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Recreational fisheries as indicators of change: species range shifts from MRIP (1981–2024)

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Abstract:

Background: In response to global climate change, many marine fish species are shifting their distributions poleward and into deeper, cooler, and more oxygenated waters. Most studies examining this phenomenon rely on fishery-independent surveys with randomized sampling strata or fishery-dependent data from commercial fisheries. However, stock assessments in the United States also incorporate marine recreational data provided by NOAA's Marine Recreational Information Program (MRIP), an intercept survey that collects data dockside and by phone to estimate fishing effort and landings. In this study, we analyze MRIP data as well as more conventional fishery-independent survey methods from 1981 to 2024 by quantifying range and latitudinal distribution shifts in four marine species (Black sea bass *Centropristis striata*, summer flounder *Paralichthys dentatus*, winter flounder *Pseudopleuronectes americanus*, and scup *Stenotomus chrysops*). These species are either structure-associated and difficult to sample with traditional methods, underrepresented in standardized trawl surveys, or lack a significant commercial fishery in the U.S.

Results: We detected significant latitudinal distribution shifts in black sea bass and summer flounder from 1981–2024, particularly in the fall season, with both species exhibiting strong poleward movement in MRIP-derived center of distribution (COD) estimates. These trends were corroborated by NOAA trawl survey data via the DisMAP tool. Black sea bass also showed moderate range expansion, while summer

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flounder exhibited range contraction. Scup displayed moderate range expansion in MRIP data but weak or non-significant COD shifts in both MRIP and DisMAP. Winter flounder showed consistent range contraction in MRIP but little movement in COD. While broad alignment was observed between MRIP and DisMAP patterns for black sea bass and summer flounder, discrepancies in scup and winter flounder trends highlight the complementary strengths and limitations of each dataset.
Conclusions: We propose that MRIP data can complement existing survey frameworks, particularly for species not well captured by conventional methods. Finally, we recommend future research investigate the responsiveness of different datasets in detecting early signals of shifting stocks.

Keywords: range shift, distribution, MRIP, DisMAP

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Background

Anthropogenic climate change has rapidly altered the marine environment, with increases in ocean temperature and deoxygenation (IPCC 2023). Changes in these physical parameters represent a form of habitat alteration (i.e. loss, shift, expansion, etc.), particularly for temperature and oxygen-sensitive species (Deutsch et al. 2024). Marine fishes, in particular, have demonstrated widespread distribution shifts, often exhibiting poleward or depth redistributions to locate optimal isotherms and oxygen gradients (Nye et al. 2009; Pinsky et al. 2013). These changes scale up from individual species to entire communities, altering biodiversity patterns and ecosystem functioning (Pinsky et al. 2020). Additionally, major shifts across state, international, or management boundaries have implications for fisheries management, spatial planning, and regional economies (Kleisner et al. 2017), especially for data-poor species where current monitoring efforts may be insufficient.

A recent review of range shift papers for marine species found that a majority of papers relied on some type of trawling data (Dahms & Killen 2023). Current assessments for such range shifts in the United States typically rely on fishery-independent surveys, such as the randomly stratified trawls of the Northeast Fishery Science Center (NEFSC) (Nye et al. 2009) or fishery-dependent data from commercial landings (Pinsky & Fogarty 2012). However, both of these data sources present limitations including selectivity and coverage issues. Bottom trawl surveys may undersample structure-associated species due to gear constraints or habitat inaccessibility (Rooper & Martin 2012), while commercial landings data exclude species with low market value or those not targeted by the commercial fishing industry. As a result, many recreationally or ecologically important species may lack proper range shift assessments due to insufficient sampling methods.

Recreational fisheries represent an underutilized but increasingly relevant data source in assessing shifts in distribution (Crear et al. 2023, Williams 2025). In the United States, recreational fishing data has been collected via dockside and phone intercept-surveys by NOAA Fisheries since 1981 via the Marine Recreational Information Program (MRIP; previously Marine Recreational Fisheries Statistics Survey [MRFSS]). This continuous dataset encompasses effort and landing metrics

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along the Atlantic coast from Maine to Florida. MRIP data are collected in waves, with each wave representing a standardized sampling period throughout the year, allowing seasonal patterns in effort and catch to be captured systematically. Recreational fisheries data have limitations, as angler derived observations can be influenced by species popularity, accessibility to fishing grounds, regulatory constraints, and seasonal fishing behavior, all of which may affect detectability independent of true population distributions. Many recreationally important species also exhibit strong seasonal movements that influence when and where they are available to both anglers and surveys. For example, black sea bass and summer flounder migrate inshore and northward during warmer months (Miller et al. 2016, Kraus & Musick 2001), while scup show pronounced inshore-offshore migrations that are difficult to sample in the spring and fall (Cadrin et al. 2015). Winter flounder often display higher residency in estuarine and nearshore habitats in both seasons (Ziegler et al. 2019), though their movement patterns are complex and can vary both among and within stocks, with different contingents exhibiting resident or migratory behavior. These seasonal dynamics mean that MRIP's bi-monthly sampling waves often capture species at different stages of their life history or migratory cycles, which must be considered when interpreting long-term distributional shifts. Recent work by Williams (2025) used MRIP data along the U.S. Atlantic coast to infer latitudinal distributional shifts in 80 species, demonstrating the potential of recreational data to capture long-term spatial dynamics. While this study provided novel utility of the MRIP database to detect range shifts in marine species, further work is needed to account for the seasonal sampling structure of MRIP waves. Additionally, MRIP-derived trends should be compared to commercial or survey data to determine gaps in either assessment strategy.

In this study, we focus the application of MRIP on four marine species: Black sea bass *Centropistis striata*, summer flounder *Paralichthys dentatus*, winter flounder *Pseudopleuronectes americanus*, and scup *Stenotomus chrysops*. Three of these species are jointly managed under the Summer Flounder, Scup, and Black Sea Bass Fishery Management Plan (MAFMC 2022), with winter flounder managed under the Northeast Multispecies Fishery Management Plan. Specifically, we quantify spatial distribution changes (center of distribution [COD], range, and maximum and minimum latitudes) in species selected for their association with structured habitats

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and high recreational interest along the East Coast of the United States from Maine to North Carolina, which is a major biogeographic boundary for many species (Pappalardo et al. 2015). We use wave-level MRIP intercept data from 1981–2024 to estimate the latitudinal COD for catch-per-unit-effort (CPUE) and compare these patterns derived from NOAA NEFSC trawl survey data, which are grouped into spring and fall.

This analysis provides as a proof of concept for using recreational fisheries data to detect seasonal range shifts. We focus on structurally associated, recreationally important species as representative test cases, demonstrating how MRIP data can be extended to species that are more data-limited or less effectively sampled by conventional surveys. We show that MRIP-derived patterns are broadly consistent with those from established fishery-independent surveys, supporting its utility as a complementary data source. Incorporating MRIP data alongside traditional surveys can improve detection of spatial change and inform adaptive management in a rapidly changing ocean.

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Methods:

Study Area—This study focuses on a portion of the Northwest Atlantic Ocean, specifically the U.S. Northeast Shelf region, including the Mid-Atlantic Bight, Southern New England, Georges Bank, and the Gulf of Maine, which encompass diverse and dynamic marine ecosystems that support many ecologically and economically important marine species (Anderson et al., 2010; Conley et al., 2017). The study area specifically spans from Cape Hatteras, North Carolina to the northern extent of the Gulf of Maine, and extends out to the continental slope. These regions are highly influenced by both cold water from the northern Labrador Current and warm water from the southern Gulf Stream (Stevenson et al., 2004; Anderson et al., 2010; Neto et al., 2021). Notably, the Gulf Stream serves as a crucial migratory pathway for numerous marine species, including fishes, marine mammals, and marine reptiles (NEFSC, 2015).

