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SPATIAL INDICATORS FOR STOCK ASSESSMENT AND ECOSYSTEM MONITORING

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SUMMARY

ICCAT's single-species management framework aims to keep stocks above B_{MSY}*, which requires rebuilding plans if biomass falls below this level. Healthy stocks are expected to occupy broader areas and show higher local densities than depleted ones. Therefore, recovery also depends on ensuring that a species' ranges align with the potential suitable habitat. Climate change may alter habitats and hence global productivity and carrying capacity, requiring adaptive management that combines* B_{MSY} *targets with spatial protection to ensure sustainable fishing for tuna and tuna-like stocks in Areas Beyond National Jurisdiction (ABNJ). To support Biodiversity Beyond National Jurisdiction (BBNJ), biomass-based metrics (like* B_{MSY}*) should be integrated with spatial management to ensure resilient, transboundary stocks. Spatial indicators describing aggregation, occupancy, and dispersion can serve as indicators of stock health and support ecosystem-based approaches to management. Catch and effort data were used to calculate spatial indicators ICCAT stocks. Despite limitations due to using the coarse 5°×5° publicly available data, indicators captured key stock dynamics. Spatial indicators offer a science-based approach to enhance ICCAT stock assessments and ecosystem monitoring and aligns with BBNJ requirements.*

RÉSUMÉ

Le cadre de gestion monospécifique de l'ICCAT vise à maintenir les stocks au-dessus de BPME, ce qui nécessite des plans de rétablissement si la biomasse tombe en dessous de ce niveau. Les stocks sains devraient occuper des zones plus étendues et présenter des densités locales plus élevées que les stocks épuisés. Par conséquent, le rétablissement dépend également de l'alignement de l'aire de distribution d'une espèce sur l'habitat potentiel adéquat. Le changement climatique peut modifier les habitats et, donc, la productivité mondiale et la capacité de transport, ce qui nécessite une gestion adaptative combinant les objectifs en termes de BPME et la protection de l'espace afin de garantir une pêche durable des stocks de thonidés et d'espèces apparentées dans les zones situées au-delà de la juridiction nationale (ABNJ). Pour soutenir la biodiversité au-delà des juridictions nationales (BBNJ), les mesures basées sur la biomasse (comme BPME) devraient être intégrées à la gestion spatiale afin de garantir la résilience des stocks transfrontaliers. Les indicateurs spatiaux décrivant l'agrégation, l'occupation et la dispersion peuvent servir d'indicateurs de la santé des stocks et soutenir les approches de gestion basées sur l'écosystème. Les données relatives aux captures et à l'effort de pêche ont été utilisées pour calculer les indicateurs spatiaux des stocks de l'ICCAT. Malgré les limites liées à l'utilisation des données publiques brutes 5°×5°, les indicateurs ont permis de saisir les principales dynamiques des stocks. Les indicateurs spatiaux offrent une approche scientifique pour améliorer les évaluations des stocks de l'ICCAT et le suivi de l'écosystème et s'alignent sur les exigences de la BBNJ.

RESUMEN

El marco de ordenación de especies únicas de ICCAT pretende mantener os stocks por encima del nivel de B_{RMS}*,que requiere planes de recuperación si la biomasa cae por debajo de este nivel. Se espera que los stocks en buen estado ocupen zonas más amplias y muestren mayores densidades locales que los stocks mermados. Por lo tanto, la recuperación también depende de garantizar que las áreas de distribución de una especie coincidan con el hábitat potencial adecuado. El cambio climático puede alterar los hábitats y, por lo tanto, la productividad global y la capacidad de carga, lo que requiere una ordenación adaptativa que combine los objetivos*

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de B_{RMS} con la protección espacial para garantizar la pesca sostenible de los stocks de túnidos y especies afines en las zonas fuera de la jurisdicción nacional (ABNJ). Para apoyar la biodiversidad más allá de las zonas bajo jurisdicción nacional (BBNJ), los parámetros basados en la biomasa (como B_{RMS}) deben integrarse con la ordenación espacial para garantizar unos stocks transzonales resilientes Los indicadores espaciales que describen la agregación, la ocupación y la dispersión pueden servir como indicadores del estado de los stocks y respaldar los enfoques de ordenación basados en los ecosistemas. Los datos de capturas y esfuerzo se utilizaron para calcular los indicadores espaciales de los stocks de ICCAT. A pesar de las limitaciones debidas a la utilización de los datos brutos de 5°×5° disponibles públicamente, los indicadores captaron la dinámica clave de los stocks. Los indicadores espaciales ofrecen un enfoque de base científica para mejorar las evaluaciones de stocks y el seguimiento de los ecosistemas por parte de ICCAT y se ajustan a los requisitos de la BBNJ.

