SSG=see style guide

Historical spatial reconstruction of a spawning-aggregation fishery

Sarah M. Buckley[1*]; Ruth H. Thurstan[1,2], Andrew Tobin[3], John M. Pandolfi[1]

[1]School of Biological Sciences, Gehrmann Building, The University of Queensland and Australian Research Council Centre of Excellence for Coral Reef Studies, St Lucia, Queensland 4071, Australia

[2]Centre for Integrative Ecology, School Life and Environmental Science, Deakin University, Burwood, Victoria 3125, Australia

[3]Centre for Sustainable Tropical Fisheries and Aquaculture, School of Earth and Environmental Sciences, James Cook University, Townsville, Queensland 4810, Australia

*mail s.buckley2@uq.edu.au

Running head

Spatial reconstruction of a spawning fishery

Keywords

Spatial reconstruction, fish-spawning aggregation, shifting baselines, commercial fishing, historical ecology, Spanish mackerel, fishing power

Abstract

Aggregations of individual animals that form for breeding purposes are a critical ecological process for many species, yet these aggregations are inherently vulnerable to exploitation . Studies of the decline of exploited populations that form breeding aggregations tend to focus on catch rate and thus often overlook reductions in geographic range. We tested the hypothesis that catch rate and site occupancy of exploited fish-spawning aggregations (FSAs) decline in synchrony over time. We used the Spanish mackerel (*Scomberomorus commerson*) spawning-aggregation fishery in the Great Barrier Reef as a case study. Data were compiled from historical newspaper archives, fisher knowledge, and contemporary fishery logbooks to reconstruct catch rates and exploitation trends from the inception of the fishery. Our fine-scale analysis of catch and effort data spanned 103 years (1911–2013) and revealed a spatial expansion of fishing effort. Effort shifted offshore at a rate of 9.4 nm /decade, and 2.9 newly targeted FSAs were reported/decade. Spatial expansion of effort masked the sequential exploitation, commercial extinction, and loss of 70% of exploited FSAs. After standardizing for improvements in technological innovations, average catch rates declined by 90.5% from 1934 to 2011 (from 119.4 to 11.41 fish/vessel/trip). Mean catch rate of Spanish mackerel and occupancy of exploited mackerel FSAs were not significantly related. Our study revealed a special kind of shifting spatial baseline in which a contraction in exploited FSAs occurred undetected. Knowledge of temporally and spatially explicit information on FSAs can be relevant for the conservation and management of FSA species.

Introduction

Mass aggregations of individuals for the purpose of breeding, migrating, feeding, or birthing in terrestrial and marine ecosystems are well known. Aggregation events that occur at predictable times and in a few restricted locations make the animals acting in these events highly vulnerable to exploitation (Bauer and Hoye 2014). Long-term declines in abundance of aggregating terrestrial species that are widespread, such as wildebeest (Connochaetes), are generally accompanied by a similar decline in the number of sites occupied (i.e., occupancy) by aggregations as a result of hunting and habitat loss (Laliberte & Ripple 2004). Similar long-term declines in the abundance and distribution of marine species that form aggregations have been documented (e.g. McClenachan & Cooper 2008). However, changes in the occupancy, in particular the breeding component, of fish populations that form spawning aggregations are rarely quantified. Accounting for fine-scale spatial changes in a widespread species is important because the decline and extirpation of the breeding component can disrupt reproductive behavior, reduce genetic diversity, and compromise the ability of a population to withstand future threats (Ciannelli et al. 2013). Quantifying spatiotemporal changes in the abundance and geographic distribution of a population can facilitate an accurate assessment of a species conservation status and help set effective recovery targets.

The vulnerability of exploited fish-spawning aggregations (FSAs) is evident from the severe and rapid declines in abundance of numerous species across a range of families (Sadovy de Mitcheson and Erisman 2012). Examples of recognized losses of FSAs include the tropical Nassau grouper (*Epinephelus striatus*), which once formed multiple FSAs throughout the entire Caribbean (Sadovy and Eklund 1999), and the long-lived deepwater orange roughy (*Hoplostethus atlanticus*), whose population collapsed within a decade of the onset of exploitation (Clark 2001). Spawning aggregations are particularly vulnerable to overfishing occurring undetected due to hyperstabilty. Hyperstabilty occurs when high catche rates are maintained while fishers sequentially deplete or extirpate aggregations, resulting in the sudden collapse of exploited populations (Sadovy de Mitcheson and Colin 2012).

One of the most documented relationships in macroecology is the abundance–occupancy relationship (AOR) (Gaston et al. 2000). A positive relationship between population abundance and occupancy is predominant within (intraspecific) and among (interspecific) terrestrial and marine taxa (Blackburn et al. 2006; Borregaard and Rahbek 2010). This relationship extends to exploited marine fishes (Fisher and Frank 2004; Webb et al. 2011). However, for highly aggregated species, a positive AOR is less likely. Instead, they may exhibit a nonsignificant or negative AOR (very high abundance of individuals occur in a few sites), although this has rarely been quantified (Webb et al. 2012).

