TOWARD ECOSYSTEM-BASED FISHERIES MANAGEMENT IN THE SARGASSO SEA

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SUMMARY

To help implement Ecosystem-Based Fisheries Management the Subcommittee on Ecosystems has developed a report card based on indicators for the different components of the ecosystem. Indicators are mainly based on fisheries dependent data and work is ongoing to develop indicators for Trophic Structure, Community and Diversity Indices, Habitat, and Social and Economic components. A task of SC-ECO is to determine if detailed reporting of regions within the ICCAT convention area is possible and necessary. In this paper, we show how the Sargasso Sea can help in developing a better understanding of the impact of environmental pressures on the Atlantic and the importance of validating indicators using fisheries independent data, i.e. vessel AIS (Automatic Identification System), remote sensing, electronic tag and oceanographic datasets. Implementing Ecosystem-Based Fisheries Management also requires a multi-stakeholder assessment; we therefore also conducted a preliminary elicitation exercise.

RÉSUMÉ

Pour aider à mettre en œuvre la gestion des pêches fondée sur l'écosystème, le Sous-comité des écosystèmes a élaboré une fiche informative sur la base des indicateurs pour les différentes composantes de l'écosystème. Les indicateurs sont principalement basés sur des données dépendantes des pêcheries et des travaux sont en cours pour développer des indicateurs de la structure trophique, des indices communautaires et de diversité, l'habitat et les composantes sociales et économiques. Le Sous-comité des écosystèmes est chargé de déterminer si une déclaration détaillée des régions dans la zone de la Convention de l'ICCAT est possible et nécessaire. Ce document expose la façon dont la mer des Sargasses peut contribuer à mieux comprendre l'impact des pressions environnementales dans l'Atlantique et l'importance de valider les indicateurs au moyen de données indépendantes de la pêche, par exemple avec des données AIS (Automatic Identification System), la télédétection, les marques électroniques et les jeux de données océanographiques. La mise en œuvre de la gestion écosystémique des pêches nécessite également une évaluation multipartite; nous avons donc également mené un exercice préliminaire d'incitation.

RESUMEN

Para ayudar a poner en práctica la ordenación pesquera basada en el ecosistema, el Subcomité de ecosistemas ha elaborado una ficha informativa basada en indicadores para los diferentes componentes del ecosistema. Los indicadores se basan principalmente en datos dependientes de la pesca y se está trabajando en la elaboración de indicadores para la estructura trófica, los índices de comunidad y diversidad, el hábitat y los componentes sociales y económicos. Una tarea del Subcomité de ecosistemas es determinar si es posible y necesario informar detalladamente sobre las regiones dentro de la zona del Convenio de ICCAT. En este documento se muestra cómo el mar de los Sargazos puede ayudar a comprender mejor el impacto de las presiones ambientales en el Atlántico y la importancia de validar los indicadores utilizando datos independientes de las pesquerías, es decir, el AIS (sistema de identificación automática) de los buques, la teledetección, los datos de marcado electrónico y los conjuntos de datos oceanográficos. La implementación de la ordenación pesquera basada en los ecosistemas también requiere una evaluación de múltiples partes interesadas; por lo tanto, también realizamos un ejercicio preliminar de obtención de información.

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Introduction

The Sargasso Sea is a haven of biodiversity and there is growing recognition of the crucial role it plays in the wider North Atlantic ecosystem as habitat, foraging and spawning grounds, and as a migratory corridor. The Sargasso Sea supports a range of endemic species and plays a critical role in supporting the life cycle of a number of threatened and endangered species (Laffoley *et al.* 2011). In order to take into account all of the important elements of the Sargasso Sea ecosystem, a comprehensive approach such as Ecosystem Based Management (EBM) is needed. EBM is generally seen not as a strategy to manage an ecosystem, but rather one that manages the human activities that have an impact on ecosystems and takes these effects into account when making management decisions (Long *et al.* 2015, Gavaris 2009).

The Regional Fishery Management Organisations (RFMOs) are important stakeholders in the North Atlantic and the Sargasso Sea region and include the International Commission for the Conservation of Atlantic Tuna (ICCAT) and the Northwest Atlantic Fisheries Organisation (NAFO). RFMOs are primarily tasked with collecting fishery statistics, assessing stocks, making management decisions and monitoring activities. The RFMOs therefore play a pivotal role in facilitating intergovernmental cooperation in fisheries management and most also have a mandate to manage according to an ecosystem approach.

One method for developing EBM is the Driver-Pressure-State-Impact-Response (DPSIR) framework (Kelble *et al.* 2013). ICCAT used an approach based on DPSIR to help develop Ecosystem-Based Fisheries Management (EBFM) to which the Sargasso Sea Commission (SSC) is actively contributing, with an emphasis on the biology and biological oceanography of tunas and tuna-like species (see Luckhurst, 2014, 2015a,b, 2016, 2017, 2018). In order to develop and implement an Ecosystem Approach to Fisheries (EAF), NAFO has produced a Roadmap, which amongst other elements, includes habitat impact assessments (Koen-Alonso *et al.* 2019). There has also been a substantial amount of work done by other organizations on the biology and importance of anguillid eels, which spawn in the Sargasso Sea but which spend much of their lives in the rivers of Europe and eastern North America (Righton *et al.* 2016).

The DPSIR framework can assist managers and stakeholders in the many steps of the decision-making process required to help protect the integrity of the Sargasso Sea ecosystem. The principal steps in building a DPSIR framework are to: 1) Define the system 2) List key elements related to the system 3) Determine relevant concepts 4) Determine linkages in the system including cause and effect, if possible. The DPSIR framework, or modifications of it, has been widely used in the last two decades and has received the endorsement of several international institutions, for example The Organisation for Economic Co-operation and Development (OECD), the European Union (EU), the U.S. Environmental Protection Agency (EPA), and the European Environment Agency (EEA). At least 27 research projects focusing on marine and coastal habitats have used frameworks based on DPSIR (Patrício *et al.* 2016). These projects have mainly provided conceptual models and a challenge remains to provide indicators and quantitative models that allow management actions to be agreed, implemented, monitored and adapted as necessary.

Kell and Luckhurst (2018) extended the DPSIR framework to the Sargasso Sea and listed seven different drivers which could be used. Given the complexity of the ecosystem, however, it was recommended focusing on three Drivers: namely 1) Fishing 2) Climate Change and 3) *Sargassum* to help implement EBM in the region. Although fishing is important in affecting the ecosystem, climate change is probably the most important driver of the ecosystem of which fishes are a part. While fishing is a Driver over which we potentially have control, the ecology of the fish community is controlled by their environment.

It is recognised therefore that EBM can be significantly improved through a better understanding of regional oceanic and atmospheric circulation and physical-biological interactions in Large Marine Ecosystems (LMEs) (Duda and Sherman 2002, Sherman *et al.* 2005). For example, changes have been documented in the Atlantic Meridional Overturning Circulation (AMOC), a system of ocean currents in the North Atlantic including the Gulf Stream (**Figure 1**) which has a major impact on climate (Caesar *et al.* 2018). The AMOC is predicted to slow down and will affect the North Brazil Current, the dominant feature of the North Brazil LME which is responsible for bringing episodic nutrient-enriched, lower salinity, South Atlantic water into the Caribbean.