KEYWORDS

Spatial indicators, stock status, fisheries management,
ecosystem monitoring, biodiversity beyond national jurisdiction, data-limited assessment, tuna

1. Introduction

A main fisheries management objective is to achieve the maximum sustainable yield (MSY), which requires the prevention of overfishing and ensuring the recovery of overfished stocks. Arrizabalaga et al., (2014) showed that the suitable habitat of commercially valuable tuna species are determined by environmental factors, and so changes in the environment will impact carrying capacity and hence reference points. Recognising that yields are affected by exogenous drivers outside the control of Regional Fisheries Management Organisations (RFMOs), a definition of MSY is the maximum catch that can be sustainably harvested from a fish stock accounting for climate-driven shifts in species productivity, distribution, and ecosystem interactions. Stock recoveries have often taken longer than predicted by stock assessment models, for example changes in migrations been observed due to climate and overfishing (Petitgas et al., 2006). Therefore, the spatial dimension needs to be considered to ensure effective fisheries' management as RFMOs move towards the Ecosystem Approach to Fisheries (EAF).

EAF requires an assessment of impacts on the broader ecosystem and mitigation of negative impacts on non-target species to maintain the balance of marine ecosystems. Assessments need to be conducted for not only the main commercially exploited stocks, for which analytical stock assessments are available, but other by-caught stocks either retained for the market or discarded. This includes, endangered, threatened or protected (ETP) populations, and keystone or hub species (Garcia 2003, Fulton and Sainsbury 2018). The designation of ETP depends on national and international legislation intended to protect highly vulnerable species and may vary by jurisdiction. The Marine Stewardship Council (MSC, 2018) also defines primary and secondary species. The former are species of commercial value for which there are management reference points, such as the biomass associated with Maximum Sustainable Yield (B_{MSY}). The latter are neither ETP nor managed according to reference points and may be retained if they are of market value or discarded if catches are undesired but unavoidable. However, definitions are not simple, for example, ICCAT has a non-retention policy and conducts an assessment for shortfin mako shark, caught unavoidably in long-line fisheries. Although ICCAT policy is non-retention, advice is based on achieving MSY; if the intention is to kill as few as possible why base advice on MSY?

To implement EAF requires moving beyond single species model estimates of MSY. Therefore, the Subcommittee on Ecosystems is developing the Ecosystem Report Card (EcoCard), which requires monitoring of ecosystem components using indicators. Components include retained species, non-retained species (including seabirds, turtles, mammals, sharks), trophic relationships, habitats, and environmental as well as fishing and pressures. This aligns with requirements under international frameworks such as the Biodiversity Beyond National Jurisdiction (BBNJ) Agreement, which emphasising area-based management tools and environmental impact assessments. Under the BBNJ framework (Articles 7 and 19), area-based management tools (ABMTs) must be grounded in the best available science, and should include robust spatial distribution data to identify critical habitats and migration corridors. Management plans must account for spatial connectivity between ecosystems, maintain ecological integrity, and enhance resilience to climate change impacts. The provisions emphasise the need for dynamic, science-driven spatial planning to address transboundary challenges in marine conservation and sustainable resource use.

Monitoring of ABMT effectiveness, will increase the need for spatial indicators. Spatial indicators that quantify distribution, aggregation, and occupancy of fish populations are potential tools for fisheries assessment and ecosystem monitoring. Since they can capture spatial dynamics that are often linked to abundance and stock status, providing early warning signals of changes in population health (Woillez et al., 2009; Cotter et al., 2009). Spatial indicators enable the identification of aggregation hotspots and ecologically significant areas, directly informing the design of ABMT proposals. By tracking spatial contractions or expansions of species distributions or habitats, such indicators provide early warnings of stock depletion, ecosystem shifts, or recovery progress. Furthermore, they facilitate cross-sectoral coordination, essential under the BBNJ Agreement and frameworks like the Socio-Ecosystem Diagnostic Analysis being conducted for the Sargasso Sea Ecological and Biological Sensitive Area (EBSA, Roe et al., 2022); helping to harmonise data on overlapping human activities (e.g., fishing, shipping, mining) and ensuring transparent reporting. Therefore, taking a spatially explicit approach will strengthen ecosystem-based management and align international efforts to safeguard biodiversity in areas beyond national jurisdiction.

2. Materials and Methods

Two ICCAT databases, **Catch Distribution (CATDIS)** and **Effort Distribution (EFFDIS**), were obtained via the ICCAT website to develop spatial indicators based on catch per unit effort (CPUE) for selected ICCAT stocks. The datasets contain estimates rather than observations and come with various problems. However, the intention here is not to use the results for advice, but to demonstrate the use and benefits of spatial indicators. To quote G.K. Chesterton *"anything worth doing is worth doing badly"*, i.e. it is better to start and improve over time than to wait for the perfect moment, which may never come.

EFFDIS and CATDIS are based on ICCAT Task 2 catch and effort datasets ("Task II Catch-Effort" or "T2CE") and compiled by the International Commission for the Conservation of Atlantic Tunas (ICCAT) to support stock assessment, fisheries monitoring, and management.