Reconstructions of the size of breeding populations that form FSAs are often deduced from landings collected at the fishery level (Sadovy de Mitcheson et al. 2008). However, due to hyperstability in species that aggregate when they spawn , catch data alone do not accurately reflect the abundance changes in the breeding population (Erisman et al. 2011). We devised an alternative approach to estimate abundance of aggregating species for which reliable data are lacking. Specifically, we sought to quantify the geographic changes in fishery targeting of FSAs and catch rate over time.

Spanish mackerel (*Scomberomorous commerson*) sustains local commercial, recreational, and artisanal fisheries throughout its Indo-Pacific distribution (Juan-Jordá et al. 2011). Where stock assessments exist (Southern Arabian Gulf and Oman), generally, the fisheries are fully exploited (i.e., a stock is fished to the maximum and an increase leads to overfishing) or overfished, likely due to the predictable aggregating behavior exhibited during spawning, feeding, and migrating (Grandcourt 2005; Govender et al. 2006). In some cases, overfishing has caused steep declines in mackerel biomass and collapse of the fishery (Collette et al. 2011). A few studies have provided evidence of recovery of taxa within the scombrids (Juan-Jordá et al. 2011). However, these assessments do not provide a specific analysis of the history of the fishery or of the exploitation of the FSAs of Spanish mackerel populations.

We reconstructed the catch rate and history of occurrence of exploited FSAs of a commercial fishery that has targeted the Spanish mackerel within the Great Barrier Reef (GBR) for over a century (McPherson 1985). Spanish mackerel is a pelagic predator that exhibits site fidelity by migrating long distances to a few discrete breeding sites in the central GBR, forming FSAs between October and November each year (Tobin et al. 2014). These FSAs form part of a commercial fishery that targets Spanish mackerel along the east coast of Australia, termed the east coast Spanish mackerel (ECSM) fishery. Despite the limited spatial extent of the FSAs, which are restricted to a small number of reefs within the GBR, the landings from these aggregations represent a disproportionately large component of the total annual catch of the ECSM fishery (Tobin et al. 2013).

Concerns have been raised regarding the vulnerability of the GBR Spanish mackerel to decline due to its transient aggregating behavior and the sustainability of the commercial fishery (McPherson 2007; Tobin et al. 2013). The most recent stock assessment shows that the current stock biomass ranges between 39–51%, which is within the range of maximum sustainable yield (approximately 50%) and maximum economic yield (approximately 40%) (Campbell et al. 2012). However, the 95% confidence intervals show current biomass could be as low as 34%. Hence, Spanish mackerel could be overfished because the biomass may be <40%. There are a number of uncertainties surrounding the stock assessment due to data quality (a lack of fishing effort time and zero catch records) and accounting for hyperstability of the aggregating species.

We sought to determine the trajectory of both the catch rate and occupancy of the Spanish mackerel FSAs and whether a relationship between the 2 exists. Occupancy was estimated as the proportion of FSAs (total number of fished FSA sites/total number of known FSA sites) per decade. We hypothesized that catch rate and occurrence of exploited FSAs decline over time and the relationship between catch rate and occupancy over time is negative or nonsignificant. We extracted and combined data from historical newspapers, fisher knowledge, and commercial logbook records to reconstruct spatially explicit catch and effort trends for the Spanish mackerel commercial fishery. We evaluated two factors critical for assessing temporal trends in commercial catch: changes in recalled catch rate at a fishery (Townsville and Cairns) scale and catch rates from the contemporary Townsville fishery standardized for improvements in gear and technology.

Methods

Data review

We compiled data on catch rate, the geographic distribution of fishing effort, and temporal changes in fishing power (i.e., the efficiency of an average vessel at catching Spanish mackerel) in the spawning fishery from historical archives (1911–1980), fisher interviews (1948–2013), and contemporary commercial fisheries logbooks (1990–2011).

We searched newspaper records archived by the National Library of Australia and the State Library of Queensland for references relating to the GBR FSA fishery. Metropolitan newspapers were examined in digital archives (1803 -1954) and hard copies of regional newspapers were searched (National Library of Australia 2014). For the digital archives, standardized searches were conducted using the key phrases *Spanish mackerel spawning* and *Spanish mackerel catch*. During the early period of the fishery, Spanish mackerel were referred to as kingfish and snook, and these terms were included in our search. We extracted all quantitative information specific to the FSA fishery (i.e., weight landed (8 kg = 1 fish), date landed, vessel) from the historical archives to construct catch rates, which we calculated as the number of Spanish mackerel fishing vessels per trip. We also gathered descriptions of fishing gear and technology, fishing location, fishing effort, and perceptions of the fishery (Supporting Information). Other historical sources were investigated for spawning-specific data, including the annual reports of the Queensland Marine Department (1901 to 1935) and Queensland Fish Board records (1946 -1981).