The status of *Sargassum* production in the Atlantic has changed dramatically since 2011 when the North Equatorial Convergence Region developed into a major new production area with large volumes of *Sargassum* being carried by currents into the eastern Caribbean with deleterious effects on fishing and tourism. Barange *et al.* (2018) summarised some recent impacts related to *Sargassum* including massive accumulations of *Sargassum* on the coasts of some Caribbean islands and tropical countries in West Africa. These *Sargassum* influxes are disrupting fishing operations and have brought changes in the abundance and distribution of several commercially important fish species, e.g. dolphinfish *Coryphaena hippurus*. Although, it has been clearly documented that the Sargasso Sea is not the origin of these *Sargassum* influxes (Doyle and Franks 2015) changes in *Sargassum* production and distribution clearly need to be monitored. The status of the volume of *Sargassum* in the Sargasso Sea itself is currently unknown but given its significance as a nursery habitat, it is important to attempt to estimate the possible effects of changes in the volume of *Sargassum*.

Indicators

While it is possible to propose many alternative indicators to detect and describe the effects of anthropogenic impacts on marine ecosystems, it is important that the indicators actually monitor the state of the system. Fulton *et al.* (2005) showed that indicators at the community level are the most reliable, and that it is necessary to use a variety of indicators simultaneously to detect the full range of impacts from fishing. The main biological groups included were: 1) habitat-defining groups 2) those with fast turnover rates (e.g. phytoplankton, zooplankton, bacteria) 3) those targeted by fisheries and 4) charismatic (or sensitive) groups. The development of indicators will require building on the trophic studies already conducted by the SSC (Luckhurst, 2015b; 2017; 2018) and others presented to ICCAT (Juan-Jordá *et al.* 2018a).

The Ecosystem Report Card generated by ICCAT is seeking to develop reliable indicators of the effects of fishing on various stocks (Juan-Jordá *et al.* 2018b). In contrast, Climate Change is operating at a global level and is impacting both the atmosphere and the oceans. Recent warnings by the IPCC (2018) indicate that climatic and oceanic conditions will seriously deteriorate by 2030 if urgent action is not taken to decrease CO_2 emissions. A principal action that can be conducted in relation to the Sargasso Sea ecosystem is to monitor its state and the impact of Climate Change using appropriate indicators. The intention is to continue the use of the indicators already developed in the ICCAT Ecosystem Report Card (Juan-Jordá *et al.* 2018b) but to extend these as appropriate, e.g. to include those used by other RFMOs in the region and to monitor impacts of importance to the Sargasso Sea ecosystem.

With respect to ecosystem indicators, the total number of indicators should be minimised and be complementary and non-redundant (Shin *et al.* 2010, Kershner *et al.* 2011). They should be robust proxies for corresponding ecosystem attributes or pressures (Fulton *et al.* 2005). They therefore need to be screened using appropriate selection criteria. In addition, reference points for management are required as targets, limits, cautionary zones or thresholds (FAO 1996).

ICCAT developed the Ecosystem Report Card to monitor the pressures that affect the state of the different ecosystem components and thereby ensure that ICCAT fisheries will have minimal impacts on critical habitat and the ecology of the communities including trophic interactions. The Ecosystem Report Card is intended to: a) provide a succinct summary of the state of select ecosystem components b) increase the visibility and usefulness of important ecosystem data and research c) strengthen ties between ecosystem research and fisheries management d) provide the context that will allow the incorporation of ecosystem considerations into management decisions e) represent the progress towards implementing EBFM objectives and f) encourage a more holistic and integrated approach.

The ICCAT Ecosystem Report Card has a number of components; i.e. Assessed Species, Retained Species: Non-assessed Sharks, Turtles, Seabirds, Mammals, Trophic Structure, Community and Diversity Indicators, Habitat, Socio-economic, Fishing Pressure, and Environmental Pressure. For each component, state indicators and reference levels to define values, i.e. thresholds or triggers, that will initiate a reaction/response need to be developed (Curtin and Prellezo 2010). Each component can also potentially be reported by region within the ICCAT convention area. Indicators for assessed and by-catch species are based on catches, rather than Environmental Pressure. Although work has mainly concentrated on summarising the status of the main commercial, retained species and by-catch species, indicators have been proposed for ecoregions within the ICCAT convention area, namely, mean trophic level (see Young *et al.* 2015) and the mean maximum length of fishes (Juan-Jordá *et al.* 2018b).

NAFO explicitly considers ecosystem interactions by adopting a Three-Tiered Approach (Koen-Alonso *et al.* 2019). Tier 1 is based on an assessment of Ecosystem State and its total productivity in order to set a total catch limit, then under Tier 2 a multi-species assessment is conducted to allocate catches across stocks, and under Tier 3 the state of each stock is assessed relative to single stock target and limit reference points. In addition, NAFO also conducts benthic habitat impact assessments to assess the impact of trawling.

For the Sargasso Sea, a first step is to develop indicators that assess the Fishing Pressure in the region and any changes in habitat due to climate change. The latter is covered in the Ecosystem Report Card by the Environmental Pressure component, where it is hoped the monitoring of larger scale ocean-wide environmental or oceanographic indicators can provide insight into the pressures on productivity and recruitment processes. Changes in core habitat due to climate change could result in displacement of species, biodiversity, productivity and fishing effort while loss of habitat for by-catch species (such as sharks, turtles, seabirds, and marine mammals) that are already under pressure may increase migration times and could exacerbate population declines or inhibit recovery (Hazen *et al.* 2013).

Indicators are mainly based on fisheries dependent data and work is ongoing to develop indicators for Trophic Structure, Community and Diversity, Habitat and Social and Economics components. A task of SC-ECO is to determine if detailed reporting to regions within the ICCAT convention area is possible and necessary. In this paper we show how the Sargasso Sea can help in developing a better understanding of the impact of environmental pressure on the Atlantic and the importance of validating indicators using fisheries independent data, i.e. vessel AIS, remote sensing, electronic tag and oceanographic datasets.

The types of questions that can be addressed are: Is fishing effort increasing in the Sargasso Sea and, if so, is this due to an expansion of fishing area as a response to a reduction in overall stock levels, changes in targeting or a change in distribution of the stocks? To develop an indicator for trophic structure is difficult, however, since this requires a time series and reference points against which to assess changes. The Ecosystem Report Card does include an indicator based on changes in mean size, primarily of target species and such changes in species in the Sargasso Sea, compared to the mean size across the region, may help highlight changes in community structure.