- **CATDIS**: catch estimates for nine major tuna and tuna-like species, stratified by 5°×5° grid cells, trimester, flag, fleet, gear group, stock and school type.
- **EFFDIS**: estimated fishing effort for longline fleets, stratified by 5°×5° grid cells, month, flag, and gear type.

Both datasets provide coverage of the Atlantic Ocean and adjacent seas within ICCAT's convention area, with a time series extending from 1950 to 2023 for CATDIS and 1950 to 2015 for EFFDIS.

However, there are problems with the EFFDIS database, due to gaps and incomplete or duplicated observations (ICCAT, 2020; ICCAT, 2023a; ICCAT, 2023b; ICCAT, 2024). CATDIS often poorly represent small-scale or artisanal fisheries, limiting their utility for ecoregion analyses (ICCAT, 2022b). These issues hinder ICCAT's ability to advise on spatially explicit measures, since poor resolution potentially masks local stock depletion, forcing reliance on stock-wide assessments that may overlook critical trends (ICCAT, 2023a).

2.1 Data Processing

CATDIS and EFFDIS were merged to create CPUE indices by year, species, and 5°×5° latitude/longitude squares via several steps:

1. **Temporal alignment**: Converting EFFDIS monthly data to trimesters to match CATDIS
2. **Spatial standardisation:** Ensuring consistent grid referencing between datasets
3. **Consistent Naming Conventions:** Standardising Field Names Between Databases
4. **CPUE calculation**: Calculating catch (tons) per 1000 hooks for each 5°×5° cell

2.3 Spatial indicators

After harmonising temporal and spatial strata, indicators such as Gini, D95, and occupancy can be calculated. Even with the coarse 5°×5° grid, these aggregation indicators will hopefully provide robust signals for spatial structure. For example, do Gini and D95 values correspond to periods of lower or higher stock status, indicating changes in distribution?

Kidd et al. (submitted) provide a rigorous validation framework that could be adopted to refine spatial metrics, particularly for data-limited stocks. Both this study and Kidd et al., (submitted) calculate **Gini index** and **D95**, but with methodological differences (**Table 1**).

Several indicators were calculated using the relatively coarse spatial resolution (5°×5°) of ICCAT data.

- ***Gini index (G):*** Measures the equality of CPUE distribution across grid cells. The values range from 0 to 1, with 1 indicating highly aggregated populations.
- ***D95:*** Represents the minimum proportion of the surveyed area that contains 95% of the population. Values range from 0 to 0.95, with higher values indicating a more uniform distribution of biomass throughout the space.
- ***Centre of Gravity (CoG):*** The abundance-weighted mean position of the population.

A low Gini index indicates a more even distribution of biomass across the surveyed area (i.e., less aggregation). A high Gini index signals greater biomass concentration in specific areas (e.g., schools or patches). The Gini index reflects spatial evenness, not rarity. The properties of the aggregation indices are summarised in **Table 2**. A rare but highly aggregated species would have a high Gini index. A low D95 means the top 95% of biomass occupies a smaller area, indicating high aggregation. A high D95 implies biomass is spread over a larger area, reflecting a diffuse distribution. A rare, aggregated species would have high Gini (concentrated biomass) and low D95 (small area for 95% biomass); a common, solitary species would show low Gini (even spread) and high D95 (large area for 95% biomass).

The Gini index does not necessarily measure total biomass change; for example, a shrinking biomass patch with redistribution increases the Gini index. D95 can detect range contraction/expansion but can confuse abundance and distribution. Neither index directly measures abundance; they quantify spatial patterns, which may correlate with population size depending on behaviour and ecology.

3. Results

Simulations for contrasting populations were performed to illustrate the behaviour of the indicators, solitary vs. schooling (**Figure 1a**), carrying capacity vs. overfished (**Figure 1b**), and number of schools (**Figure 1c**).

The trends in the Gini and D95 indices derived from CATDIS and EFFDIS are presented by stock in **Figure 2**. Higher levels of aggregation of a rare species are indicated by low Gini and D95 indices. For a common schooling species the Gini index is expected to be high and the D95 to be low, while for a common solitary species, you may expect a low Gini and a high D95. Together, these indices illustrate changes in spatial aggregation and range contraction or expansion over time for each stock.

For Albacore Tuna (ALB ATN, ALB ATS), both stocks show increasing Gini values over time while D95 decreases, indicating a trend toward more concentrated distributions. Bigeye Tuna (BET AT) shows a similar pattern to Albacore. Atlantic Bluefin Tuna (BFT ATE, BFT ATW) stocks show more variable patterns with significant fluctuations in both indicators, suggesting changing distribution patterns possibly related to environmental or changes in fishing pressure under the recovery plan. Both swordfish stocks (SWO ATN, SWO ATS) show increasing Gini trends and generally decreasing D95 values, particularly since the 1980s, indicating increasing spatial concentration. Skipjack (SKJ ATE, SKJ ATW) in contrast, shows highly variable patterns with less clear directional trends compared to other species.