To gather catch and effort data we conducted semi structured interviews with 47 commercial fishers who had fished the SAF. We interviewed fishers living along the east coast of Queensland and covered a distance of 1500 km (Fig. 1). Participants were selected by snowball sampling (i.e., fishers were recruited by interviewee referral). This method ensured that we sampled expert SAF fishers (i.e., those with a minimum of ten years fishing experience targeting the SAF). Our research protocol was approved by from the University of Queensland Ethics Committee and informed consent was obtained from all fishers. All interviews were conducted individually and lasted from 1.5 to 5 hours.

To verify whether fishers recalled the exploitation of FSAs rather than exploitation of fish schooling, we asked them how they knew the fish were spawning. To be included in the study, fishers had to report one of the defined criteria that represented direct or indirect indicators of a spawning aggregation (Domeier 2012). Direct indicators included gamete release in the water and multiple gravid females. Indirect indicators included the density of fish being 3 times or more of the non spawning density or catch rates, high gonadosomatic index, courtship, and coloration changes exclusively associated with spawning (Sadovy 2003).

We gathered records of FSA site names, number of hours spent fishing, and fishing effort (number of vessels fishing per operation, total number of vessels in the fleet, and distance traveled offshore) for both the beginning and end or the most recent period of each fisher's career. We also recorded the timing and rate of adoption of each gear and technology used (global positioning systems [GPS], color depth sounders, paravanes [device that allows baited hooks to be trolled deep in the water column] throughout their fishing careers (O'Neill et al. 2003). In the final part of the interview, we asked fishers to recall good, average, and poor catch rates (numbers of fish caught per hour) during the past year or when they last fished, when they first fished, and any other periods they recalled (Daw et al. 2011). We reconstructed time series of spatially explicit catch rate from fishers' perceptions (1940-2013). Many fishers recalled good, average, and poor catches from more than one period for a specific region (Townsville or Cairns). Finally, 42 recreational fishers were asked whether they had recently sighted Spanish mackerel in the former FSA sites.

Commercial daily-logbook catch data for the FSA fishery from 1990 to 2011 were acquired from the Queensland Department of Agriculture, Fisheries and Forestry. The data consisted of the daily catch of each operation, defined as an unknown number of vessels catching fish under one license. We used a spatial resolution of 30 x 30 minutes (latitudinal and longitudinal grids) for recorded catches and extracted catch landings for the spawning months (October and November) from the Townsville FSA fishery region. A bias that may occur within newspaper articles is the reporting of only the best catches. To improve comparability of catches between the historical newspapers and contemporary commercial logbooks, we ranked the catch of the fishers from the commercial logbooks and compared newspaper reports with reports of the 10 fishers with the highest average landings.

Calculating spatial distribution of fishing effort

We spatially partitioned data on commercial fishing effort to determine fine-scale changes in exploitation patterns of the GBR FSA fisheries. To do so, we gathered details of fishing locations and descriptions of grounds from both interviews and historical archives (Supporting Information). We summed the total number of exploited FSAs from fishers and newspapers during the spawning season per decade. Unfished FSAs were also included in our analyses – these were observed FSAs that were previously fished but are now situated in marine protected areas. The distance traveled from the home port to the farthest offshore FSA sites each decade was calculated and defined as the total distance traveled offshore. This enabled us to estimate fisher movement per decade from 1910 to 2010.

Testing accuracy of recalled catch rates

To investigate the accuracy of recalled catch rate, we used Daw et al.'s (2011) approach. We compared the memory of 10 fishers' catch rates (good, average, poor) with fishers' recorded catch for the corresponding period. We extracted all recorded catches from fishers' personal logbooks, calculated the mean, and ranked all logged catches for the same period that fishers recalled catches. We determined whether the variability of recalled catch fell within the distribution of recorded catches for each fisher.

Estimating catch rate and effort trends over time

We used linear mixed-effects (LME) models to examine the temporal changes in catch rate over time and the effects of the form of data on temporal trends. The nested structure called for a linear mixed-effect model to account for fisher identity, where individual fishers reported multiple observations of catches for more than one period of time. The random structure allowed the intercept and slope to vary randomly with interviewees in each model. Analyses were implemented using the lmer function in R lme4 package (Bates et al. 2013). The maximum-likelihood estimation and model validation were carried out by plotting standardized residuals against fitted values to identify violations of homogeneity. Data were log transformed to meet assumptions of homoscedasticity.