An indicator for Fishing Pressure could be developed using AIS data, e.g. from Global Fishing Watch (globalfishingwatch.org) to estimate total fishing activity in the Sargasso Sea (**Figure 2**) and then be compared to North Atlantic ABNJ (Areas Beyond National Jurisdiction) with ICCAT Task 2 Data. An indicator specifically for drifting longlines provides a good estimate of where longline fishing is concentrated (**Figure 3**). For Trophic Structure, Task 2 data can be used to estimate changes in mean size in the Sargasso Sea relative to North Atlantic ABNJ.

Arrizabalaga *et al.* (2015) analysed longline CPUE (catch per unit effort) data aggregated by quarter with a spatial resolution of 5 x 5 degree squares from 1958 to 2007 for albacore, Atlantic bluefin, southern bluefin, bigeye, yellowfin and skipjack tunas in the Pacific, Atlantic and Indian Oceans in order to provide a global, comparative perspective of habitat preferences using biotic and abiotic variables (**Figure 4**). Results confirmed that, compared to temperate tunas, tropical tunas prefer warm, anoxic, stratified waters. Atlantic and southern bluefin tuna prefer higher concentrations of chlorophyll than the rest and also tolerated most extreme sea surface height anomalies and highest mixed layer depths. If core habitat for different species can be identified then it may be possible to develop indicators related to carrying capacity and productivity.

An alternative is to use electronic tag data to conduct global habitat analyses based on detailed datasets. A benefit is that this allows the development of predictive habitat models, which quantify relationships between animal movements and dynamic oceanographic variables which can then be used to predict how species may respond to changes in oceanographic conditions.

If core habitat models are coupled with satellite tracks from fishing vessels it may be possible to identify hotspots or where species require conservation and management efforts.

Elicitation

The DPSIR framework links closely with the steps required to develop EBM for the Sargasso Sea. These are:

- Identify in detail the global significance of the Sargasso Sea, any known or emerging impacts and threats to the Sargasso Sea and its biodiversity, the drivers and root causes behind these issues, and proposals for prevention or mitigation.
- Conduct a multi-stakeholder assessment of an ecosystem-based approach to fisheries management including a road-map for delivery.
- Review the available data.
- Update the detailed economic analysis of global goods and services provided by the Sargasso Sea (Pendleton *et al.* 2015).

Often a first step when developing EBM is to conduct an Integrated Ecosystem Assessment (IEA). An elicitation exercise can therefore help to: i) Identify the main pressures on the Sargasso Sea Ecosystem, ii) Assess how well these pressures are taken into account in current management frameworks, iii) Determine whether the potential indicators available will allow the main impacts to be assessed and iv) if not, what other indicators are required. Such an elicitation exercise was conducted for Atlantic bluefin tuna (*Thunnus thynnus*) by ICCAT with the aim of identifying and prioritising uncertainties for inclusion in Operating Models for Management Strategy Evaluation (MSE) (Leach *et al.* 2014). Uncertainties were rated by bluefin fishery scientists according to three criteria: importance, uncertainty and degree of representation in current management models.

To develop a road-map for delivery of EBFM requires collaboration with a range of bodies that border, overlap and share management objectives in the Sargasso Sea. In addition to ICCAT and NAFO, these include the International Council for the Exploration of the Sea (ICES), the International Whaling Commission (IWC), the Caribbean Regional Fisheries Mechanism (CRFM), and the EIFAAC/ICES/GFCM Working Group on Eels. A number of experts from fisheries organisations and universities were contacted and their views were solicited on the DPSIR conducted for the Sargasso Sea (Kell and Luckhurst, 2018). The results are summarised under four categories:

Framework

"No framework leads to a single answer, rather all frameworks provide the information and knowledge to facilitate exploring the space for decision-making and policy development" (Dickey-Collas 2014)

Science

- Importance of co-production of knowledge, i.e. a way of working together across disciplines to create user-led, people-centred systems.
- ICCAT is focused on by-catch so there is little capacity to look at ecosystems, therefore the SSC could provide an example for others to follow.
- There is a need for cloud-based tools such as IMarDis, OcToPUS, that allow datasets to be combined, explored and analysed within an adaptable web-mapping interface in a targeted and topic-specific manner.

Overlaps and Gaps

- Other organizations and groups are keen to collaborate, as there are many overlaps and synergies.

Roadmap

- Implementing EAF is a marathon, not a sprint.
- In the first instance it is important to manage expectations, we need only to promise what we can achieve, as in the first stage we are conducting a proof of concept.

Discussion

Climate change is likely to impact migration, spawning and recruitment of Atlantic tunas and billfishes, however potential responses and mechanisms remain largely unknown (Muhling *et al.* 2015). A combination of historical environmental and biological data, ecological experiments and climate modeling work are needed to address this knowledge gap. Estimates of climate change impacts on highly migratory fish species is complicated by variations in habitat use during different life stages. The ability of tunas and billfishes to tolerate warm waters often decreases with age and size, while their ability to tolerate cold waters may increase, depending on physiological characteristics (Muhling *et al.* 2015). Results to date suggest that responses of highly migratory tunas and billfishes are likely to be species-specific.

An analysis of swordfish catches in the Sargasso Sea and in cooler waters north of the Gulf Stream front (**Figure 5**) were characterized by larger fish, while smaller fish were caught in the Gulf of Mexico and along the US east coast (Muhling *et al.* 2015). Consequently, temperature associations of swordfish were strongly dependent on size. Smaller fish were proportionally more common in warmer waters, while larger fish (mostly females) were associated with cooler waters. These results show that discerning temperature effects on highly migratory species brought on by climate change is likely to be complicated by the size- and sex-dependent responses of fish to their environment. (Muhling *et al.* 2015). Other temperate species such as Atlantic bluefin tuna may potentially be more vulnerable to changing oceanic conditions although they have a broad thermal tolerance.

An examination of century-scale fluctuations in the basin-scale distribution of Atlantic bluefin tuna (BFT) in relation to four different hydroclimatic factors revealed that the Atlantic Multidecadal Oscillation (AMO) demonstrated a prevailing influence on the abundance and distribution of eastern bluefin (Faillettaz *et al.* 2019). The other hydroclimatic factors tested in relation to BFT abundance were the North Atlantic Oscillation (NAO), Northern Hemisphere temperature (NHT) anomalies, and total solar irradiance (TSI), however, most of the fluctuations were related to the AMO with a relative influence of 47.1%. Higher values of the eastern bluefin tuna abundance index occurred during positive (warm) AMO phases, whereas lower values were related to negative (cold) phases (Faillettaz *et al.* 2019). An important finding from an analysis of historical data (1891-2011) is that BFT occurrence in the North Atlantic is controlled by a northeastern / southwestern "seesaw" of habitat suitability so that long-term fluctuations in BFT abundance may reflect changes in spatial distribution rather than changes in the size of eastern and western populations (Faillettaz *et al.* 2019). These results indicate the importance of taking climate variability into account when assessing stocks and developing management measures.