An inverse relationship is often seen between Gini and D95 (when one rises, the other falls) suggests that many stocks are becoming more concentrated in smaller areas over time. This pattern could indicate habitat compression due to environmental changes, changing migration patterns, contraction in range due to fishing pressure, or changes in prey distribution.

The relationship between Gini Index and D95 by Species is shown in **Figure 3**, each point represents a year for a particular stock; point size reflects mean CPUE (catch per unit effort). A strong negative relationship exists: as the Gini index increases (greater aggregation), D95 decreases (biomass occupies a smaller area). Points show a negative trend, i.e. the two indices are inversely related. Larger point sizes (higher CPUE) are scattered throughout, suggesting that aggregation can occur at both high and low abundance levels. Species (colours) show some species-specific differences, but the overall trend holds across taxa.

Spatial shifts in population centres (centres of gravity) are explored in **Figure 4**. In the North Atlantic, Albacore (ALB ATN) shows a northward shift from the subtropical to mid-Atlantic waters, Western Bluefin Tuna (BFT ATW), demonstrates a northward shift along the North American coast, and North Atlantic Swordfish (SWO ATN) a northeastern shift. For South Atlantic species, the albacore (ALB ATS) population centre has moved southward over time, while South Atlantic swordfish (SWO ATS) shows an eastward shift toward the African coast. For tropical/equatorial species, the bigeye tuna (BET AT) centre of gravity has remained near the equator but shows slight northward movement, blue Marlin (BUM AT), displays an eastward shift, and for skipjack (SKJ ATE, SKJ ATW) substantial spatial changes are seen in both stocks.

4. Discussion

These results demonstrate that for highly migratory pelagic fish stocks, spatial aggregation increases (higher Gini) are generally associated with contraction of occupied area (lower D95). The pattern is consistent across species and years; changes could signal shifts in population distribution that may have implications for management, such as increased vulnerability to local depletion as stocks become more aggregated. Spatial concentration and range contraction may occur together, and the Gini index and D95 are indicators for tracking such changes.

The consistent northward shifts observed in multiple North Atlantic species (ALB ATN, BFT ATW, SWO ATN) align with the spatial distribution patterns seen in **Figure 3**, where increasing Gini indices and decreasing D95 values indicate greater concentration of these populations. Directional shifts could reflect a response to ocean warming, with species-specific changes in suitable habitat, changes in prey distribution patterns, or fishing pressure effects reshaping population distributions. These spatial shifts demonstrate that the geographic centres of fish populations are not static, but dynamically changing over decades. Many stocks are becoming more concentrated (higher Gini, lower D95) and relocating their centres of distribution. Management boundaries based on historical distributions may need reconsideration.

The Gini index and D95 remain informative even when calculated from relatively coarse (5°×5°) spatial data. This is crucial for ICCAT applications, as finer-scale data is often unavailable. The robust performance of aggregation indicators aligns with the findings of Kidd et al. (submitted), who found that the Gini index and D95 showed good classification skill across multiple stocks and data sources. Spatial indicators appear to capture fundamental aspects of population distribution that persist even when observed at coarser spatial scales.

4.2 Implications for Stock Assessment

For data-limited stocks, spatial indicators may provide valuable supplementary information for assessment. In particular, temporal trends in aggregation indicators could help identify:

1. Declining stocks (increasing Gini, decreasing D95)
2. Recovering stocks (decreasing Gini, increasing D95)
3. Stable stocks (consistent indicator values)

4.3 Ecosystem Monitoring Applications

Spatial indicators could be integrated into ICCAT's Ecosystem Report Card, providing metrics for monitoring spatial aspects of population dynamics across species. Spatial indicators help identify spatial shifts in populations associated with climate change or other environmental drivers, supporting ICCAT's growing focus on climate-ready fisheries management.

The BBNJ Agreement places emphasis on area-based management tools and environmental impact assessments, both of which require spatial understanding of marine populations. Spatial indicators as developed here could support i) identification of ecologically important areas, ii) assessment of impacts from fishing and other activities, iii) monitoring of management effectiveness.

There are several limitations of the work, mainly based on the quality of the data available, namely:

1. ***Spatial resolution***: The 5°×5° grid cells may mask important fine-scale distribution patterns
2. ***Temporal aggregation:*** Trimester-based data may obscure seasonal dynamics
3. ***Species coverage***: Indicators are currently calculated only for major target species
4. ***Validation and verification:*** of CATDIS and EFDIS datasets is required.

Future work should focus on exploring finer-resolution data, extending indicator calculations to bycatch species, and developing threshold values to classify stock status based on indicators.

5. Verification, Validation, and Calibration (VV&C)

Verification ensures that the methods used to develop indicators adhere to best scientific standards. For example, checking that data inputs are accurate and appropriate.; such as confirming that ETP (Endangered, Threatened, and Protected) and discarded species are correctly identified and that geolocation data are reliable. Validation tests whether indicators truly reflect real-world ecosystem dynamics, by comparing model outputs to independent observations; for instance, comparing EFFDIS and CATDIS data to logbooks or observer records. Calibration involves adjusting reference levels or models to improve classification accuracy or agreement with observed trends, such as refining mesopelagic fish carbon export estimates from Ecopath with Ecosim (EwE) models to better match empirical measurements.