First, we used LME models to test whether the different types of catch rates (good, average, and poor) of exploited FSAs recalled by fishers changed significantly over time. The catch rates may not be entirely independent of each other, but given the potentially broad period of time (a year or more) that a fisher was being asked to recall catches, they were unlikely to be recalling a poor, average, and good catch from a specific trip. Hence, these different types of catch rates were treated as independent for the purpose of the analysis. In LME models 1-3 the number of fish per fisher per hour was a response variable, decade was a fixed factor, and fisher identity was a random effect for good, average, and poor daily catch respectively.

Second, we explored the effect of increasing fishing power by comparing the mean catch rate per year of the historical catch per unit effort (CPUE) and both the contemporary $CPUE_{raw}$

and contemporary $CPUE_{adjusted}$ (where catch rate was adjusted for changes in fishing power over time). First a fishing power index was constructed. The four most influential fishing operation characteristics (number of vessels per fishing operation, paravanes, colour sounders and GPS) as perceived by fishers were used to account for the effect of increasing fishing power on the catch rate. Ten of the interviewed fishers provided estimates of the proportional increase in fishing efficiency as a result of adopting each new fleet characteristic. Only data from fishers who had been operating prior to adopting the new technology were used and averaged these across the number of fishers. For each characteristic, the average percentage increase in catch by fishers employing the new characteristic was multiplied by the percentage of the fleet employing that technology per year (Marriott et al. 2011). The percentage increase of all the fleet characteristics was combined to provide annual estimates of overall change in the fishing power index (baseline value; 1 and upper value; 3.5).

The magnitude of the increasing fishing power effect on the modern catch time series data was explored by comparing the modern catch time series with modern catch time series accounting for fishing power. Two alternative models with the same fixed-effects structures but different assumptions about the random-effects structure were fitted to the data: no random effects and random fisher identity effect. We used the Akaike information criterion (Akaike 1974) to compare the null and full models. Maximal LME models were used for further inference (Barr et al. 2015). In LME models 4-6, mean number of fishing trips per year was a response variable, year was a fixed factor, and fisher identity was a random effect for historical CPUE, contemporary $CPUE_{raw}$, and contemporary $CPUE_{adjusted}$ respectively.

Investigating the abundance-occupancy relationship

We investigated the intraspecific abundance-occupancy relationship (AOR) of the Spanish mackerel FSA at a decadal scale (1940 and 2010). Abundance was measured as the mean catch rate of Spanish mackerel within fished FSAs per decade. Occupancy was estimated as the proportion of FSAs (total number of fished FSA sites/total number of known FSA sites) per decade. We used a log linear model to examine the relationship between catch rates and occupancy (Webb et al. 2007) using standard least squares with the lm function for each decade. Spearman's rank-correlation coefficients between time and abundance and the correlation of occupancy and time were estimated (Fisher and Frank 2004) to determine whether one or both of these variables were associated with the strength and form of the intraspecific relationship.

Results

Historical expansion and contraction of exploited FSAs

Commercial fishing of FSAs commenced in the inshore grounds off Townsville in 1911 (Townsville Daily Bulletin 1934). Reports from newspaper archives indicated a rapidly increasing fleet depleted inshore FSAs within three decades (1911-1941). During this time, fishers increased the total distance traveled offshore by an order of magnitude, from 5 to 51.4 nm (Fig. 2a & b; Supporting Information). Fisher interviews revealed that after 1940 the Townsville FSA fishery continued to shift offshore, increasing its range to both the north and south. By 2000 the fishery had contracted and today remains completely offshore. In contrast, exploitation of the Cairns FSA fishery showed a pattern of discovery, expansion, contraction, and collapse within four decades (1950-1990; Fig. 2a). From the early 1980s, fishers began exiting the Cairns fishery, and by 1995 the entire Cairns FSA fishery fleet had either exited the fishery or displaced effort to the offshore spawning grounds off Townsville.

A gradual increase in the total number of FSAs exploited was observed during the early period (1911-1949) of the spawning fishery in the GBR. From 1950 to 1990, the total number of FSAs exploited per decade increased from 10 to 23. From 1910-1990, the total distance traveled offshore rose from 5 to 80 nm (Fig. 2b,c), an expansion rate of 9.4 nm/ decade. By 2000 the total number of FSAs exploited on the GBR was reduced to 30% of the total number of exploited FSAs (Fig. 2c). No recreational fishers (n=42) had fished or sighted an inshore Townsville or Cairns FSA in the past 20 years.

