Res. 188, 100–111. https://doi.org/10.1016/j.fishres.2016.12.008.

Cavole, L.M., Demko, A.M., Diner, R.E., Giddings, A., Koester, I., Pagniello, C.M.L.S., Paulsen, M.L., Ramirez-Valdez, A., Schwenck, S.M., Yen, N.K., Zill, M.E., Franks, P.J.S., 2016. Biological impacts of the 2013–2015 warm-water anomaly in the northeast pacific: winners, losers, and the future. Oceanography 29 (2), 273–285. https://doi.org/10.5670/oceanog.2016.32.

Chen, K.S., Shimose, T., Tanabe, T., Chen, C.Y., Hsu, C.C., 2012. Age and growth of albacore *thunnus alalunga* in the north Pacific Ocean. J. Fish. Biol. 80 (6), 2328–2344.

Childers, J., Snyder, S., Kohin, S., 2011. Migration and behavior of juvenile north pacific albacore (Thunnus alalunga). Fish. Oceanogr. 20 (3), 157–173. https://doi.org/10.1111/j.1365-2419.2011.00575.x.

Christian, J.R., Holmes, J., 2016. Changes in albacore tuna habitat in the northeast Pacific Ocean under anthropogenic warming. Fish. Oceanogr. 25 (5), 544–554. https://doi.org/10.1111/fog.12171.

Chust, G., Goikoetxea, N., Ibaibarriaga, L., Sagarminaga, Y., Arregui, I., Fontán, A., Irigoien, X., Arrizabalaga, H., 2019. Earlier migration and distribution changes of albacore in the northeast atlantic. Fish. Oceanogr. 28 (5), 505–516. https://doi.org/10.1111/fog.12427.

R. Core Team. (2023). R: A language and environment for statistical computing. R Foundation for Statistical Computing (4.2.3). ⟨https://www.R-project.org/⟩.

Di Lorenzo, E., Schneider, N., Cobb, K.M., Franks, P.J.S., Chhak, K., Miller, A.J., McWilliams, J.C., Bograd, S.J., Arango, H., Curchitser, E., Powell, T.M., Rivière, P., 2008. North pacific gyre oscillation links ocean climate and ecosystem change. Geophys. Res. Lett. 35 (8). https://doi.org/10.1029/2007GL032838.

Dudley, P.N., Rogers, T.L., Morales, M.M., Stoltz, A.D., Sheridan, C.J., Beulke, A.K., Pomeroy, C., Carr, M.H., 2021. A more comprehensive climate vulnerability assessment framework for fisheries Social-Ecological systems. Front. Mar. Sci. 8. https://doi.org/10.3389/fmars.2021.678099.

Erauskin-Extramiana, M., Arrizabalaga, H., Hobday, A.J., Cabré, A., Ibaibarriaga, L., Arregui, I., Murua, H., Chust, G., 2019. Large-scale distribution of tuna species in a warming ocean. Glob. Change Biol. 25 (6), 2043–2060. https://doi.org/10.1111/gcb.14630.

Farchadi, N., Welch, H., Braun, C.D., Allyn, A.J., Bograd, S.J., Brodie, S., Hazen, E.L., Kerney, A., Lezama-Ochoa, N., Mills, K.E., Pugh, D., Young-Morse, R., Lewison, R.L., 2024. Marine heatwaves redistribute pelagic fishing fleets. Fish Fish 25 (4), 602–618. https://doi.org/10.1111/faf.12828.

Feist, B.E., Buhle, E.R., Baldwin, D.H., Spromberg, J.A., Damm, S.E., Davis, J.W., Scholz, N.L., 2017. Roads to ruin: conservation threats to a sentinel species across an urban gradient. Ecol. Appl. 27 (8), 2382–2396. https://doi.org/10.1002/eap.1615.

Field, J.C., Francis, R.C., Aydin, K., 2006. Top-down modeling and bottom-up dynamics: linking a fisheries-based ecosystem model with climate hypotheses in the Northern california current. Prog. Oceanogr. 68 (2–4), 238–270. https://doi.org/10.1016/j.pocean.2006.02.010.

Frawley, T.H., Muhling, B.A., Brodie, S., Fisher, M.C., Tommasi, D., Le Fol, G., Hazen, E. L., Stohs, S.S., Finkbeiner, E.M., Jacox, M.G., 2021. Changes to the structure and function of an albacore fishery reveal shifting social-ecological realities for pacific northwest fishermen. Fish Fish 22 (2), 280–297. https://doi.org/10.1111/faf.12519.