Survey Data—Recreational fishing catch and effort data were downloaded from the NOAA MRIP database using the respective query tools (NOAA 2023). Queries were run in June 2025, downloaded as CSV files, aggregated, and uploaded into the R Statistical Software where all further analyses took place (R Core Team 2024; R version 4.4.1). The effort query included 1981–2024 by wave**,** mode combined**,** and area combined**,** where modes refer to fishing methods (e.g., private/rental boats, shore-based fishing, charter boats, etc.) and areas refer to the spatial management units defined by MRIP along the U.S. Atlantic coast (e.g., state waters, federal exclusive economic zone, state territorial seas, etc.). Catch queries were structured similarly, including 1981–2024 by wave, mode, and area for the Northwest Atlantic by state. These queries were run for black sea bass, summer flounder, winter flounder, and scup.

All data were filtered to include states from Maine to North Carolina (Figure 1). Additionally, catch and effort location were provided at the state level in the MRIP database; therefore, each East Coast state’s coastline was assigned a central/midpoint latitude (Suppl. Table 1). While data are reported as total catch and total effort, and there is no known estimate of variance between months, there is a reported proportional standard error (PSE), for each total catch value. This PSE

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represents the standard error of the estimate expressed as a percentage of the estimate itself (i.e., PSE = [standard error / estimate] x 100). PSE provides a relative measure of uncertainty, with higher values indicating lower precision in the estimated catch. To align with seasonal sampling in fishery-independent surveys, MRIP intercept data were filtered to include only Wave 2 (March–April) and Wave 5 (September–October), corresponding approximately to the spring and fall sampling periods of the NEFSC bottom trawl survey. Although MRIP data are available for additional waves, including summer months when recreational activity and catch rates for some species are highest, these were excluded here to maintain consistent seasonal alignment with trawl survey-derived products. Wave-by-wave analysis is, however, included within the supplementary material to provide additional resolution and transparency, and to evaluate whether seasonal aggregation obscures intra-seasonal variability in catch and effort estimates.

Range indicators for black sea bass, summer flounder, winter flounder, and scup were downloaded in R from the NOAA DisMAP user tool using the package dismapr (Best & Karp 2025). DisMAP (Distribution Mapping and Analysis Portal) is an online tool enabling users to access and visualize data on species distributions derived from NOAA fishery-independent survey data (primarily bottom trawl surveys). Range indicators included center of distribution (COD; discussed below), and leading / trailing edges of total range. DisMAP does not account for differences in survey design, gear, and vessel changes (including the use of conversion factors to account for the transition from the Albatross IV to the Henry B. Bigelow in 2008/2009), but should in future iterations of the tool. Years with incomplete survey coverage (such as disruptions during 2020 associated with the COVID-19 pandemic) are also excluded outright. As a result, DisMAP provides a shelf-wide representation of species distributions that differs fundamentally from MRIP, which reflects coastal recreational catch and effort aggregated at the state level. Detailed information on DisMAP's processing and analysis can be found in the Technical Report linked on the portal's website.

Analysis—For each species, state, and season, we divided MRIP catch data by MRIP effort (measured as the number of fishing trips) to calculate catch-per-unit-effort (CPUE; fish per fishing trip) over time. We examined minimum and maximum

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central latitudes (range edges) with non-zero CPUE and calculated a seasonal range for each year from 1981–2024 (Eqn. 1).

$$Range = Lat_{max} - Lat_{min} \quad (1)$$

In years when a species was captured in only a single state within a season, this calculation yielded a range of zero. These zero values were treated as undefined spatial extent and were therefore replaced with NA values.

Normality was determined for each species' range using a Shapiro-Wilk normality test, then linear regressions were run on species ranges over time. We ran monotonic Mann-Kendall trend tests to determine significant trends in range, minimum latitude, and maximum latitude over time using the 'Kendall' package, with a significant alpha threshold of 0.05 (McLeod 2005). For significant trends, we used the fitted linear regression to estimate predicted range values in 1981 and 2024, and calculated the change in range between these two years as the difference between model predicted values.

The center of distribution (COD; or center of gravity) was calculated for CPUE (Eqn. 2), where n is the number of samples, c_i is the CPUE value of the ith sample, and Lat_i is the latitude at an ith sample (Thorson et al. 2016).

$$\underline{COD} = \frac{\sum_{i=1}^{n} c_i Lat_i}{\sum_{i=1}^{n} c_i} \quad (2)$$

We calculated the COD (Eqn. 2) for each species in each wave from 1981–2024 to estimate the distribution based on CPUE in a given year, and examined normality using a Shapiro-Wilk normality test. We then ran a Mann-Kendall test on the COD over time to determine temporally significant relationships. Linear regressions were also applied to the time series, using 1981 and 2024 as endpoints to estimate overall latitudinal change

We similarly ran the Shapiro-Wilk normality test and Mann-Kendall test on the range edges and COD of the DisMAP distribution indicators. We then calculated 1981 and 2024 model-predicted values and compared range shifts, range expansions, and range contractions to those calculated from the MRIP data.

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Results:

Species distributions exhibited significant changes in both center of distribution (COD) and latitudinal range over the last four decades, with distinct seasonal patterns supported by Mann-Kendall trend analysis (Figs. 2, 3). In fall, black sea bass showed the strongest and most consistent northward movement, with MRIP-derived COD increasing by 2.1° latitude between 1981 and 2024 (Fig. 3), equivalent to approximately 240 km along the U.S. East Coast. This trend was highly significant ($\tau = 0.73$, $p < 0.001$), accompanied by a moderate but significant expansion in range ($\tau = 0.35$, $p = 0.005$; Fig. 2). Summer flounder also showed clear poleward redistribution. In fall, COD increased by approximately 0.9° latitude ($\tau = 0.39$, $p < 0.001$; Fig. 3) with a simultaneous contraction in range ($\tau = -0.27$, $p = 0.029$; Fig. 2). Scup displayed a non-significant negative trend in COD during fall ($\tau = -0.16$, $p = 0.13$; Fig. 3), though its range expanded moderately ($\tau = 0.33$, $p = 0.005$; Fig. 2). Winter flounder's fall distribution showed no significant COD shift ($\tau = -0.10$, $p = 0.360$; Fig. 3) but a significant contraction in range ($\tau = -0.30$, $p = 0.006$; Fig. 2), indicating potential reduction in range without any meaningful shift in COD.

Spring trends were more variable. Black sea bass experienced a significant equatorial shift in COD (-1.7°, $\tau = -0.21$, $p = 0.041$; Fig. 3), paired with a moderate range expansion ($\tau = 0.29$, $p = 0.020$; Fig. 2). Summer flounder also shifted northward in COD (+2.2°, $\tau = 0.26$, $p = 0.016$; Fig. 3) and exhibited a significant contraction in range ($\tau = -0.34$, $p = 0.008$; Fig. 2). Scup showed no significant change in COD ($\tau = 0.26$, $p = 0.16$; Fig. 3) and no detectable trend in range ($\tau = 0.00$, $p = 1.00$; Fig. 2). Winter flounder exhibited no significant shift in COD in the spring ($\tau = -0.07$, $p = 0.510$; Fig. 3) but a strong contraction in range ($\tau = -0.50$, $p < 0.001$; Fig. 2).

When compared to the distribution indicators from the DisMAP tool, which are derived from data from the NEFSC bottom trawl survey, there is a general alignment of trends, with some notable discrepancies (Figs. 4, 5). In the fall, black sea bass exhibited a significant northward shift in COD ($\tau = 0.46$, $p < 0.001$; Fig. 5), consistent with a sustained poleward trend. However, this was accompanied by a modest contraction in latitudinal range ($\tau = -0.34$, $p < 0.001$; Fig. 4), indicating the population is not only shifting north but becoming more spatially concentrated.

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Summer flounder showed a similar pattern, with a strong northward shift in COD ($\tau = 0.75$, $p < 0.001$; Fig. 5) and a marked contraction in range ($\tau = -0.61$, $p < 0.001$; Fig. 4). Winter flounder displayed a moderate northward trend in COD ($\tau = 0.35$, $p < 0.001$; Fig. 5) and also showed range contraction ($\tau = -0.37$, $p < 0.001$; Fig. 4). In contrast, scup showed only a weak COD increase ($\tau = 0.21$, $p = 0.038$; Fig. 5) and no significant change in range ($\tau = 0.04$, $p = 0.680$; Fig. 4), suggesting a more spatially stable fall distribution.