Declines in perceived, good, average, and poor catch rates

In our interviews, fishers recalled catch rates that supported the decline in the targeting of FSAs of the Cairns and Townsville fisheries. A substantial declining trend was observed in all the catch rate types recalled by fishers for each fishery (Fig. 3). The good and average (but not poor) catch rates reported by Cairns fishers showed a significant decline from 1970 to 1990 (LME1 good n= 24, $F_{1, 18}$ = 6.740, p= 0.047; LME2 average n= 25, $F_{1, 18}$ = 9.593, p = 0.012) (Fig. 3a & Supporting Information). The Cairns catch-rate reduction was so large by 1995 all fishers had either exited the fishery or shifted effort to the Townsville fishery (Fig. 3a). Similarly, Townsville catch rates observed by fishers exhibited significant declines, with the exception of good catch, which remained stable over time (LME2 average n=107, $F_{1,105}$ = 14.03, p = 0.017; LME3 poor n=107, $F_{1,105}$ = 19.82, p <0.001; (Fig. 3b & Supporting Information). Despite an 87% decline in the Townsville fleet size by 2000, there were no more new FSAs to exploit, so catch rates continued to decline for the Townsville fishery (Fig. 3; Supporting Information).

Relationship between catch rate and occurrence of exploited FSAs

Mean catch rate and occurrence of exploited FSAs were not related (r = -0.294, p = 0.479; Fig. 4a). Of the temporal correlations, Spearman's rank correlation coefficient showed a significant negative (r = -0.321, p <0.001; Fig. 4b) trend between catch rate and time. We also found a negative but nonsignificant (r = -0.418, p = 0.173; Fig. 4c) temporal change in the occurrence of exploited FSAs.

Standardized catch rate and historical baseline

Between 1934 and 1947, newspaper articles provided 304 quantitative records of historical catch from 159 vessels. Although the annual average catch rate for Spanish mackerel was highly variable during the historical period, no statistically significant time-series trend was observed (Fig. 5a [LME4],Table 1, Supporting Information). Notable advancements in fishing power commenced following World War II; the mean number of dory vessels fishing per operator increased (Fig. 5b). Fishers quantified this operational variable as the most influential in that it inflated the catch rate by 93.8% (Supporting Information). Peak fishing efficiency in the mid-1980s coincided with the adoption of GPS and color sounders, but efficiency declined after 1990 as the number of vessels fished by a single operator decreased (Fig. 5b; Supporting Information). Mean contemporary catch rate differed significantly when the contemporary $CPUE_{raw}$ was adjusted using the fishing power index from fisher perceptions. Prior to adjusting for fishing power, mean contemporary catch rate was 21.74 (95% CI 21.11–22.37) fish/operation/trip (95% CI 10.78–12.04) reducing to 11.41 fish/vessel/trip (95% CI 10.78–12.04) after adjustment (Figure 5a [LME5 and LME6], Table 1, Supporting Information). Despite the use of only the top 10 fishers' catches (which minimizes estimated declines relative to those based on all fishers' catches), a significant difference between the historic and modern period was observed. The mean catch rate of Spanish mackerel decreased to 9.5% of the historical catch rate, from 119.79 (95% confidence interval, 110.22–129.35) to 11.41 (95% confidence interval, 10.78–12.04) fish/vessel/trip.

Discussion

Conservation of a transient aggregating species is intrinsically linked to the effective management of FSAs (Sadovy de Mitcheson et al. 2008; Erisman et al. 2015). For species with FSAs that are affected by anthropogenic activities, such as exploitation, understanding the complete historical perspective of exploitation can contextualize the current status of a fishery (e.g. Cardinale et al. 2011). In our historical approach, we examined long-term trends and the relationship between the catch rate and occupancy of FSAs for the Spanish mackerel FSA fishery from 1911 to 2013. We found a significant decline in both the catch rates and occurrence of exploited FSAs. We observed a loss of exploited FSAs and an offshore shift in exploration of additional FSAs within 2 decades of initial commercial exploitation of the Townsville fishery, as well as the commercial extinction of FSAs in the Cairns fishery, when the catch rate decreased to a point where fishing was no longer economically viable and fishers stopped fishing in those grounds (Safina 1994). The spatial pattern exhibited by Spanish mackerel is consistent with the serial depletion and collapse of FSA fisheries (e.g. Clark 2001), and fishers' lack of awareness of former FSAs can be identified as shifting baselines. We suggest that in the century since fishing began, the lack of spatial data on exploited FSAs and spawning catch data prior to 1988 has contributed to shifting baselines.

We found a 90.5% decline in catch rates from the Townsville FSA fishery from 1934 to 2011, despite a significant decline in the total fleet effort in the contemporary fishery. Fisher observations provided new insights into the catch trends and occurrence of a second, unrecorded spawning fishery, in Cairns, located within the ECSM. The declining catch trends observed within the Cairns fishery were steeper than for the Townsville fishery despite similar improvements in gear and technology and spatial expansion of exploited FSAs. We suggest that the FSAs supporting the fishery have died out because recreational fishers who still target Spanish mackerel within the areas where Spanish mackerel FSAs once formed since 1980 stated that they have not sighted any Spanish mackerel FSAs. The decline in catch rate and exploited FSAs can probably be extrapolated to mean the loss of some of the local spawning population because the commercial fishers target both aggregations before spawning and spawning FSAs (Tobin et al. 2014).