Hartig, F.. (2024). DHARMa: Residual Diagnostics for Hierarchical (Multi-Level / Mixed) Regression Models_. R package version 0.4.7, <⟨https://CRAN.R-project.org/package=DHARMa⟩>

Harvey, C.J., Garfield, N., Williams, G.D., Tolimieri, N., 2021. Ecosystem status report of the california current for 2020-21. A Summ. Ecosyst. Indic. Compil. Calif. Curr. Integr. Ecosyst. Assess. Team (CCIEA). https://doi.org/10.25923/x4ge-hn11.

Hastie, T., Tibshirani, R., 1986. Generalized additive models. Stat. Sci. 1 (3), 297–318. https://doi.org/10.1214/ss/1177013604.

Holder, P.E., Jeanson, A.L., Lennox, R.J., Brownscombe, J.W., Arlinghaus, R., Danylchuk, A.J., Bower, S.D., Hyder, K., Hunt, L.M., Fenichel, E.P., Venturelli, P.A., Thorstad, E.B., Allen, M.S., Potts, W.M., Clark-Danylchuk, S., Claussen, J.E., Lyle, J. M., Tsuboi, J. ichi, Brummett, R., Cooke, S.J., 2020. Preparing for a changing future in recreational fisheries: 100 research questions for global consideration emerging from a horizon scan (Springer). Rev. Fish. Biol. Fish. 30 (1), 137–151. https://doi.org/10.1007/s11160-020-09595-y.

Holts, D., 1985. Recreational albacore, thunnus alalunga, fishery by U.S. West coast commercial passenger fishing vessels. Mar. Fish. Rev. 47 (3), 48–53.

Howard, K.G., von Biela, V., 2023. Adult spawners: a critical period for subarctic chinook salmon in a changing climate. Glob. Change Biol. 29 (7), 1759–1773. https://doi.org/10.1111/gcb.16610.

Industrial Economics Incorporated (2014) Marine Sector Analysis Report: Non-Tribal Fishing Revised Final Report | October 31, 2014. Prepared for the Washington Coastal Marine Advisory Council under Contract No. SC 14-327. Accessed from https://www.msp.wa.gov/wp-content/uploads/2014/03/FishingSectorAnalysis.pdf May 2nd 2025.

IPCC, Lee, H., & Romero, J. (2023). Climate Change 2023: Synthesis Report. A Report of the Intergovernmental Panel on Climate Change. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

Jacox, M.G., Hazen, E.L., Zaba, K.D., Rudnick, D.L., Edwards, C.A., Moore, A.M., Bograd, S.J., 2016. Impacts of the 2015–2016 el Niño on the california current system: early assessment and comparison to past events. Geophys. Res. Lett. 43 (13), 7072–7080. https://doi.org/10.1002/2016GL069716.

Kerr, L.A., Connelly, W.J., Martino, E.J., Peer, A.C., Woodland, R.J., Secor, D.H., 2009. Climate change in the U.S. Atlantic affecting recreational fisheries. Rev. Fish. Sci. 17 (2), 267–289. https://doi.org/10.1080/10641260802667067.

Koehn, L.E., Essington, T.E., Marshall, K.N., Kaplan, I.C., Sydeman, W.J., Szoboszlai, A.I., Thayer, J.A., 2016. Developing a high taxonomic resolution food web model to assess the functional role of forage fish in the california current ecosystem. Ecol. Model. 335, 87–100. https://doi.org/10.1016/j.ecolmodel.2016.05.010.

Kovács, L., 2024. Feature selection algorithms in generalized additive models under concurvity. Comput. Stat. 39 (2), 461–493. https://doi.org/10.1007/s00180-022-01292-7.

Laurs, R.M., & Lynn, R.J. (1975). The Association of Oceanic Boundary Features and Albacore Tuna in the Northeast Pacific.

Laurs, R.M., Fiedler, P.C., Montgomery, D.R., 1984. Albacore tuna catch distributions relative to environmental features observed from satellites. Deep Sea Res. Part A. Oceanogr. Res. Pap. 31 (9), 1085–1099. https://doi.org/10.1016/0198-0149(84)90014-1.

Link, J.S., Nye, J.A., Hare, J.A., 2011. Guidelines for incorporating fish distribution shifts into a fisheries management context. Fish Fish 12 (4), 461–469. https://doi.org/10.1111/j.1467-2979.2010.00398.x.