In spring, black sea bass exhibited the strongest COD trend across all species and seasons, with a very high Kendall's tau ($\tau = 0.82$, $p < 0.001$; Fig. 5), but no significant change in range ($\tau = 0.07$, $p = 0.520$; Fig. 4), indicating a strong poleward shift without concurrent expansion or contraction. Summer flounder also shifted significantly northward ($\tau = 0.61$, $p < 0.001$; Fig. 5), again paired with a significant range contraction ($\tau = -0.56$, $p < 0.001$; Fig. 4). Winter flounder displayed a moderate COD northward shift ($\tau = 0.47$, $p < 0.001$; Fig. 5) and a corresponding range contraction ($\tau = -0.33$, $p = 0.001$; Fig. 4). For scup, no significant trends were detected in either COD ($\tau = 0.00$, $p = 1.00$; Fig. 5) or range ($\tau = -0.06$, $p = 0.680$; Fig. 4), potentially reflecting sparse early-season detections or inconsistent spring coverage in the survey. Summaries for COD and range shifts in MRIP-derived CPUE and DisMAP distribution indicators can be found in Figure 6.

Percent standard error (PSE) values for recreational landings exhibited strong seasonal structure when evaluated by MRIP wave (Fig. 7). Across species, the highest uncertainty consistently occurred during Wave 2 (March–April) and Wave 6 (November–December), during which more than half of observations exceeded 50% PSE for most species. This pattern was particularly pronounced for scup and summer flounder, for which over 90% of Wave 2 estimates and more than 75% of Wave 6 estimates exceeded 50% PSE. In contrast, Wave 4 (July–August) exhibited the lowest uncertainty across all species, with fewer than 25% of observations exceeding 50% PSE and a majority falling within the 0–30% range. Intermediate levels of uncertainty were observed during Waves 3 and 5, with species-specific differences in the distribution of PSE values. Across multiple waves, scup and winter flounder stand out as the two species with the most persistent high PSE values. Wave-specific analyses further indicated that winter flounder exhibited the

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strongest temporal trends during Waves 3 and 4 (Supplemental Figures 1, 2), while seasonal patterns for the other species were broadly consistent across waves.

Figure 1 A map displaying 11 U.S. East Coast states and the midpoint latitude for their coastline (specific coordinates indicated in Suppl. Table 1).

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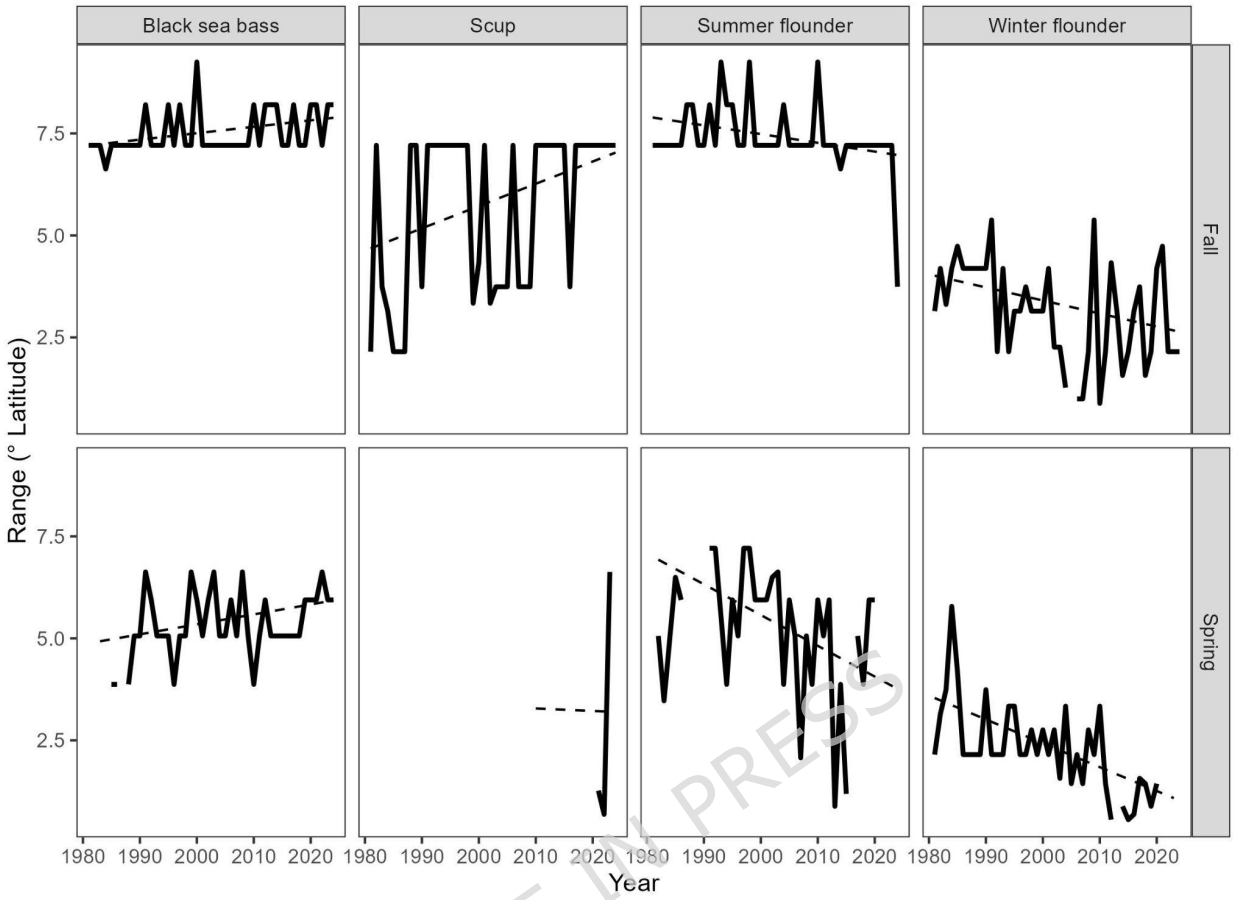

Figure 2 Time series of annual range in degrees latitude from 1981–2024 for four recreationally targeted fish species (black sea bass, scup, summer flounder, and winter flounder) on the U.S. East Coast, using the MRIP (Marine Recreational Information Program) database. Results are shown separately for fall and spring seasons which represent Wave 5 and 2 in the MRIP survey, respectively. Dashed lines display linear regressions.