The world's oceans have continued to warm substantially over the last century and some of the largest changes in the net sea surface temperature have been seen in the Large Marine Ecosystem (LMEs) of the North Atlantic Region (Belkin 2009). As well as a general trend in warming, discrete periods of extreme regional ocean warming (marine heatwaves, MHWs) have increased in frequency with deleterious effects across a wide range of biological processes and taxa (Smale *et al.* 2019). One of the regions mostly heavily impacted by MHWs is the mid-west Atlantic which includes the southern portion of the Sargasso Sea (**Figure 6**). It is postulated that MHWs are likely to increase with anthropogenic climate change and have the capacity to restructure entire ecosystems and disrupt the provision of ecological goods and services such as fisheries landings and biogeochemical processes (Smale *et al.* 2019). Amongst documented regional impacts of MHWs are widespread mortality, species range shifts and community reconfiguration.

Another important oceanographic phenomenon affecting the North Atlantic are changes in the Atlantic Meridional Overturning Circulation (AMOC) where the Gulf Stream is slowing and the North Atlantic is cooling (Caesar *et al.* 2018). AMOC brings warm water north from the tropics and returns south with cold water (**Figure 1**) but this oceanographic heat pump is weakening and is believed to have slowed down by 15% since the 1950s. Global warming is considered to be the principal influence on AMOC (Caesar *et al.* 2018). In addition, meltwater from the Arctic sea ice and Greenland ice sheet is diluting the waters of the North Atlantic reducing salinity thus making water less dense and harder to sink.

In assessing the global habitats for six species of tuna from 1958 to 2007 (Arrizabalga *et al.* 2015) showed that the habitat preference for albacore in the year 2000 (**Figure 7**) indicated that the Sargasso Sea was a favourable habitat at that time. However, changes in the suitability of the habitat will affect the behaviour of fishing fleets and the fishing effort. There is anecdotal evidence that the level of fishing effort for albacore in the Sargasso Sea declined substantially after the 1990s but it is unknown if this was due to a change in targeting or a change in suitability of habitat.

Core habitats can also be estimated using electronic tags and, if coupled with output from climate models, potential changes in core habitat can be estimated for different climate change scenarios. This will allow patterns of habitat change, and the resultant displacement of species and biodiversity across the North Atlantic to be evaluated.

Conclusions

The Sargasso Sea is defined by large scale oceanographic processes, and a benefit of adopting the Sargasso Sea as a case study for the development of EBFM is that there is a significant body of work on ecology and biological oceanography and the Sargasso Sea Commission is actively collaborating with a range of data providers and management bodies. The next step is to develop indicators for habitat, and the impacts of environmental pressure and fishing pressure on by-catch species by building on the ecological risk assessments conducted by ICCAT. Following this, reference points and management plans can be proposed and their robustness to uncertainty evaluated, e.g. using Management Strategy Evaluation in collaboration with stock assessment working groups. The generic utility of indicators, reference points and management plans could be tested in other ICCAT regions and applied as appropriate. The robustness of indicators to environmental pressure could also be evaluated by developing scenarios linking oceanographic processes to climate change.
Any development of EBFM should also be accompanied by an elicitation excercise to ensure that the requirements of stakeholders are met.

Acknowledgements

References

Arrizabalaga, H., Dufour, F., Kell, L., Merino, G., Ibaibarriaga, L., Chust, G., Irigoien, X., Santiago, J., Murua, H., Fraile, I. and Chifflet, M., 2015. Global habitat preferences of commercially valuable tuna. *Deep Sea Research Part II: Tropical Studies in Oceanography*, *113*, pp.102-112.

Barange, M, Bahri T., Beveridge, M., Cochrane, K., Funge-Smith, S. and Poulain, F. 2018. Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options. FAO Fisheries and Aquaculture Technical Paper (FAO) eng no. 627. URL http://www.fao.org/3/I9705EN/i9705en.pdf.

Belkin, I.M. 2009. Rapid warming of large marine ecosystems. Progress in Oceanography, 81(1-4):207–213.

Caesar, L. S., Rahmstorf, A., Robinson, G., Feulner, and Saba,V. 2018. Observed fingerprint of a weakening Atlantic Ocean overturning circulation. Nature, 556(7700):191.

Dickey-Collas, M. 2014. Why the complex nature of integrated ecosystem assessments requires a flexible and adaptive approach. ICES Journal of Marine Science, 71(5):1174–1182.

Curtin, R .and Prellezo, R., 2010. Understanding marine ecosystem-based management: a literature review. *Marine Policy*, *34*(5), pp.821-830.

Doyle, E. and Franks, J., 2015. Sargassum fact sheet. Gulf and Caribbean Fisheries Institute (www.gcfi.org)

Duda, M. and Sherman, K.. 2002. A new imperative for improving management of large marine ecosystems. Ocean & Coastal Management, 45(11-12):797–833, 2002.L.

Faillettaz, R., Beaugrand, G., Goberville, E. and Kirby, R.R.. 2019. Atlantic Multidecadal Oscillations drive the basin-scale distribution of Atlantic bluefin tuna. *Sci. Adv.* 5, eaar699.

FAO 1996. Precautionary approach to capture fisheries and species introductions. FAO Tech Guidelines for Responsible Fisheries:54

Fulton, E.A., Smith A.D.M. and Punt AE. 2005. Which ecological indicators can robustly detect effects of fishing? ICES J Mar Sci 62:540–551.

Gavaris, S. 2009. Fisheries management planning and support for strategic and tactical decisions in an ecosystem approach context. Fish Res, 100 , pp. 6-14.

Hazen, E. L., Jorgensen, S., Rykaczewski, R., Bograd S. J., Foley, I. D. Jonsen, D.G., Shaffer,S.A., Dunne, J.P.,Costa, D.P., Crowder, L.B. and Block, B.A. 2013. Predicted habitat shifts of Pacific top predators in a changing climate. Nature. Climate. Change 3, 234–238.

IPCC 2018. Summary for policy makers of special report for global warming of 1.5°C.

Juan-Jordá, M.J., Zarrad, R., and Hanke, A. 2018a. A proposal of ecosystem indicators to monitor the trophic relationships component for the ICCAT Ecosystem Report Card (SCRS/2018/073).

Juan-Jordá M.J. and Murua, H. 2018b. Selecting ecosystem indicators for fisheries targeting highly migratory species (SCRS/2018/077).

Kelble, C.R., Loomis, D.K., Lovelace, S., Nuttle, W.K., Ortner, P.B., Fletcher, P., Cook, G.S., Lorenz, J.J. and Boyer, J.N., 2013. The EBM-DPSER conceptual model: integrating ecosystem services into the DPSIR framework. PloS one, 8(8), p.e70766.

Kell, L. and Luckhurst, B.E. 2018. Extending the indicator-based Ecosystem Report Card to the whole ecosystem; a preliminary example based on the Sargasso Sea. ICCAT Collect. Vol. of Sci. Pap., 75(67):258–275.

Kershner, J., Samhouri J.F., James C.A. and Levin PS 2011. Selecting indicator portfolios for marine species and food webs: A Puget Sound case study. PLoS One 6:e25248–e25248.