Marra, G., Wood, S.N., 2011. Practical variable selection for generalized additive models. Comput. Stat. Data Anal. 55 (7), 2372–2387. https://doi.org/10.1016/j.csda.2011.02.004.

Mendelssohn, R. (2022). rerddapXtracto: Extracts Environmental Data from "ERDDAP" Web Services (1.1.4). ⟨https://CRAN.R-project.org/package=rerddapXtracto⟩.

Muhling, B., Brodie, S., Snodgrass, O., Tommasi, D., Dewar, H., Childers, J., Jacox, M., Edwards, C.A., Xu, Y.I., Snyder, S., 2019. Dynamic Habitat Use of Albacore and Their Primary Prey Species in the California Current System (Vol. 60). ⟨http://oceanmodeling.ucsc.edu/ccsnrt⟩.

Muhling, B.A., Snyder, S., Hazen, E.L., Whitlock, R.E., Dewar, H., Park, J.-Y., Stock, C.A., Block, B.A., 2022. Risk and reward in foraging migrations of north pacific albacore determined from estimates of energy intake and movement costs. Front. Mar. Sci. 9. https://doi.org/10.3389/fmars.2022.730428.

Nickels, C.F., Portner, E.J., Snodgrass, O., Muhling, B., Dewar, H., 2023. Juvenile albacore tuna (Thunnus alalunga) foraging ecology varies with environmental conditions in the california current large marine ecosystem. Fish. Oceanogr. 32 (5), 431–447. https://doi.org/10.1111/fog.12638.

Nieto, K., Xu, Y., Teo, S.L.H., McClatchie, S., Holmes, J., 2017. How important are coastal fronts to albacore tuna (Thunnus alalunga) habitat in the northeast Pacific Ocean? Prog. Oceanogr. 150, 62–71. https://doi.org/10.1016/j.pocean.2015.05.004.

Nikolic, N., Morandeau, G., Hoarau, L., West, W., Arrizabalaga, H., Hoyle, S., Nicol, S.J., Bourjea, J., Puech, A., Farley, J.H., Williams, A.J., Fonteneau, A., 2017. Review of albacore tuna, thunnus alalunga, biology, fisheries and management. In: In Reviews in Fish Biology and Fisheries, 27. Springer International Publishing, pp. 775–810. https://doi.org/10.1007/s11160-016-9453-y.

Noordman, L. (2024). Commercial and Recreational Harvest of Albacore Tuna (Thunnus alalunga) Oregon Albacore Port Sampling Program 2023 Annual Report.

Phillips, A.J., Ciannelli, L., Brodeur, R.D., Pearcy, W.G., Childers, J., 2014. Spatio-temporal associations of albacore CPUEs in the northeastern pacific with regional SST and climate environmental variables. ICES J. Mar. Sci. 71 (7), 1717–1727. https://doi.org/10.1093/icesjms/fst238.

Pinsky, M.L., Mantua, N.J., 2014. Emerging Adaptation Approaches for Climate-Ready Fisheries Management. 27(4), 146–159. https://doi.org/10.2307/24862219.

Pozo Buil, M., Jacox, M.G., Fiechter, J., Alexander, M.A., Bograd, S.J., Curchitser, E.N., Edwards, C.A., Rykaczewski, R.R., Stock, C.A., 2021. A dynamically downscaled ensemble of future projections for the california current system. Front. Mar. Sci. 8. https://doi.org/10.3389/fmars.2021.612874.

Santora, J.A., Mantua, N.J., Schroeder, I.D., Field, J.C., Hazen, E.L., Bograd, S.J., Sydeman, W.J., Wells, B.K., Calambokidis, J., Saez, L., Lawson, D., Forney, K.A., 2020. Habitat compression and ecosystem shifts as potential links between marine heatwave and record whale entanglements. Nat. Commun. 11 (1), 536. https://doi.org/10.1038/s41467-019-14215-w.

Schroeder, I.D., Santora, J.A., Mantua, N., Field, J.C., Wells, B.K., Hazen, E.L., Jacox, M., Bograd, S.J., 2022. Habitat compression indices for monitoring ocean conditions and ecosystem impacts within coastal upwelling systems. Ecol. Indic. 144. https://doi.org/10.1016/j.ecolind.2022.109520.