6. Conclusions

The Sargasso Sea's Socio-Ecosystem Diagnostic Analysis (SEDA) offers a structured framework, similar to the Driver-Pressure-State-Impact-Response (DPSIR, Kell et al., 2018, 2023) framework used for developing the EcoCard indicators. The Sargasso Seas designation as an Ecologically and Biologically Significant Area (EBSA) within an Area Beyond National Jurisdiction (ABNJ) makes it valuable for validating indicators across jurisdictional boundaries essential for BBNJ compliance. The Sargasso Sea case study demonstrates how verification, validation, and calibration (VV&C) support BBNJ's requirements for best available science, adaptive management, and transboundary governance. By integrating VV&C into indicator development, the case study aims to produce robust indicators that help ensure ICCAT's EcoCard meets BBNJ standards for spatial management and climate-resilient fisheries, ultimately strengthening ICCAT's capacity for ecosystem monitoring and high-seas governance.

Spatial indicators offer promising tools for supporting stock assessment, ecosystem monitoring, and alignment with international management requirements. Our preliminary analysis demonstrates that aggregation indicators (Gini, D95) appear to capture meaningful aspects of population distribution and status. As ICCAT continues to advance ecosystem-based fisheries management and adapt to evolving international frameworks, spatial indicators represent a valuable addition to the scientific toolbox, helping bridge the gap between single-species management and ecosystem-based approaches. We recommend incorporating spatial indicators into ICCAT's Ecosystem Report Card, exploring their application for data-limited stock assessment, and conducting further research to validate and refine these indicators.

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Table 1. Summary of indicator methodology.

Indicator	*Kell et al. (ICCAT)*	*Kidd et al. (ICES)*
Gini Index	Calculated from CPUE distribution across 5°×5° grid cells	Uses survey density data (fish/haul), filtered for mature individuals (L50)
D95	Minimum proportion of area containing 95% of population (coarse 5° grid)	Proportion of surveyed rectangles/hauls containing 95% of biomass

Table 2. Summary of spatial indicator.

Scenario	*Gini*	*D95*	*Explanation*
Rare, aggregated	High	Low	Biomass is concentrated in a few areas, despite low abundance.
Common, schooling	High	Low	Dense aggregations (schools) in limited areas
Common, solitary	Low	High	Evenly spread across a large spatial range
Rare, diffuse	Low	High	Sparse individuals spread widely (difficult to detect in practice)

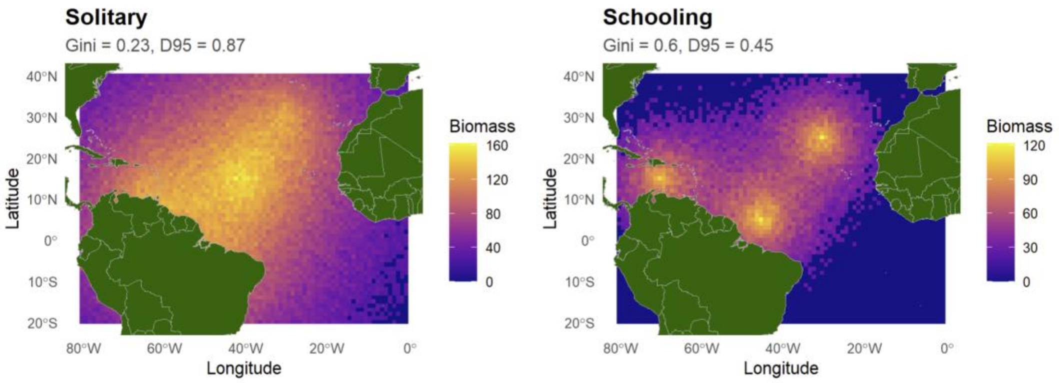

Figure 1a. Simulated distributions comparing a solitary well-dispersed population with a schooling population.

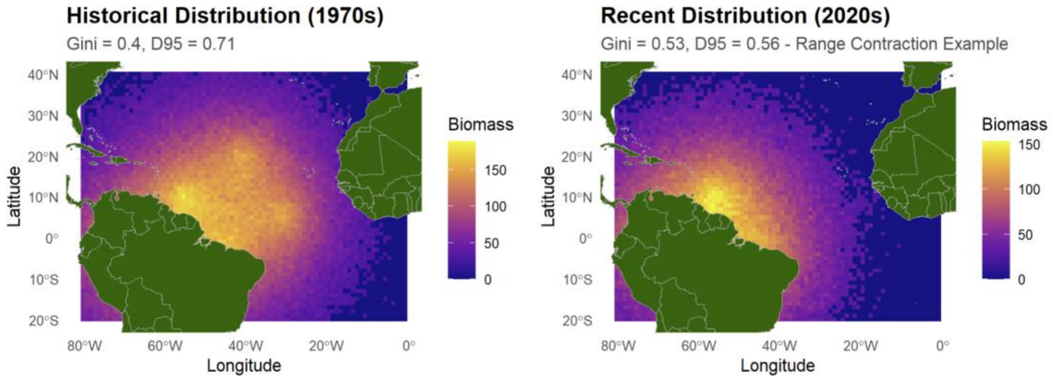

Figure 1b. Simulated distributions for a stock at carrying capacity compared to an overfished stock.