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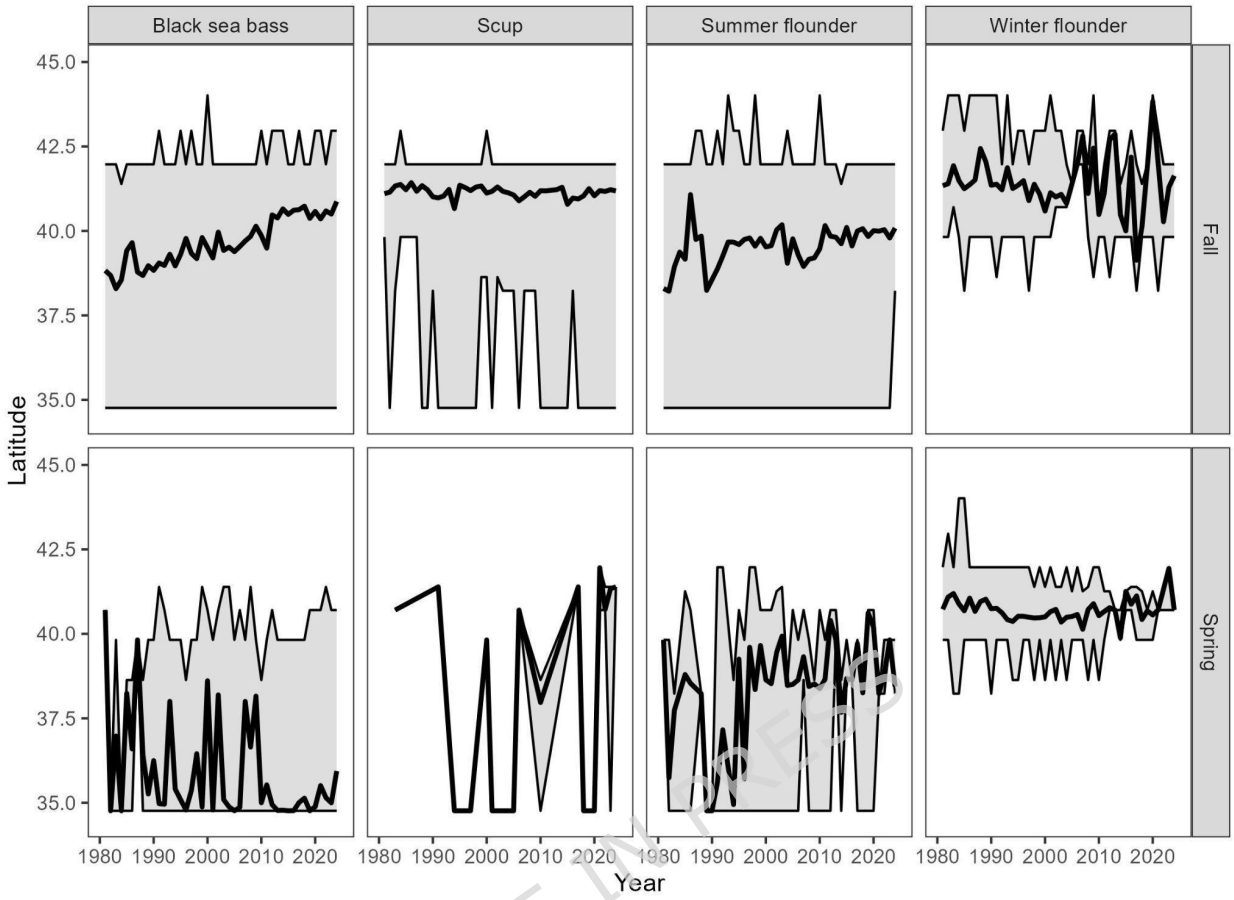

Figure 3 Total latitudinal distribution (gray ribbons) and time series of the center of distribution (COD; solid black lines) from 1981–2024 for four recreationally targeted fish species (black sea bass, scup, summer flounder, and winter flounder) on the U.S. East Coast, using the MRIP (Marine Recreational Information Program) database. Results are shown separately for fall and spring seasons, which represent Wave 5 and 2 in the MRIP survey, respectively.

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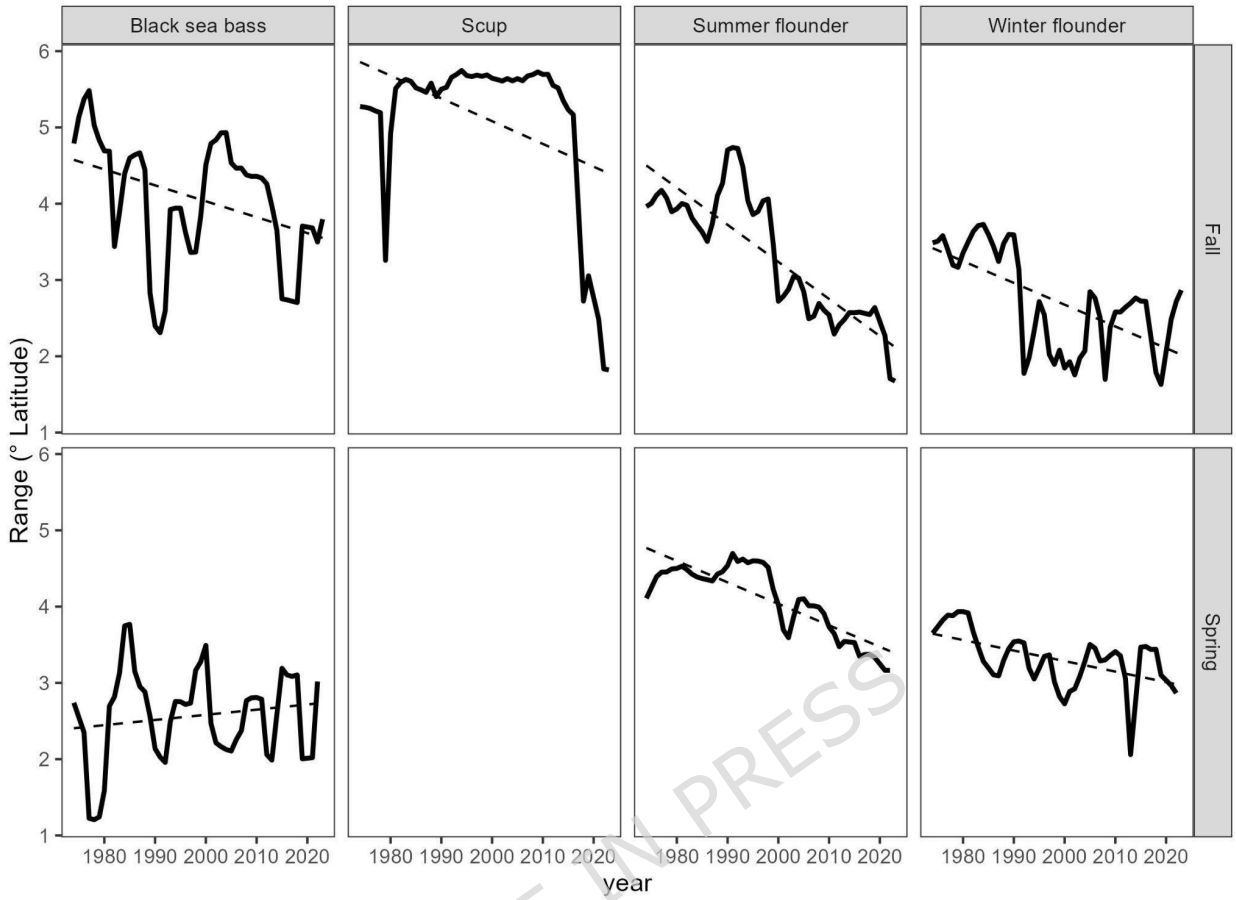

Figure 4 Time series of annual range in degrees latitude from 1981–2024 for four recreationally targeted fish species (black sea bass, scup, summer flounder, and winter flounder) on the U.S. East Coast, using the DisMAP visualization tool (downloaded from R package dismapr). Results are shown separately for fall and spring seasons. Dashed lines display linear regressions. Scup lacked data for the spring.