Smith, J.A., Pozo Buil, M., Muhling, B., Tommasi, D., Brodie, S., Frawley, T.H., Fiechter, J., Koenigstein, S., Himes-Cornell, A., Alexander, M.A., Bograd, S.J., Cordero Quirós, N., Crowder, L.B., Curchitser, E., Green, S.J., Hardy, N.A., Haynie, A.C., Hazen, E.L., Holsman, K., Jacox, M.G., 2023. Projecting climate change impacts from physics to fisheries: a view from three california current fisheries. Prog. Oceanogr. 211. https://doi.org/10.1016/j.pocean.2023.102973.

Snyder, S., 2016. Navigating a seascape: physiological and environmental motivations behind juvenile north pacific albacore movement patterns. Univ. Calif. San. Diego.

Snyder, S., Franks, P.J.S., Talley, L.D., Xu, Y., Kohin, S., 2017. Crossing the line: tunas actively exploit submesoscale fronts to enhance foraging success. Limnol. Oceanogr. Lett. 2 (5), 187–194. https://doi.org/10.1002/lol2.10049.

Squire, J.L., 1983. Warm water and Southern california recreational fishing: a brief review and prospects for 1983. Mar. Fish. Rev. 45 (4–6), 27–34.

Sydeman, W.J., Santora, J.A., Thompson, S.A., Marinovic, B., Lorenzo, E.Di, 2013. Increasing variance in north pacific climate relates to unprecedented ecosystem variability off california. Glob. Change Biol. 19 (6), 1662–1675. https://doi.org/10.1111/gcb.12165.

Townhill, B.L., Radford, Z., Pecl, G., van Putten, I., Pinnegar, J.K., Hyder, K., 2019. Marine recreational fishing and the implications of climate change. Fish Fish 20 (5), 977–992. https://doi.org/10.1111/faf.12392.

Vaux, F., Bohn, S., Hyde, J.R., O'Malley, K.G., 2021. Adaptive markers distinguish north and south pacific albacore amid low population differentiation. Evolut. Appl. 14 (5), 1343–1364. https://doi.org/10.1111/eva.13202.

Waldman, J.R., Quinn, T.P., 2022. North American diadromous fishes: drivers of decline and potential for recovery in the anthropocene. Sci. Adv. 8 (4), 5486. https://doi.org/10.1126/sciadv.abl5486.

Ward, H.G.M., Askey, P.J., Post, J.R., 2013. A mechanistic understanding of hyperstability in catch per unit effort and density-dependent catchability in a multistock recreational fishery. Can. J. Fish. Aquat. Sci. 70 (10), 1542–1550. https://doi.org/10.1139/cjfas-2013-0264.

Watson, J.R., Fuller, E.C., Castruccio, F.S., Samhouri, J.F., 2018. Fishermen follow fine-scale physical ocean features for finance. Front. Mar. Sci. 5 (FEB). https://doi.org/10.3389/fmars.2018.00046.

WDFW. (2008). Economic Analysis of the Non-Treaty Commercial and Recreational Fisheries in Washington State.

WDFW. (2017). Washington State Department of Fish and Wildlife Ocean Sampling Program Overview. ⟨*https://www.recfin.org/wp-content/uploads/2024/04/Washington-Ocean-Sampling*-Program-OSP-Overview-for-RECFIN-UPDATEDNOV-2.pdf⟩.

Wen, C., Kumar, A., Xue, Y., 2008. North pacific gyre oscillation links ocean climate and ecosystem change. Geophys. Res. Lett. 35 (8). https://doi.org/10.1029/2007GL032838.

Whittingham, M.J., Stephens, P.A., Bradbury, R.B., Freckleton, R.P., 2006. Why do we still use stepwise modelling in ecology and behaviour? J. Anim. Ecol. 75 (5), 1182–1189. https://doi.org/10.1111/j.1365-2656.2006.01141.x.

Wood, S.N., 2010. Fast stable restricted maximum likelihood and marginal likelihood estimation of semiparametric generalized linear models. J. R. Stat. Soc. B 73.

Xu, Y., Nieto, K., Teo, S.L.H., McClatchie, S., Holmes, J., 2017. Influence of fronts on the spatial distribution of albacore tuna (Thunnus alalunga) in the northeast pacific over the past 30 years (1982–2011). Prog. Oceanogr. 150, 72–78. https://doi.org/10.1016/j.pocean.2015.04.013.

Zaba, K.D., Rudnick, D.L., 2016. The 2014-2015 warming anomaly in the Southern california current system observed by underwater gliders. Geophys. Res. Lett. 43 (3), 1241–1248. https://doi.org/10.1002/2015GL067550.