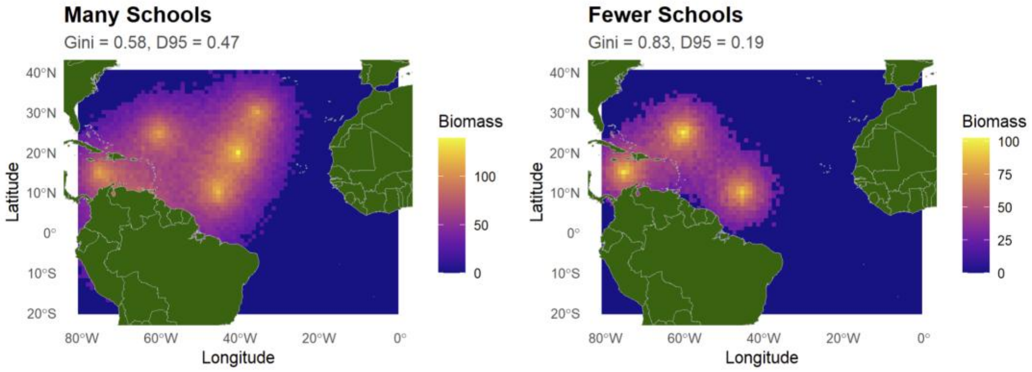

Figure 1c. Simulated distributions for a reduction in the number of schools.