Koen-Alonso, M., Pepin, P., Fogarty, M.J., Kenny, A. and Kenchington, E. 2019. The northwest Atlantic fisheries organization roadmap for the development and implementation of an ecosystem approach to fisheries: structure, state of development, and challenges. Marine Policy, 100:342–352.

Laffoley, D.d'A., Roe, H.S.J., Angel, M.V., Ardron, J., Bates, N.R, Boyd, L.L., Brooke, S., Buck,K.N., Carlson, C.A., Causey, B., Conte, M.H., Christinsen, S., Cleary, J., Donnelly, J., Earle, S.A., Edwards, R., Gjerde, K.M., Giovannoni, S.J., Gulick, S., Gollock, M., Hallet, J., Halpin, P., Hanel, R., Hemphill, A., Johnson, R.J., Knap, A.H., Lomas, M.W., McKenna, S.A., Miller, M.J., Miller, P.I., Ming, F.W., Moffitt, R., Nelson, N.B., Parson, L., Peters, A.J., Pitt, J., Rouja, P., Roberts, J., Roberts, J., Seigel, D.A., Siuda, A., Steinberg, D.K., Stevenson, A., Sumaila, V.R., Swartz, W., Trott, T.M., and Vats, V. (2011). The protection and management of the Sargasso Sea: The golden floating rainforest of the Atlantic Ocean. Summary Science and Supporting Evidence Case. Sargasso Sea Alliance, 44pp. ISBN# -978-0-9847520-0-3 available at http://www.sargassoalliance.org/case-for-protection.

Leach, A.W., Levontin, P., Holt, J., Kell, L.T. and Mumford, J.D. 2014. Identification and prioritization of uncertainties for management of Eastern Atlantic bluefin tuna (*Thunnus thynnus*). Marine Policy 48 84–92.

Long, R.D., Charles, A. and Stephenson, R.L. 2015. Key principles of marine ecosystem-based management. *Marine Policy*, *57*, pp.53-60.

Luckhurst, B.E. 2014. Elements of the ecology and movement patterns of highly migratory fish species of interest to ICCAT in the Sargasso Sea. ICCAT Collect. Vol. of Sci. Pap., (70):2183–2206.

Luckhurst, B.E. 2015a. Analysis of ICCAT reported catches of tunas and swordfish in the Sargasso Sea (1992-2011). ICCAT Collect. Vol. of Sci. Pap., (71): 2900-2912.

Luckhurst, B.E. 2015b. A preliminary food web of the pelagic environment of the Sargasso Sea with a focus on the fish species of interest to ICCAT. Collect. Vol. Sci. Pap. ICCAT, 71(6): 2913-2932.

Luckhurst, B.E. 2016. Evidence of spawning in the southern Sargasso Sea of fish species managed by ICCAT – albacore tuna, swordfish and white marlin. Collect. Vol. Sci. Pap. ICCAT 72(8): 1949-196.

Luckhurst, B.E. 2017. Aspects of the migration, seasonality and habitat use of two mid-trophic level predators, dolphinfish (*Coryphaena hippurus*) and wahoo (*Acanthocybium solandri*), in the pelagic ecosystem of the western Atlantic including the Sargasso Sea. Collect. Vol. Sci. Pap. ICCAT 73(9): 3163-3174.

Luckhurst, B. 2018. A preliminary assessment of the ecological role and importance of squid in the pelagic trophic web of the northwest Atlantic Ocean including the Sargasso Sea. Collect. Vol. Sci. Pap. ICCAT, 74(7): 3679-3691.

Muhling, B.A., Lin, Y., Lee, S-K., Lamkin, J.T., Malea, E., Llopiz, J., Ingram, G.W., Quattro, J.M., Walter, J.F., Doering, K., Roffer, M.A. and Muller-Karger, F. 2015. Past, ongoing and future research on climate change impacts on tunas and billfishes in the wester Atlantic. Collect. Vol. Sci. Pap. ICCAT, 71(4): 1716-1727.

Patrıcio, J., Elliott, M., Mazik, K., Papadopoulou, K-N. and Smith, C.J. 2016. DPSIR-two decades of trying to develop a unifying framework for marine environmental management? Frontiers in Marine Science, 3:177.

Pendleton, L., Krowicki., F., Strosser, P. and Hallett-Murdoch, J. 2014. Assessing the Economic Contribution of Marine and Coastal Ecosystem Services in the Sargasso Sea. NI R 14-05. Durham, NC: Duke University.

Righton, D., Westerberg, H., Feunteun, E., Økland, F., Gargan, P., Amilhat, E., Metcalfe, J., Lobon-Cervia, J., Sj¨oberg,N. and Simon, J. 2016. Empirical observations of the spawning migration of european eels: The long and dangerous road to the Sargasso Sea. Science Advances, 2(10):e1501694.

Rindorf, A., Mumford, J., Baranowski, P., Worsøe, L., Clausen, García, D., Hintzen, N.T., Kempf, A.,Leach, A., Levontin, P., Maceg, P., Mackinson, S., Maraveliasi, C., Prellezo, R., Quetglas, A.,Tserpes, G.,Voss, R. and D. Reid. 2017. Moving beyond the MSY concept to reflect multidimensional fisheries management objectives. Marine Policy 85, 33–41.

Sherman, K., Sissenwine, M., Christensen, V., Duda, A., Hempel, G., Ibe, C., Levin, S., Lluch-Belda, D., Matishov,G. and McGlade, J. 2005. A global movement toward an ecosystem approach to management of Marine resources. Marine Ecology Progress Series, 300:275–279.

Shin, Y.J., Bundy A., Shannon L.J., Simier M., Coll M., Fulton E.A., Link J.S., Jouffre D., Ojaveer H., MacKinson S., Heymans J..J and Raid T. 2010. Can simple be useful and reliable? Using ecological indicators to represent and compare the states of marine ecosystems. ICES J Mar Sci 67:717–731.

Smale, D.A., Wernberg, T., Oliver, E.C.J., Thomsen, M., Harvey, B.P., Straub, S.C., Burrows, M.T., Alexander, L.V., Benthuysen, J.A., Donat, M.G., Feng, M., Hobday, A.J., Holbrook, N.J., Perkins-Kirkpatrick, S.E., Scannell, H.A., Sen Gupta, A., Payne, B.L. and Moore, P.J. 2019. Marine heatwaves threaten global biodiversity and the provision of ecosystem services. Nature Climate Change. URL https://doi.org/10.1038/s41558-019-0412-1.

White, T.D., Ferretti, F., Kroodsma, D.A., Hazen, E.L., Carlisle, A.B., Scales, K.L., Bograd, S.J. and Block, B.A., 2019. Predicted hotspots of overlap between highly migratory fishes and industrial fishing fleets in the northeast Pacific. *Science advances*, *5*(3), p.eaau3761.