Abundance-occupancy relationships are typically positive (Blackburn et al. 2006), but we hypothesized that the AOR for a species that exhibits highly aggregated behavior is negative or nonsignificant. We found a nonsignificant, albeit slightly negative, trend. Overall, the local catch rate decreased by 90.5%, and occupancy mirrored that decline. However, we propose that the nonsignificant trend observed over time was due to only a small proportion of FSAs being exploited in the earliest three decades; the number of fished FSAs expanded and then contracted sharply (by 70%) within two decades.

Historical data are subject to many problems, and their potential biases must be examined if the data set is to be used as a reference point for past fisheries productivity. The main issues for our findings were that the data were derived from disparate data sources, and each data type havd inherent biases, which could result in incomplete time series and uncertainty in analytical robustness. The significant difference between the historic and modern catch rates must be interpreted with caution because the time series of catch rate were incomplete. No other data sources were available from that period to compare and determine the reliability of the catch rate data. Despite these caveats, newspaper data were numerous and were considered representative of the historical period due to the variability in catches landed by vessels within one spawning season and newspaper articles described landings from multiple vessels as good, average, or poor.

Commercial logbook data were plentiful but represented a small sample size (the top ten fishers with the highest catch rates) of the current fisher population. Furthermore, we accounted for only the top four gear and technology options adopted by fishers. This could have led to an overestimated catch rate in the modern period; hence, our modern, adjusted data are likely conservative. Fishers stated that the total number of hours fished increased per day throughout their fishing careers, so we did not account for the effect of fishers taking longer to catch fish. Our comparison of fishers' recalled catch rates (good, average, and poor) were observed within the distribution of recorded logbook catches. Hence, we considered fishers' perceptions of catch trends reliable.

Previous studies show that the collection of data during the development of the fishery can extend the time series relevant for models and reduce the influence of changing baselines (e.g. Engelhard et al. 2015). Quantifying and accounting for key parameters, such as historical changes in fishing effort, fishing efficiency, and spatial changes, could be used in stock assessments to reconstruct catch rates with greater certainty (Hilborn and Walters 1992). However, historical data sources are challenging to incorporate into stock assessment due to their respective biases, including incomplete data, bias in reporting of data, and the temporal and spatial scale of data.

Raising awareness of the spatial loss of FSAs occurring undetected may encourage communication between fisheries and conservation management (Erisman et al. 2015). Both fisheries and conservation management consider FSAs a priority to manage but for different purposes. For example the objective of managing FSAs for Queensland fisheries management is the sustainable exploitation of the stock while for the Great Barrier Reef Marine Park Authority (conservation management) the goal is to ensure decreases and local extinctions of FSAs within the GBR are minimized or do not occur at all (Russell and Pears 2008;

Campbell et al. 2012). Thus, the decline in FSAs represents a focal point for both conservation and sustainable management (Erisman et al. 2015).

Shifting spatial baselines represent a state where the decline in geographic extent has been lost to human memory. We suggest that a lack of historical data, sequential exploitation, and increases in fishing power in the GBR spawning fishery have contributed to resource users and management not incorporating the past distribution and abundance of this species into conservation frameworks. Despite concerns and research conducted in the earlier decades of exploitation of the ECSM FSAs (Munro 1942), no management mitigation has occurred that explicitly addresses the loss of Spanish mackerel FSAs. Furthermore, at present empirical data are lacking to test the effectiveness of this specific management measure to protect FSAs of Spanish mackerel (Tobin et al. 2014). We believe that documenting historical spatial baselines improves our perceptions of, and expectations for, breeding aggregations and the overall population size of aggregating species (Cardinale et al. 2011) and creates an enhanced framework for setting conservation targets.

Acknowledgments

We especially thank to all the Spanish mackerel fishers who not only provided the data used here but also shared their memories, photographs, and time with us. We thank Queensland Fisheries for access to contemporary catch rate data and L. McClenachan of Colby University, D. Cameron of the Great Barrier Reef Marine Park Authority, L. Litherland, and the UQ Marine Palaeoecology lab members for their comments on the manuscript. P. Rachello-Dolmen assisted in constructing the ARC GIS figures. The manuscript was considerably improved by comments from 4 anonymous reviewers, 1 anonymous editor, and the regional editor E. Johnston. S.B., R.T., and J.P. were supported by the Australian Research Council (ARC) Centre of Excellence for Coral Reef Studies and the Fisheries

Research and Development Corporation (project 2013-018). A.T. and S.B. were supported by funding from the Fisheries Research Development Corporation (project 2010-007) on behalf of the Australian Government.