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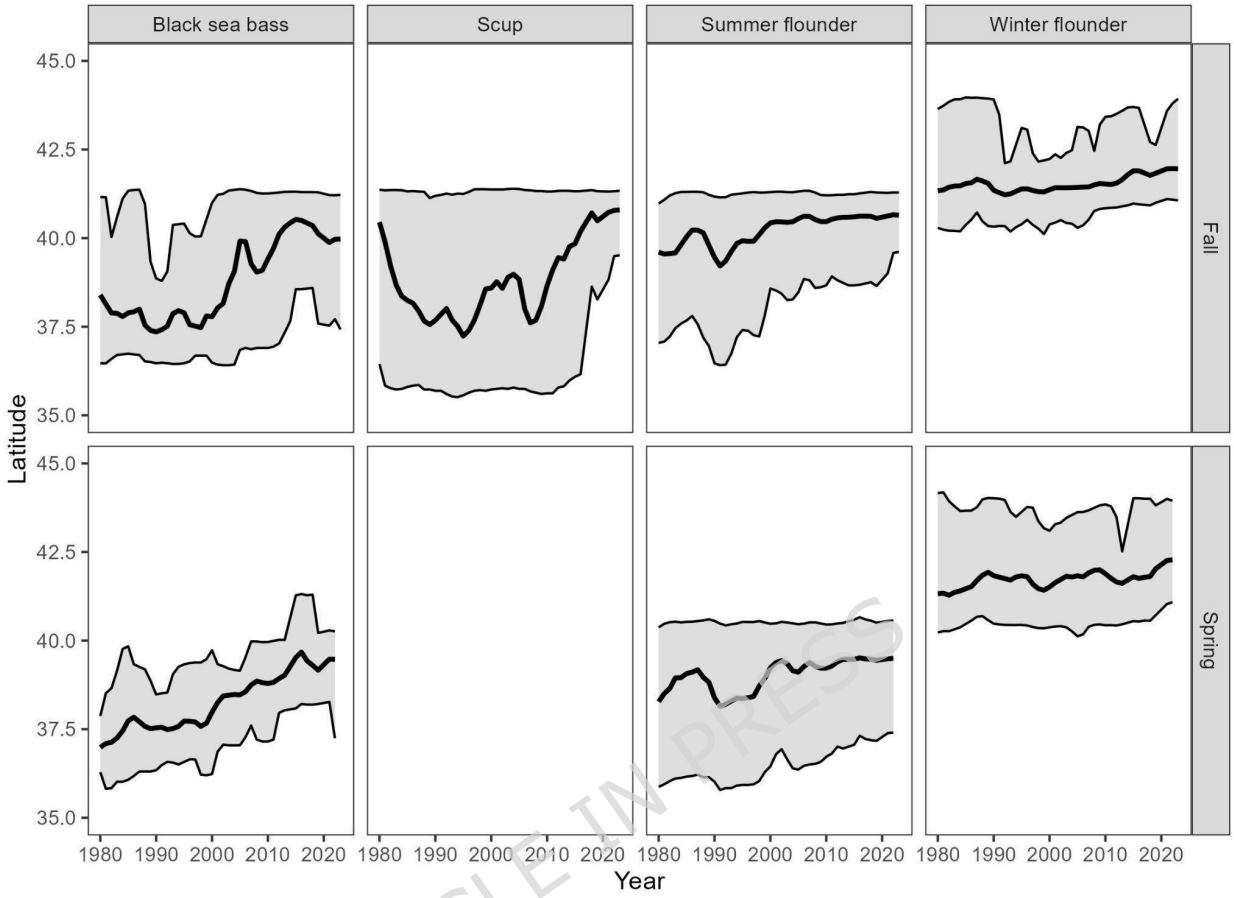

Figure 5 Total latitudinal distribution (gray ribbons) and time series of the center of distribution (COD; solid black lines) from 1981–2024 for four fish species (black sea bass, scup, summer flounder, and winter flounder) on the U.S. East Coast, downloaded from NOAA's DisMAP user tool. Panels are separated by season. Scup lacked data in the spring.

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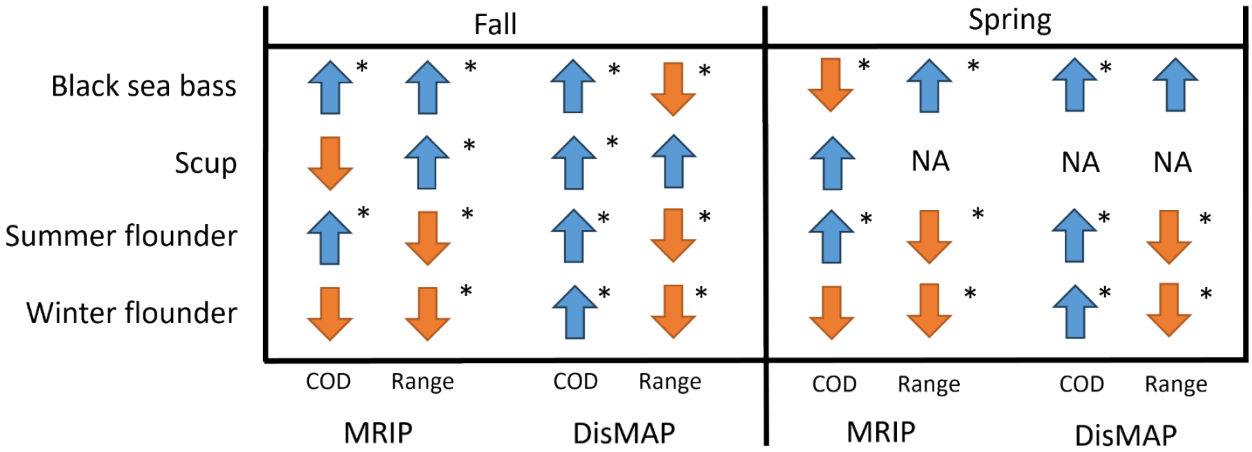

Figure 6 Seasonal trends in center of distribution (COD) and latitudinal range for four focal species over the past four decades based on MRIP (Marine Recreational Information Program) and DisMAP (Distribution Mapping and Analysis Portal) datasets. Arrows indicate the direction of change: ↑ denotes a northward shift or range expansion, ↓ denotes a southward shift or range contraction. Asterisks (*) indicate statistically significant trends (Mann-Kendall test, $p < 0.05$). "NA" indicates unavailable data. Species include black sea bass, scup, summer flounder, and winter flounder, assessed separately for fall and spring seasons.

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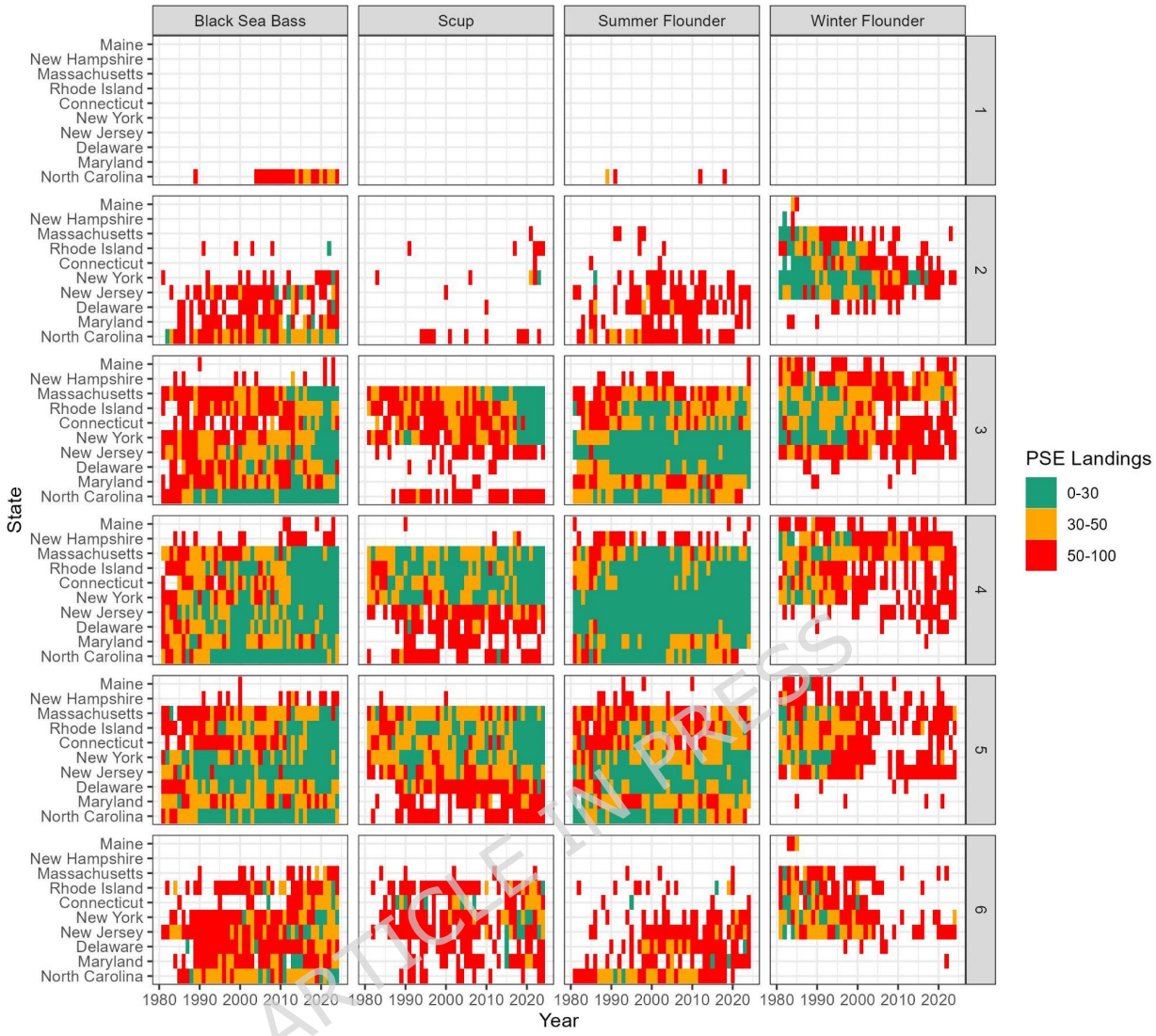

Figure 7 Percent standard error (PSE) of total recreational landings for four fish species by state, year, and wave using MRIP data from 1981–2024. Colors indicate uncertainty bins: green (PSE <30), orange (30–50), and red (>50). High PSE values reflect lower confidence in estimates.