Young, J.W., Hunt, B., Cook, T., Llopiz ,J., Hazen, E.L., Pethybridge, H., Ceccarelli, D., Lorrain, A., Olson, R.J., Allain, V., Menkes, C. Patterson, T., Nicol, S., Lehodey, P., Kloser, R., Arrizabalaga, H. and Choy,C.A. 2015. The trophodynamics of marine top predators: current knowledge, recent advances and challenges. Deep-SeaRes. Part II113,170–187.http://dx.doi.org/10.1016/j.dsr2.2014.05.015.
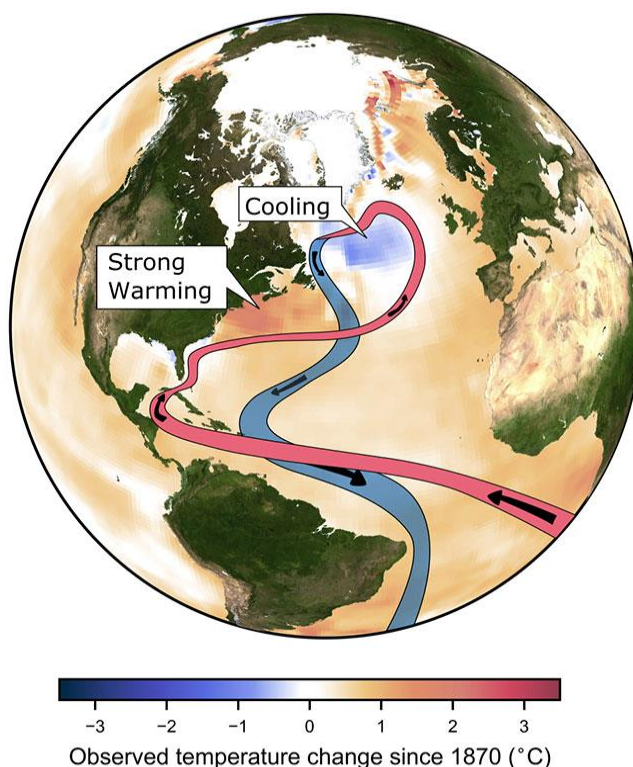
Figure 1. The Atlantic Meridional Overturning Circulation (AMOC), a system of ocean currents in the North Atlantic. The western boundary current (Gulf Stream) has been shown to be slowing down (Caesar *et al.* 2018).
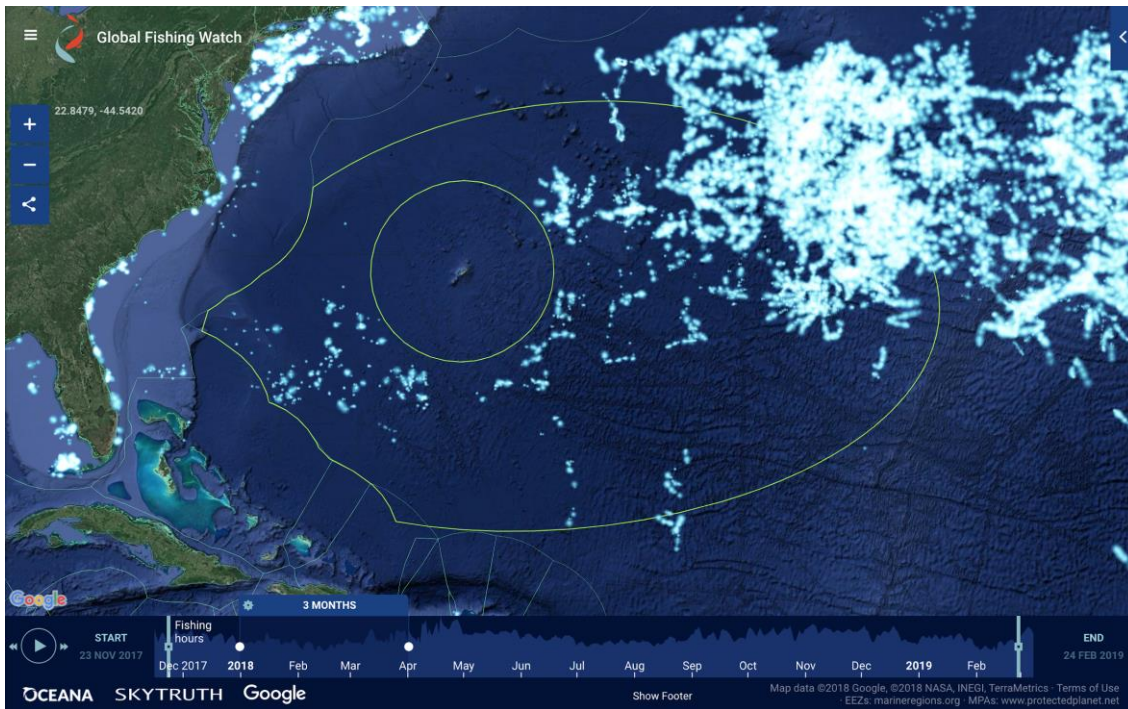
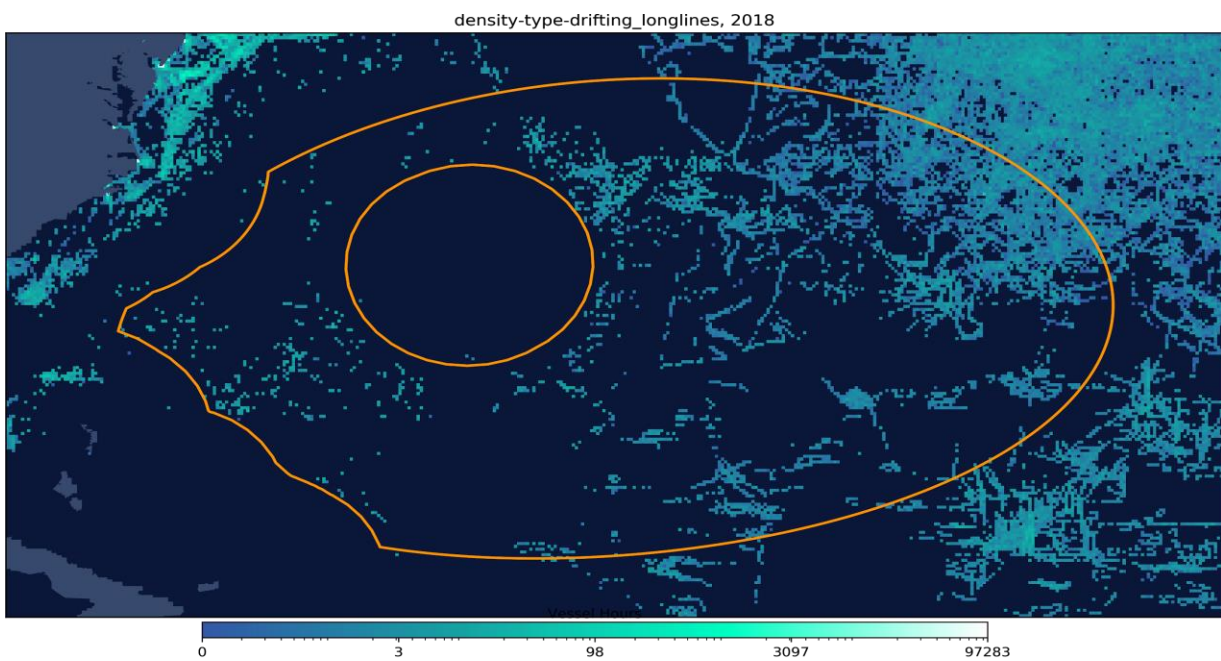**Figure 2.** Fishing effort estimated from AIS (Automatic Identification System) data in the Sargasso Sea Commission region in the first quarter of 2018 (see https://globalfishingwatch.org/). Circle is Bermuda's EEZ.