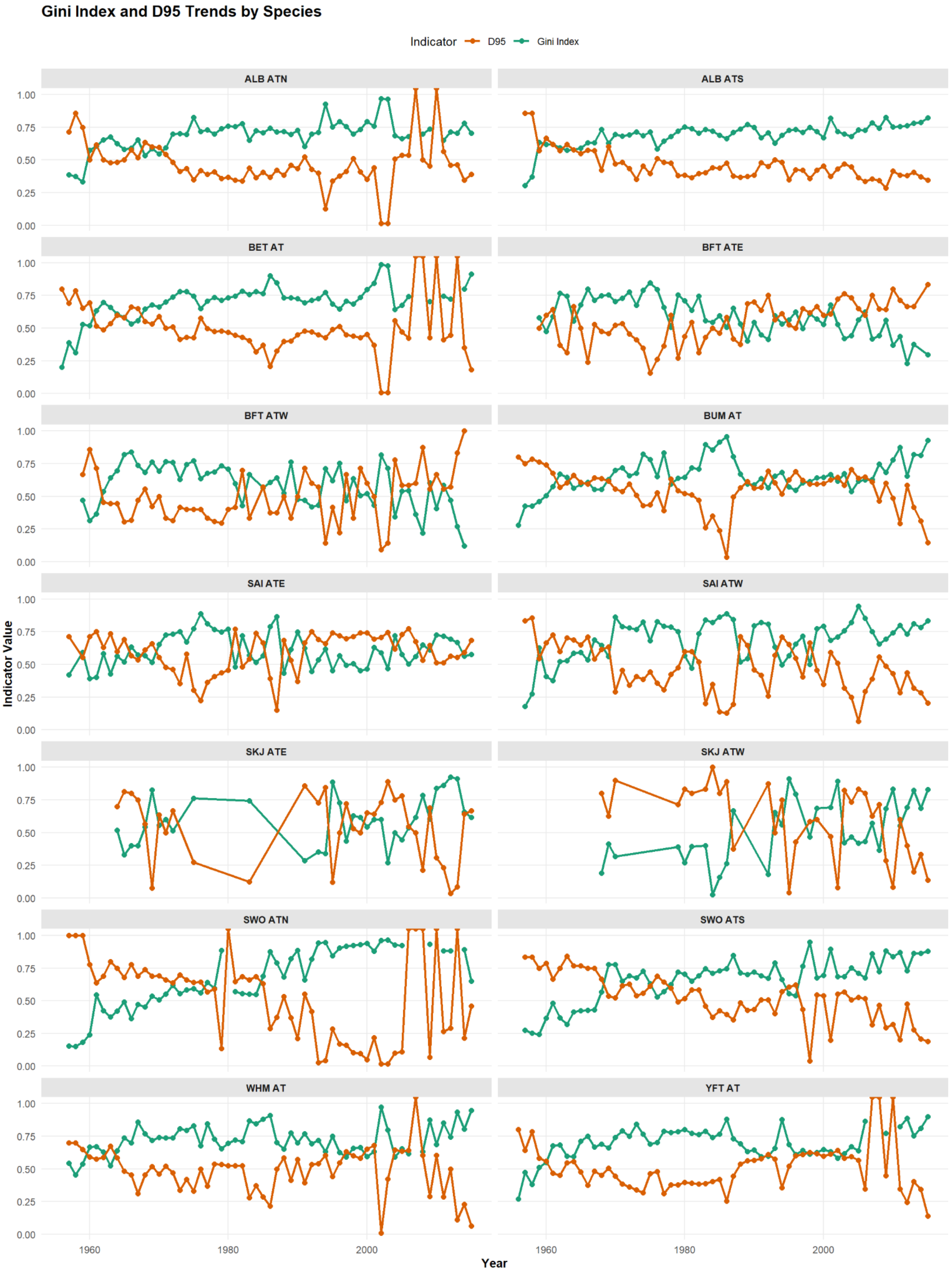

Figure 2. Gini Index and D95 Trends by Species. Temporal trends in spatial distribution indices for 14 Atlantic pelagic fish stocks from 1960 to 2010. Each panel represents a different stock. The green line shows the Gini index (higher values indicate greater spatial aggregation of biomass), and the orange line shows the D95 index (proportion of area containing 95% of biomass; lower values indicate greater concentration in a smaller area).

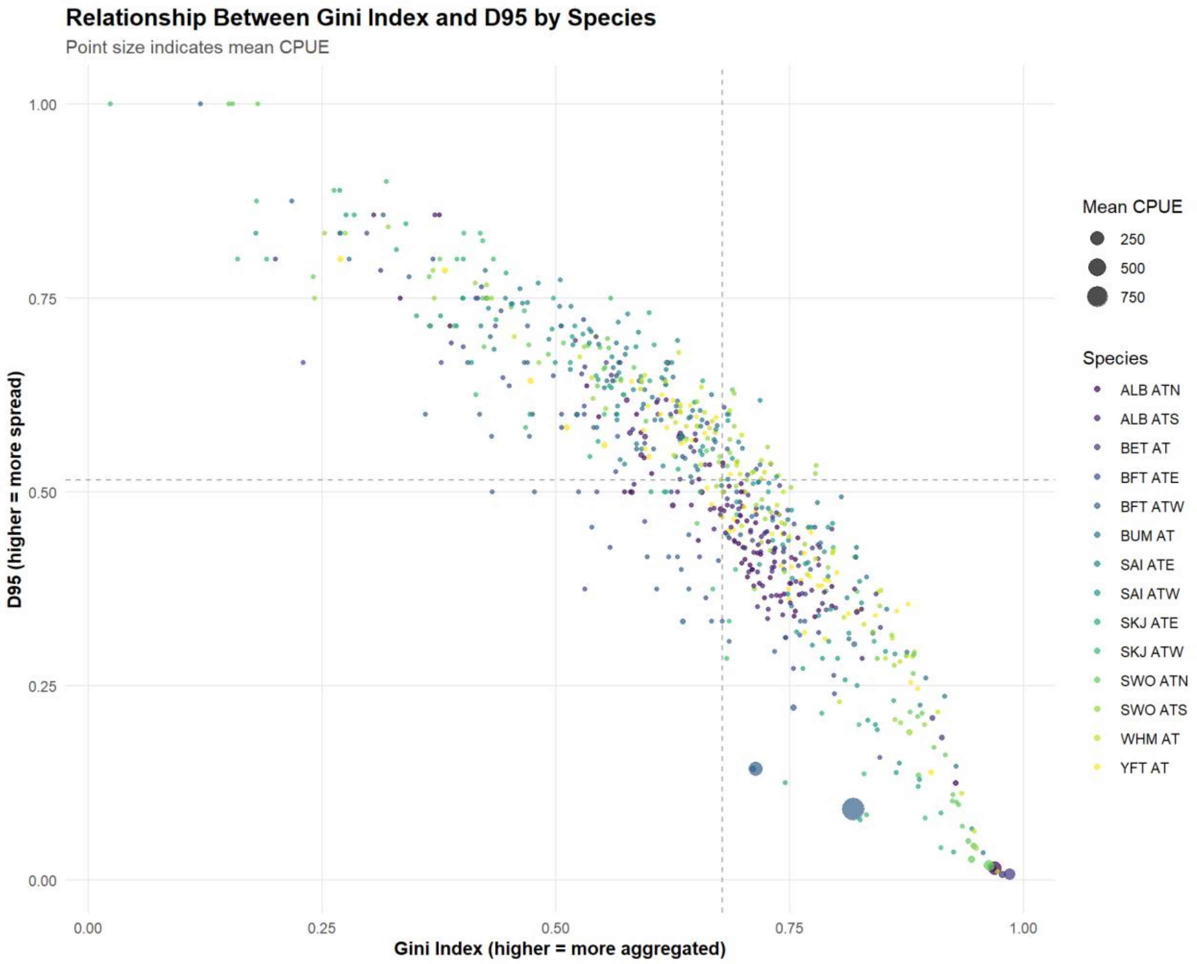

Figure 3. Relationship Between Gini Index and D95 by Species. Scatterplot showing the relationship between the Gini index (x-axis, higher = more aggregated) and D95 (y-axis, higher = more spatially spread) for all stocks and years. Each point represents a stock-year combination, coloured by species. Point size indicates mean CPUE (catch per unit effort) for that year and stock. The negative relationship demonstrates that as populations become more aggregated (higher Gini), their occupied area contracts (lower D95).