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Discussion:

This study demonstrates that recreational fisheries data, specifically NOAA's Marine Recreational Information Program (MRIP), can be used to detect latitudinal range shifts and distributional changes in certain demersal species along the U.S. East Coast. By focusing on four key recreationally targeted species, including black sea bass (*Centropristis striata*), summer flounder (*Paralichthys dentatus*), scup (*Stenotomus chrysops*), and winter flounder (*Pseudopleuronectes americanus*), we assessed whether changes in center of distribution (COD) and range extent based on MRIP catch-per-unit-effort (CPUE) data align with patterns observed in NOAA's fishery-independent trawl survey, as analyzed in NOAA's DisMAP as a proxy for the raw trawl data. Our findings provide support for the complementary value of recreational landing datasets in tracking species distributions, particularly for species that are structure-associated or underrepresented in traditional surveys, and highlight the need for higher data standards and certainty for recreational estimates.

It is important to note that MRIP-derived distribution metrics reflect coastal availability to recreational fisheries rather than continuous species occupancy across the continental shelf. Because MRIP CPUE integrates both fish presence and angler access, inferred centers of distribution should be interpreted as availability-weighted coastal indicators. However, this distinction is not unique to recreational data. Fishery-independent trawl surveys are also constrained by gear selectivity, habitat accessibility, and fixed sampling footprints, which can underrepresent structure-associated species or nearshore dynamics. Taken together, these differences underscore that MRIP and trawl surveys capture complementary dimensions of species distributions, and that recreational fisheries data provide a valuable and policy-relevant perspective on climate-driven redistribution within the coastal zone where human-ecosystem interactions are most intense.

Black sea bass and summer flounder exhibited the clearest and most consistent signs of northward distributional shifts, particularly in the fall (MRIP Wave 5). Both species showed significant northward shifts in fall COD over time in MRIP data, which were mirrored by northward shifts in DisMAP trawl survey estimates. For summer flounder, MRIP-derived trends were especially consistent with DisMAP

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across both COD and range metrics, including the direction and significance of observed shifts, strengthening confidence that these signals reflect underlying redistribution rather than sampling artifacts. These results reinforce previous work documenting poleward expansions for black sea bass into the Gulf of Maine (Bell et al., 2015; McMahan, 2017) and northward shifts in summer flounder distribution, fishing effort, and biomass (Nye et al., 2009; Dubik et al., 2019; Perretti and Thorson, 2019). The consistency between fall MRIP and DisMAP patterns strengthens the interpretation of temperature-driven displacement, especially given regional sea surface temperature increases of 0.8–1.2°C over the study period (Fox-Kemper et al., 2021). Importantly, agreement between MRIP and DisMAP should not be interpreted as either dataset providing a complete depiction of population distribution. Rather, concurrence is most likely during periods when nearshore availability to recreational fisheries and offshore occupancy sampled by trawl surveys respond similarly to warming. Summer flounder may be particularly well suited for such cross-dataset comparisons because they support both substantial recreational fisheries and consistent representation in fishery-independent surveys. In contrast, discrepancies between MRIP and DisMAP for other species or seasons likely reflect differences in availability, survey design, and spatial resolution, rather than contradictions in biological trends.

Seasonal dynamics further complicate the interpretation of MRIP-derived distribution metrics. In spring, black sea bass exhibited equatorial shifts in COD, despite long-term regional warming, suggesting seasonal range compression, lagged responses to environmental change, or changes in availability to the recreational fishery during early-season periods, rather than true southward redistribution. Fixed MRIP sampling waves may also increasingly intersect populations earlier or later in their seasonal migration cycles as phenology shifts under climate change. These effects are likely amplified by regulatory constraints and limited early-season access in northern states, where delayed openings and low fishing effort reduce detectability even when offshore distributions are expanding. Together, these patterns highlight the importance of multi-season analyses and reinforce that divergence between spring MRIP and trawl-based estimates likely reflects seasonal availability and access rather than conflicting biological signals.

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Scup exhibited more variable distributional patterns than the other species. In the MRIP analyses, the fall showed significant range expansions, but without consistent shifts in COD, suggesting a broader spread rather than directional shift in range. DisMAP similarly showed weak or non-significant fall trends, possibly due to survey limitations or scup's high seasonal mobility; DisMAP reported no data for scup in the spring, likely because the species was not captured in enough tows to meet the threshold to keep in the analysis. Scup are known for strong inshore-offshore migrations, in addition to concentrated schooling, which reduces detectability in standardized trawl surveys or other capture efforts (Cadrin et al. 2015). In MRIP, these dynamics are further compounded by highly localized fishing effort and episodic encounters with dense schools, which can inflate variance and obscure directional shifts in center of distribution. Prior work (Palacios-Abrantes et al. 2023) also found scup shifting both northward and offshore, especially in fall, and highlighted the sensitivity of their apparent distribution to how management zones are drawn. Offshore movements during fall may also reduce scup availability to both fisheries and surveys, further constraining the data available for distributional analyses. Collectively, these findings reinforce the need to incorporate seasonal movement and multiple data sources when tracking climate-driven changes in dynamic species like scup.

Winter flounder exhibited consistent fall range contraction in both MRIP and DisMAP datasets, yet only DisMAP detected a significant poleward shift in COD. This divergence likely reflects differences in spatial resolution, survey design, and the stock-specific structure of winter flounder populations. Winter flounder are managed as three distinct stocks: the Gulf of Maine (GOM), Southern New England-Mid-Atlantic (SNEMA), and Georges Bank stocks differ in productivity, thermal exposure, and recent population trajectories. Winter flounder are cold-water, estuarine and coastal spawners with high site fidelity (Collette and Klein-MacPhee, 2002; Bell et al., 2015), and their southern populations associated with the SNEMA stock near Long Island have collapsed in recent decades (Yencho et al., 2015). As a result, MRIP may be especially sensitive to the disappearance of winter flounder at the southern fringe, presenting as a range contraction without necessarily registering large-scale centroid shifts. In contrast, DisMAP’s broader geographic coverage across the continental shelf and stock domains allows it to capture more gradual

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redistribution within and among stocks, revealing poleward movement driven largely by the persistence of northern populations, particularly in the GOM, which may otherwise not be picked up by MRIP analyses. Such divergence between the two data sources is therefore expected given the coastal, state-aggregated nature of MRIP data, and does not necessarily imply contradictory biological signals. Rather, the two datasets capture different aspects of the same pattern: contraction toward colder, northern portions of the range. Consistent contraction across MRIP and DisMAP increases confidence in the signal of decline, while divergent COD trends highlight the role of stock structure and spatial scale in shaping detectability. Winter flounder therefore highlight how discrepancies between recreational and fishery-independent surveys can be informative, providing complementary insight into stock-specific vulnerability and spatial reorganization, especially for species with fragmented populations or complex life histories, rather than reflecting shortcomings of either data source. Taken together, these results are consistent with existing ecological understanding of winter flounder populations, though confirming the accuracy of these inferred mechanisms would require targeted analyses beyond the scope of this study.