Supporting Information

Examples of data sourced from newspaper archives (Appendix S1), estimates of fishing power (Appendix S2), linear mixed-effect results of recalled catch (Appendix S3), comparison of recalled and recorded catches (Appendix S4), trends in fleet size and gear and technology (Appendix S5), and diagnostic statistics for linear mixed effects with a random effect structure (Appendix S6) are available online. The authors are responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding authors.

Literature Cited

Akaike H. 1974. A new look at the statistical model identification. *IEEE Transactions on Automatic Control* **19**:716–723.

Barr DJ, Levy R, Scheepers C, Tily HJ. 2013 Random effects structure for confirmatory hypothesis testing: Keep it maximal. *Journal of Memory and Language* **68**: 255-278.

Bates D, Maechler M, Bolker B, Walker S. 2013. lme4: linear mixed-effects models using Eigen and S4 classes. https://cran.r-project.org/wed/packages/lme4/ (accessed March 2016).

Blackburn TM, Cassey P, Gaston KJ. 2006. Variations on a theme: sources of heterogeneity in the form of the interspecific relationship between abundance and distribution. *Journal of Animal Ecology* **75**: 1426–1439.

Borregaard MK, Rahbek C. 2010. Causality of the relationship between geographic distribution and species abundance. *Quarterly Review of Biology* **85**: 3–25.

Bauer S, Hoye BJ. 2014. Migratory animals couple biodiversity and ecosystem functioning worldwide. *Science* **344**:e1242552.

Campbell AB, O'Neill MF, Staunton-Smith J, Atfield J, Kirkwood J. 2012. Stock assessment of the Australian East Coast Spanish mackerel (*Scomberomorus commerson*) fishery. Department of Employment, Economic Development and Innovation, Queensland Government, Brisbane, Queensland.

Cardinale M, Bartolino V, Llope M, Malorano L, Skoid M, Hagberg J. 2011. Historical spatial baselines in conservation and management of marine resources. *Fish and Fisheries* **108**:289–298.

Ciannelli L, Fisher J, Skern-Mauritzen M, Hunsicker ME, Hidalgo M, Frank KT, and Bailey KM. 2013. Theory, consequences and evidence of eroding population spatial structure in harvested marine fishes: a review. *Marine Ecology Progress Series* **480**:227–243.

Clark M. 2001. Are deepwater fisheries sustainable? The example of orange roughy (*Hoplostethus atlanticus*) in New Zealand. *Fisheries Research* **51**:123–135.

Collette BB, Chang SK, Di Natale A, Fox W, Juan-Jorda M, Miyabe N, Nelson R. 2011. *Scomberomorus commerson*. The IUCN Red List of Threatened Species. Available from http://www.iucnredlist.org/details/170316/0 (accessed July 2014).

Daw TM, Robinson J, Graham NAJ. 2011. Perceptions of trends in Seychelles artisanal trap fisheries: comparing catch monitoring, underwater visual census and fishers' knowledge. *Environmental Conservation* **38**:75–88.

Domeier ML. 2012. *Revisiting Spawning Aggregations: Definitions and challenges. Pages 1-20. Reef Fish Spawning Aggregations: Biology, Research and Management.* Fish & Fisheries Series Volume 35.

Engelhard, G.H., Thurstan, R.H., MacKenzie, B.R., et al. (2015) ICES meets marine historical ecology: placing the history of fish and fisheries in current policy context. *ICES Journal of Marine Science* **73**: 1386-1403.

Erisman BE, Allen LG, Claisse JT, Pondella II DJ, Miller EF, Murray JH, Walters C. 2011. The illusion of plenty: hyperstability masks collapses in two recreational fisheries that target fish spawning aggregations. *Canadian Journal of Fisheries and Aquatic Sciences* **68:**1705–1716.

Erisman BE, Heyman WD, Kobara S, Ezer T, Pittman S, Aburto-Oropeza O, Nemeth RS. 2015. Fish spawning aggregations: where well-placed management actions can yield big benefits for fisheries and conservation. *Fish and Fisheries* **18**: 128-144.

Fisher JAD, Frank KT. 2004. Abundance-distribution relationships and conservation of exploited marine fishes. *Marine Ecology Progress Series* **279**: 201–213.

Gaston KJ, Blackburn TM, Greenwood JJD, Gregory RD, Quinn RM, Lawton JH. 2000. Abundance-occupancy relationships. *Journal of Applied Ecology* **37**: 39–59.

Govender A, Al-Oufi H, McIlwain JL, Claereboudt MC. 2006. A per-recruit assessment of the kingfish (*Scomberomorus commerson*) resource of Oman with an evaluation of the effectiveness of some management regulations. *Fisheries Research* **77**:23–247.

Grandcourt EM, Abdessalaam TZA, Francis, Shamsi ATA. 2005. Preliminary assessment of the biology and fishery for the narrow-barred Spanish mackerel, *Scomberomorus commerson* (Lacépède, 1800), in the southern Arabian Gulf. *Fisheries Research* **76**: 277–290.