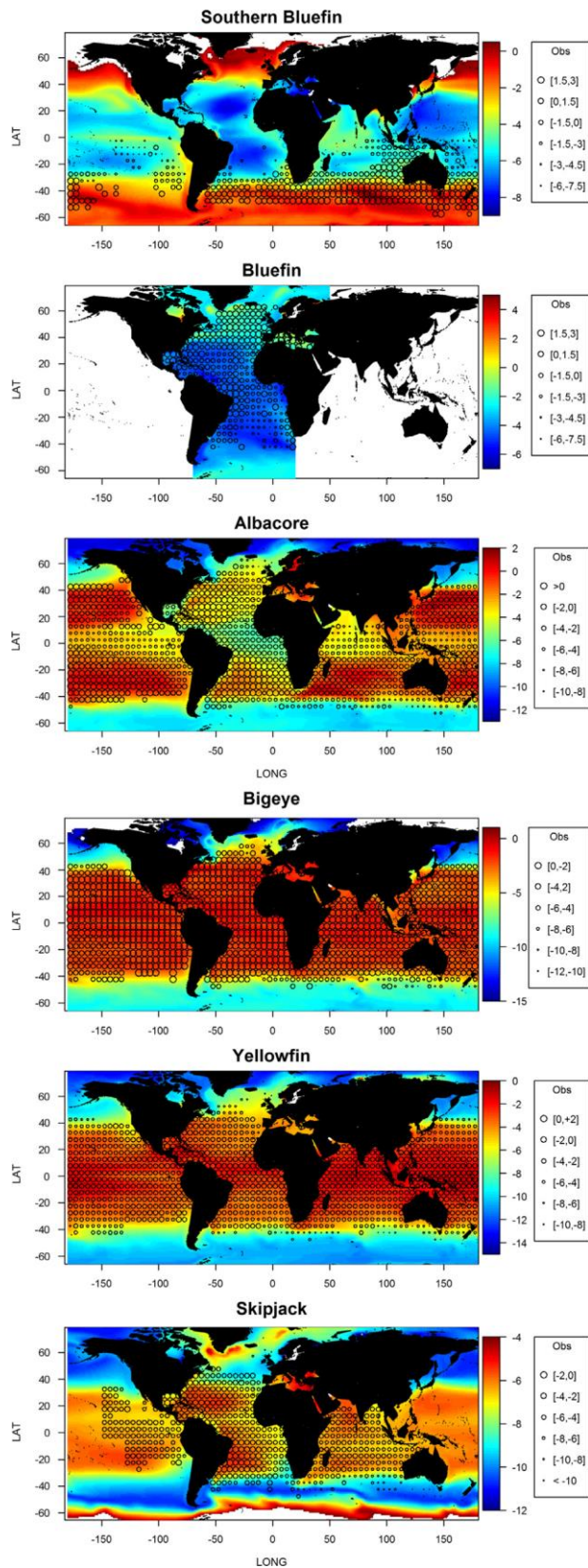**Figure 3.** Drifting long-line fishing effort in the Sargasso Sea Commission region in 2018 estimated from AIS data (https://globalfishingwatch.org/). Circle is Bermuda's EEZ.