Several limitations of the MRIP dataset should be noted. Chief among these is the high variability in PSE, which is influenced by sample size, effort distribution, and response rates. As NOAA cautions, estimates with PSE > 50 should not be used in isolation for decision-making and may require spatial or temporal aggregation. Importantly, this uncertainty is not evenly distributed across species, seasons, or states. In our analysis, spring MRIP estimates for scup were particularly sensitive to high PSE values, likely due to sparse sampling or low landings in key regions, as fishing effort and landings are access- and weather-dependent. These levels of uncertainty limit the precision of MRIP-based estimates and support the need for statistical approaches that can incorporate or mitigate error, such as Bayesian smoothing or spatio-temporal interpolation (Thorson et al., 2016).

Additionally, MRIP reports catch and effort at the state level, which constrains the spatial resolution of derived distribution metrics and can obscure finer-scale patterns of habitat use. This discretization effectively partitions the coastline into spatial bins of unequal size. Consequently, these metrics reflect areas of high

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recreational fishing effort rather than uniform sampling of coastal habitats. As a result, coastal shifts inferred from MRIP may differ from cross-shelf survey products if species expand offshore without immediately increasing nearshore presence. Open recreational seasons vary by state and species, and may not coincide with survey-based sampling windows. In addition to sampling variability or access related constraints, recreational fishing seasons and regulatory frameworks can strongly influence when and where species are observed in MRIP data. For example, recreational seasons for black sea bass and summer flounder in northern states often peak during summer months (MRIP Waves 3 and 4), which were not included in this analysis to align with NEFSC spring and fall trawl surveys (Supplemental Figures 1,2). Conversely, in southern portions of the study region, species such as summer flounder may be available to anglers over longer portions of the year due to extended seasons and milder environmental conditions. These spatial and temporal asymmetries in recreational access can affect apparent distribution patterns in MRIP-derived metrics, independent of underlying population dynamics, and represent an important distinction between recreational and fishery-independent survey data. To investigate seasonal patterns in MRIP-derived trends, we also applied Mann-Kendall tests across additional waves (Supplemental Figure 1, 2). These results suggest that peak seasonal availability may influence MRIP-derived spatial signals for certain species, particularly when recreational access is highest. However, overall conclusions regarding seasonal range shifts were robust across species.

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Despite these caveats, MRIP remains a potentially useful tool for tracking broad-scale seasonal distributions, range expansions/contractions, and nearshore dynamics in recreationally targeted species, especially where other data sources are limited. For structure-associated species like black sea bass, MRIP may offer the only large-scale insight into nearshore distribution dynamics. However, the dataset should be used alongside fishery-independent surveys and interpreted with attention to its inherent limitations.

The observed shifts in species distribution have direct implications for fisheries governance and resource allocation. As species like black sea bass and summer flounder move poleward, they cross jurisdictional boundaries between regional

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management bodies such as the Mid-Atlantic and New England Fishery Management Councils (MAFMC, NEFMC), between state agencies, and international borders. Samhouri et al. (2024) emphasize that static governance structures often lag behind ecological change, leading to access inequities and quota conflicts. For example, North Carolina retains a disproportionately large share of the summer flounder quota based on historic landings from the 1980s, despite the species' biomass now centering off states like New York and New Jersey, where access is more constrained under current allocations (Palacios-Abrantes et al. 2023). This misalignment between current species distributions and static quota frameworks illustrates how outdated governance mechanisms can create inequities in access and undermine adaptive capacity.

In this context, recreational datasets like MRIP and other complementary tools (e.g. eLogbooks, tournament records, or smartphone reporting apps) may serve as early indicators of shifting fishing opportunities and stakeholder access, helping managers anticipate and adapt to emerging distributional trends. However, these data are often met with skepticism by anglers and managers. Mistrust in MRIP is widely acknowledged and is commonly attributed to concerns about survey-based estimation methods, high variance at fine spatial scales, perceived mismatches between reported catches and anglers' lived experiences, and limited transparency in how data are collected, analyzed, and used in management decisions (National Academy of Sciences, Engineering, and Medicine 2017). Without addressing these concerns, the utility of recreational data for adaptive management may be constrained despite their growing relevance under climate change.

To fully leverage the potential of recreational data as complementary indicators of coastal availability and fishing opportunity, we recommend several key improvements. Future research should integrate additional recreational data sources (e.g. for-hire logbooks and community- (previously citizen-) science platforms) to enhance spatial and temporal resolution. Furthermore, adopting model-based statistical approaches is crucial for addressing high data uncertainty and allowing interpolation across under-sampled regions. Importantly, these methodological advances should be paired with improved communication and data dissemination strategies. Transparent reporting of uncertainty, clear explanations of

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how MRIP estimates are generated, and timely sharing of results with the recreational angling community could help bridge the gap between scientific assessments and stakeholder perceptions. By combining MRIP with these complementary monitoring tools and improving accessibility and transparency, researchers can build a more comprehensive and nuanced understanding of species dynamics under climate change, while simultaneously increasing public trust and supporting more responsive, climate-ready management strategies.

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Conclusions

This study demonstrates that recreational fisheries data, particularly from MRIP, can capture broad-scale range shifts in certain demersal species along the U.S. Atlantic coast. While the dataset presents challenges such as high uncertainty in some regions and seasons, its ability to track poleward movement in species like black sea bass and summer flounder highlights its utility in complementing traditional survey data. These findings emphasize the value of integrating diverse data streams in climate-adaptive fisheries management.

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List of Abbreviations

MRIP: Marine Recreational Information Program
NOAA: National Oceanic and Atmospheric Administration
COD: Center of distribution
SST: Sea surface temperature
CPUE: Catch per unit effort
NEFSC: Northeast Fishery Science Center
PSE: Percent standard error
DisMAP: Distribution Mapping and Analysis Portal
MAFMC: Mid-Atlantic Fishery Management Councils
NEFMC: New England Fishery Management Councils
MRFSS: Marine Recreational Fisheries Statistics Survey

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Declarations

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Availability of data and materials

No new data were generated during the current study. All data are publicly accessible via NOAA webpages. The datasets analyzed during the current study are available in the following repository github.com/rroday/MRIPRangeShift

Competing interests

The authors declare that they have no competing interests

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Authors' contributions

RER: study conception, study design, data collection, interpretation of results, analysis, and draft manuscript preparation. REH: study conception, study design, data collection, interpretation of results, analysis, and draft manuscript preparation. DRM: study design and draft manuscript preparation. ABC: study conception, study design, interpretation of results. EAH: study conception, study design, interpretation of results. All authors reviewed the results and approved the final version of the manuscript.

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Version of record at: https://doi.org/10.1186/s40850-026-00266-2

Work Cited:

Anderson M. G., J. Odell, & C. Shumway. (2010). Ch. 1 Introduction. *In.* The Northwest Atlantic Marine Ecoregional Assessment: Species, Habitats and Ecosystems, Phase One (J. K. Greene, M. G. Anderson, J. Odell, and N. Steinberg, eds.), p. 1-15. The Nature Conservancy, Eastern U.S. Division, Boston, MA.

Bell, R. J., Richardson, D. E., Hare, J. A., Lynch, P. D., & Fratantoni, P. S. (2015). Disentangling the effects of climate, abundance, and size on the distribution of marine fish: an example based on four stocks from the Northeast US shelf. ICES Journal of Marine Science, 72(5), 1311-1322.

Best B, Karp M (2025). dismapr: NOAA's Distribution Mapping and Analysis Portal (DisMAP) data retrieval. R package version 0.5.0, https://bbest.github.io/dismapr/.

Cadrin, S., Maguire, J. J., & Leaf, R. (2015). Scup Stock Assessment Team Report.

Collette, B.B. and G. Klein-MacPhee (eds.). 2002. Bigelow and Schroeder's fishes of the Gulf of Maine, third ed. Caldwell, N.J. : Blackburn Press, 577 p.: ill.; 27 cm

Conley, M. F., M. G. Anderson, L. Geselbracht, R. Newton, K. J. Weaver, A. Bernett, J. Prince, & N. Steinberg. (2017). The South Atlantic Bight Marine Assessment: Species, Habitats, and Ecosystems. The Nature Conservancy, Eastern Conservation Science.