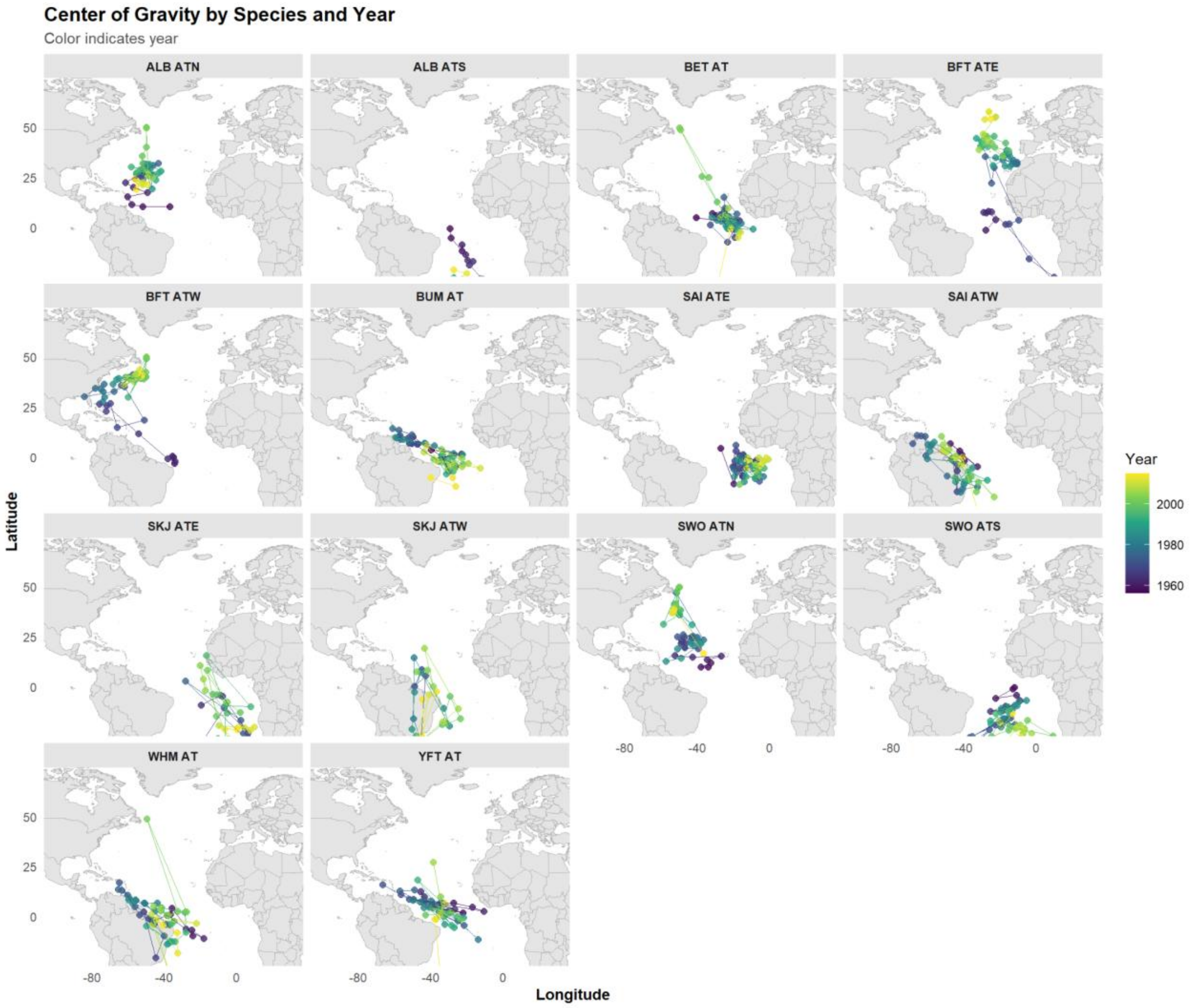

Figure 4. Centre of Gravity by Species and Year. Maps showing the annual geographic centre of gravity for each stock from 1960 to 2010. Each panel represents a different stock, with points coloured by year (purple = 1960, yellow/green = 2000). Lines connect sequential years to illustrate the trajectory of spatial shifts in population centres over time. These maps reveal directional shifts in distribution, such as northward or eastward movements, for each stock across the Atlantic.