Figure 4. Global habitats for six species of tuna (southern bluefin, Atlantic bluefin, albacore, bigeye, yellowfin and skipjack) as estimated by Arrizabalga *et al.* (2015) using longline catch per unit effort (CPUE). See text for details.
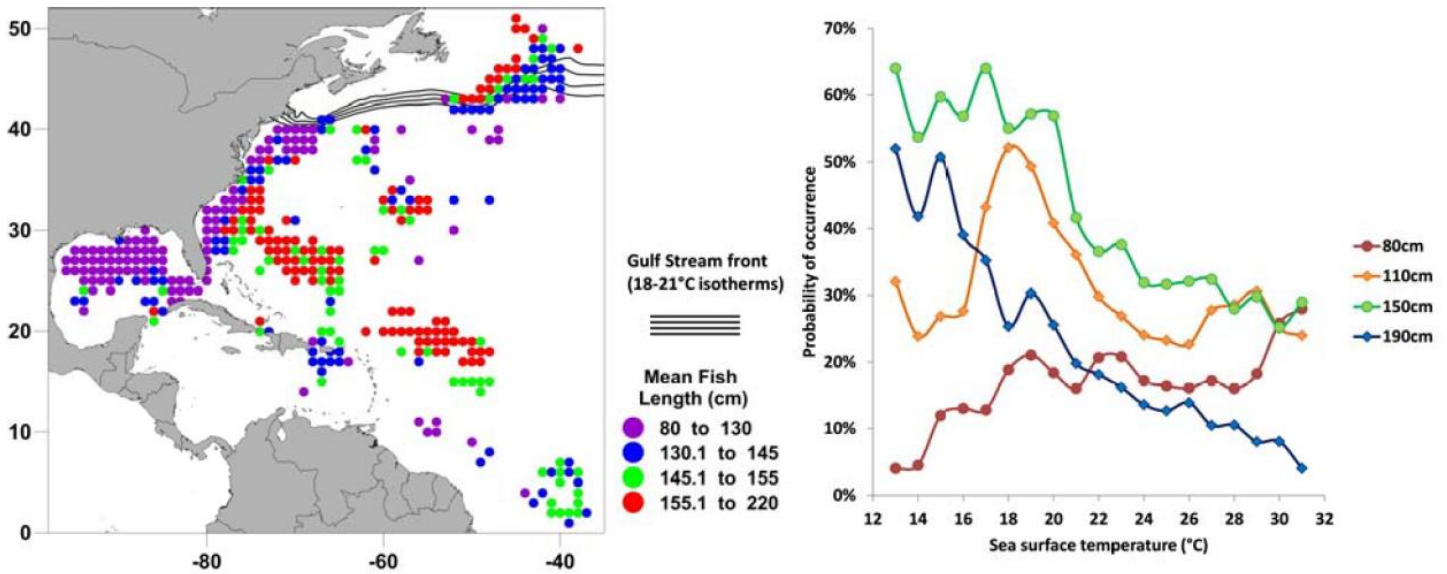
Figure 5. – Left – Mean swordfish body lengths from NOAA database 1992-2011. Right – Sea surface temperature associations by swordfish size range (from Muhling *et al.* 2015).
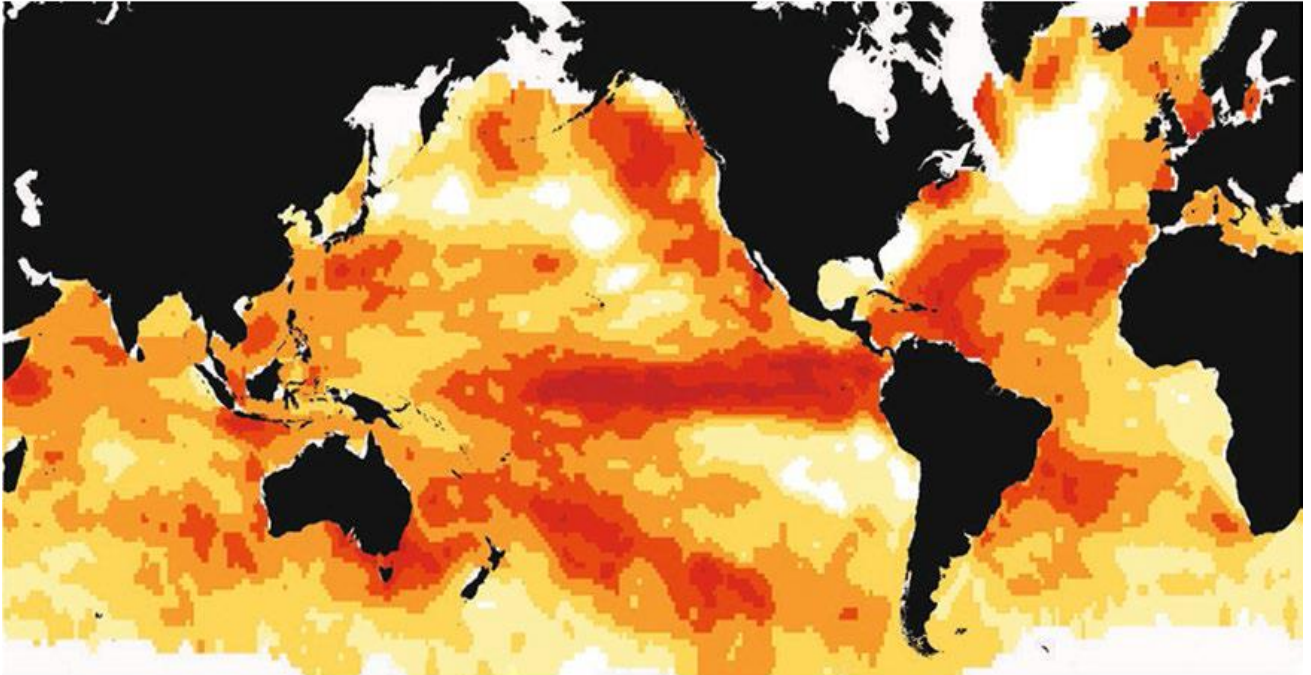
Figure 6. Marine Heat Waves (MHWs) map showing oceanic regions of greatest intensity (from Smale *et al.* 2019). Note southern Sargasso Sea region.
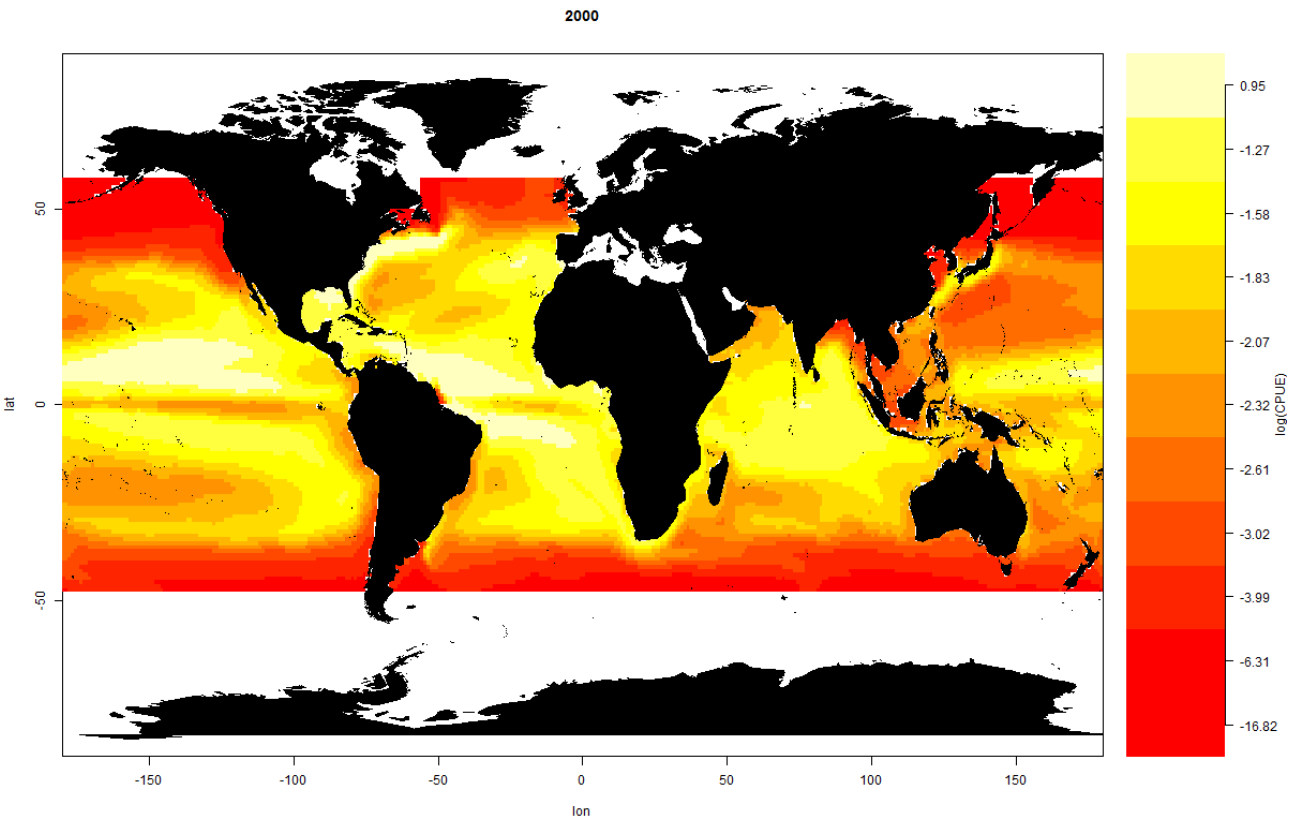

Figure 7. Predictions of global habitat for albacore tuna in 2000 from Arrizabalaga *et al.* (2015).