Crear, D. P., Curtis, T. H., Hutt, C. P., & Lee, Y. W. (2023). Climate-influenced shifts in a highly migratory species recreational fishery. Fisheries Oceanography, 32(4), 327-340.

Dahms, C., & Killen, S. S. (2023). Temperature change effects on marine fish range shifts: A meta-analysis of ecological and methodological predictors. Global Change Biology, 29(16), 4459-4479.

Deutsch, C., Penn, J. L., & Lucey, N. (2024). Climate, oxygen, and the future of marine biodiversity. Annual Review of Marine Science, 16(1), 217-245.

ARTICLE IN PRESS

ARTICLE IN PRESS
Version of record at: https://doi.org/10.1186/s40850-026-00266-2

Dubik, B. A., E. C. Clark, T. Young, S. B. J. Zigler, M. M. Provost, M. L. Pinsky, & K. S. Martin.
(2019). Governing fisheries in the face of change: Social responses to long-term geographic shifts in a US fishery. Mar. Policy 99:243-251.

Fox-Kemper, B., H. T. Hewitt, C. Xiao, G. Aðalgeirsdóttir, S. S. Drijfhout, T. L. Edwards, N. R.
Golledge, M. Hemer, R. E. Kopp, G. Krinner, A. Mix, D. Notz, S. Nowicki, I. S. Nurhati, L. Ruiz, J. B. Sallée, A. B. A. Slangen, & Y. Yu. (2021). Ocean, Cryosphere and Sea Level Change. *In* Climate Change (2021): the physical science basis (V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy,J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, eds.), p. 1211-1362. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (Intergovernmental Panel on Climate Change). (2023). Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC. https://www.ipcc.ch/report/sixth-assessment-report-synthesis-report/

Kleisner, K. M., Fogarty, M. J., McGee, S., Hare, J. A., Moret, S., Perretti, C. T., & Saba, V. S. (2017). Marine species distribution shifts on the US Northeast Continental Shelf under continued ocean warming. Progress in Oceanography, 153, 24-36.

Kraus, R. T., & Musick, J. A. (2001). A brief interpretation of summer flounder, Paralichthys dentatus, movements and stock structure with new tagging data on juveniles. Marine Fisheries Review, 63(3), 1-6.

Gonçalves Neto, A., Langan, J.A. & Palter, J.B. (2021).Changes in the Gulf Stream preceded rapid warming of the Northwest Atlantic Shelf. *Commun Earth Environ* 2, 74. https://doi.org/10.1038/s43247-021-00143-5

ARTICLE IN PRESS
Version of record at: https://doi.org/10.1186/s40850-026-00266-2

National Academies of Sciences, Engineering, and Medicine (2017). Review of the Marine Recreational Information Program. Washington, DC: The National Academies Press.

Nye, J. A., Link, J. S., Hare, J. A., & Overholtz, W. J. (2009). Changing spatial distribution of fish stocks in relation to climate and population size on the Northeast United States continental shelf. Marine Ecology Progress Series, 393, 111-129.

McLeod, A. I. (2005). Kendall rank correlation and Mann-Kendall trend test. R package Kendall, 602, 1-10.

McMahan, M. D. (2017). Ecological and socioeconomic implications of a northern range
expansion of black sea bass, *Centropristis striata*. Ph.D diss., Northeastern University, Boston, Massachusetts, United States.

MAFMC (Mid-Atlantic Fishery Management Council). (2022). Summer flounder, scup, and black sea bass commercial/recreational allocation amendment: Amendment 22 to the Summer Flounder, Scup, and Black Sea Bass Fishery Management Plan: Environmental assessment, regulatory impact review, and initial regulatory flexibility act analysis (Final, June 24, 2022).

Miller, A. S., Shepherd, G. R., & Fratantoni, P. S. (2016). Offshore habitat preference of overwintering juvenile and adult black sea bass, Centropristis striata, and the relationship to year-class success. PloS one, 11(1), e0147627.

National Academies of Sciences, Engineering, and Medicine (2017). *Review of the Marine Recreational Information Program*. Washington, DC: The National Academies Press.

NEFSC (Northeast Fisheries Science Center). (2015). Ecology of the Northeast US continental shelf. Northeast Fisheries Science Center Ecosystem Assessment

ARTICLE IN PRESS
Version of record at: https://doi.org/10.1186/s40850-026-00266-2

Program. [Available from https://apps-nefsc.fisheries.noaa.gov/nefsc/ecosystem-ecology/]

NOAA (National Oceanic and Atmospheric Administration). (2023). Marine Recreational Information Program (MRIP): Recreational Fisheries Statistics Queries. NOAA Fisheries. [Available at https://www.fisheries.noaa.gov/data-tools/recreational-fisheries-statistics-queries]

NOAA Fisheries. 2024-07. DisMAP data records. Retrieved from apps-st.fisheries.noaa.gov/dismap/DisMAP.html. Accessed October 1 2025.

Palacios-Abrantes, J., Crosson, S., Dumas, C., Fujita, R., Levine, A., Longo, C., & Jensen, O. P. (2023). Quantifying fish range shifts across poorly defined management boundaries. PLoS One, 18(1), e0279025.

Pappalardo, P., Pringle, J. M., Wares, J. P., & Byers, J. E. (2015). The location, strength, and mechanisms behind marine biogeographic boundaries of the east coast of North America. Ecography, 38(7), 722-731.

Perretti, C. T., & J. T. Thorson. (2019). Spatio-temporal dynamics of summer flounder (Paralichthys dentatus) on the Northeast US shelf. Fish. Res. 215:62-68.

Pinsky, M. L., & Fogarty, M. (2012). Lagged social-ecological responses to climate and range shifts in fisheries. Climatic change, 115(3), 883-891.

Pinsky, Malin L., Rebecca L. Selden, and Zoë J. Kitchel. "Climate-driven shifts in marine species ranges: scaling from organisms to communities." Annual review of marine science 12, no. 1 (2020): 153-179.

Pinsky, M. L., Worm, B., Fogarty, M. J., Sarmiento, J. L., & Levin, S. A. (2013). Marine taxa track local climate velocities. Science, 341(6151), 1239-1242.

R Core Team (2024). _R: A Language and Environment for Statistical Computing_. R Foundation for Statistical Computing, Vienna, Austria. <https://www.R-project.org/>.

ARTICLE IN PRESS
Version of record at: https://doi.org/10.1186/s40850-026-00266-2

Rooper, C. N., & Martin, M. H. (2012). Comparison of habitat-based indices of abundance with fishery-independent biomass estimates from bottom trawl surveys. Fishery Bulletin, 110(1).

Samhouri, J. F., Feist, B. E., Jacox, M., Liu, O. R., Richerson, K., Steiner, E., ... & Selden, R. L. (2024). Stay or go? Geographic variation in risks due to climate change for fishing fleets that adapt in-place or adapt on-the-move. PLOS Climate, 3(2), e0000285.

Stevenson, D., L. Chiarella, D. Stephan, R. Reid, K. Wilhelm, J. McCarthy, and M. Pentony.
(2004). Characterization of the fishing practices and marine benthic ecosystems of the northeast
US shelf, and an evaluation of the potential effects of fishing on essential habitat. NOAA Tech.
Memo. NMFS-NE-181, 179 p.

Thorson, J. T., Pinsky, M. L., & Ward, E. J. (2016). Model-based inference for estimating shifts in species distribution, area occupied and centre of gravity. Methods in Ecology and Evolution, 7(8), 990-1002.

Williams, E. H. (2025). Marine fish distribution shifts inferred from a recreational fishing survey along the US East Coast. North American Journal of Fisheries Management, vqaf030.

Yencho, M. A., Jordaan, A., Cerrato, R. M., Baumann, H., & Frisk, M. G. (2015). Growth and mortality in coastal populations of winter flounder: implications for recovery of a depleted population. Marine and Coastal Fisheries, 7(1), 246-259.

Ziegler, C. M., Zacharias, J. P., & Frisk, M. G. (2019). Migration diversity, spawning behavior, and habitat utilization of winter flounder. Canadian Journal of Fisheries and Aquatic Sciences, 76(9), 1503-1514.

ARTICLE IN PRESS