Hilborn R, Walters CJ. 1992. Quantitative Fisheries Stock Assessment. *Reviews in Fish Biology and Fisheries* **2**: 177–178.

Juan-Jordá MJ, Mosqueira I, Cooper AB, Freire J, Dulvy NK. 2011. Global population trajectories of tunas and their relatives. *Proceedings of the National Academy of Sciences of the United States of America* **51**: 20650–20655.

Laliberte AS, Ripple WJ. 2004. Range Contractions of North American Carnivores and Ungulates. *BioScience* **54**:123.

McClenachan L, Cooper AB. 2008. Extinction rate, historical population structure and ecological role of the Caribbean monk seal. *Proceedings of the Royal Society B: Biological Sciences* **275**:1351–1358.

McPherson GR. 1985. Development of the northern Queensland mackerel fishery. *Australian Fisheries* **44**:15–17.

McPherson GR. 2007. Historical stock definition research on *Scomberomorus commerson* in Queensland waters. Pages 33–60 in RC Buckworth, SJ Newman, JR Ovenden, RJG Lester, and GR McPherson, editors. *The Stock Structure of Northern and Western Australian Spanish Mackerel.* Northern Territory Government, Australia. Fishery Report FRDC 98/159.

Munro I. 1942. The eggs and early larvae of the Australian barred Spanish mackerel, *Scomberomorus commersoni* (Lacépède) with preliminary notes on the spawning of that species. *Proceedings of the Royal Society of Queensland* **54**:33–48.

National Library of Australia. 2014. Available from http://www.trove.nla.gov.au (accessed July 2014).

O'Neill MF, Courtney AJ, Turnbull CT, Good NM, Yeomans KM, Smith JS, Shootingstar C. 2003. Comparison of relative fishing power between different sectors of the Queensland trawl fishery, Australia. *Fisheries Research* **65**:309–321.

Russell MW, Pears R. 2008. Workshop Summary: Management and Science of Fish Spawning Aggregations in the Great Barrier Reef Marine Park 12-13 July 2007. Great Barrier Reef Marine Park Authority, Townsville.

Sadovy YJ. 2003. Fisher survey interview format general guidelines. Society for the Conservation of Reef Fish Aggregations.

Sadovy Y, Eklund AM. 1999. Synopsis of biological data on the Nassau grouper, *Epinephelus striatus* (Bloch, 1792), and the jewfish, *E. itajara* (Lichenstein, 1822). NOAA/National Marine Fisheries Service.

Sadovy de Mitcheson YS, Cornish A, Domeier M, Colin PL, Russekk M, Lindeman, KC. 2008. A Global Baseline for Spawning Aggregations of Reef Fishes. *Conservation Biology* **22**:1233–1244.

Sadovy de Mitcheson Y, Erisman BE. 2012. *Fishery and Biological Implications of Fishing Spawning Aggregations, and the Social and Economic Importance of Aggregating Fishes. Pages 225–284 Reef Fish Spawning Aggregations: Biology, Research and Management.* Fish and Fisheries Series Volume 35.

Safina C. 1994. Where have all the fishes gone. *Issues in Science and Technology* **10**: 37-43.

Shepherd TD, Litvak ML. 2004. Density-dependent habitat selection and the ideal free distribution in marine fish spatial dynamics: considerations and cautions. *Fish and Fisheries* **5**: 141- 152.

Tobin, A., L. Currey, and C. Simpfendorfer. 2013. Informing the vulnerability of species to spawning aggregation fishing using commercial catch data. *Fisheries Research* **143**:47–56.

Tobin A, Heupel M, Simpfendorfer C, Pandolfi JM, Thurstan RH, Buckley SM. 2014. Utilising innovative technology to better understand spawning aggregations and he protection offered by marine protected areas. FRDC 2010/007.

Townsville Daily Bulletin. 1934. Available from http://trove.nla.gov.au/ndp/del/article/61866410?searchTerm=king%20fish&searchLimits=l-state=Queensland%7C%7C%7Cltitle=97%7 C%7C%7Cl-decade=193 (accessed July 1934).

Webb TJ, Noble D, Freckleton RP. 2007. Abundance-occupancy dynamics in a human dominated environment: linking interspecific and intraspecific trends in British farmland and woodland birds. *Journal of Animal Ecology* **76**: 123-134.

Webb TJ, Dulvy NK, Jennings S, Polunin NV. 2011. The birds and the seas: body size reconciles differences in the abundance-occupancy relationship across marine and terrestrial vertebrates. *Oikos* **120**: 537–549.

Webb TJ, Freckleton RP, Gaston KJ. 2012. Characterizing abundance-occupancy relationships: there is no artefact. *Global Ecology and Biogeography* **21**: 952–957.