Range contraction of large pelagic predators in the Pacific

PhD research proposal – DRAFT

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Overview

The objective of this PhD thesis is to develop and assess methods to detect range contraction, explore the impacts of species life-history traits and dispersal strategies on the relationship between abundance and range size, and identify key impacts of range contraction on the management of fisheries for large, highly mobile species.

Large pelagic predators such as tuna and billfish play a unique role in the pelagic communities of the Pacific. They can be both predator and prey at various stages of their life cycles (Young et al., 2010; Cox et al., 2002; Hinke et al., 2004), occupy a wide range of the water column (Schaefer and Fuller, 2009) and store and move important quantities of carbon and nutrients between coastal and pelagic ecosystems, and along large distances through their migratory behavior (Allain et al., 2012).

In addition, tuna and billfish fisheries serve as an important source of proteins to Pacific islands nations, and offer what is often the only source of foreign revenue to the local economies of these states. Many of these species are heavily exploited by modern fisheries, with more than 60% of the tuna consumed globally coming from the Western and Central Pacific (Williams and Terawasi, 2012).

There has been anecdotal reports from fisheries organizations that various species of tuna have disappeared from locales where they used to be abundant (S. Harley, *pers. comm*). Management advice currently provided to Pacific Islands states does not account for a potential change in the range of target species and a number of countries have showed concern in this regard (S. Harley, *pers. comm*).

Abundance-range relationships are defined in this thesis as an observed link, direct or indirect, between species total or local abundance and the area of its geographic range. A number of studies in ecology have observed a link between population abundance and range size (Gaston et al., 2000; MacCall, 1990; Lawton, 1993) and it is likely that the range of harvested species, like large pelagics, could be

affected by such behaviour as their biomass declines under management. If so, the optimal strategy for the regional management of large pelagics could be impacted as some regions would be overtly affected by biomass depletion even though the overall stock is considered healthy. Changes in range size over time could also bias estimates of biomass since stock assessments often implicitly assume that range area stays constant over time.

To understand whether abundance-range relationships exist in large pelagics, we need to understand the links between population dynamics and the use of habitat by individuals. The geographical range of tuna and billfish can be partly explained through features of the marine environment (e.g. Reygondeau et al., 2012). On small temporal scales they track specific conditions in the water column like sea surface temperature, depth of the thermocline, salinity and oxygen concentration (e.g. Fiedler and Bernard, 1987; Reese et al., 2011). Large-scale climate cycles that affect these conditions – and are also prevalent in the Pacific (e.g. ENSO, El Nino Southern Oscillation) – can thus result in important changes in the geographic distribution of some of these species between years (Lehodey et al., 1997).

Fishing pressure is another important factor to account for. A recent report indicated that the range of many tuna and billfish had contracted since the 1970s (Worm and Tittensor, 2011), although the link to fishing pressure was based on correlative rather than mechanistic evidence. There are multiple examples from the conservation literature of range contraction resulting from over-harvesting (e.g. Laliberte and Ripple, 2004). Furthermore, one of the most important fishery collapse of the 20th century, that of the Atlantic cod, has been linked to the failure to detect a range contraction in the species (Rose and Kulka, 1999). This failure was in part attributed to the species' strong schooling instincts, a behavior that is also prevalent in tuna and billfish.

In this PhD thesis, I intend to assess the potential for range contraction in large pelagic predators of the Pacific and the consequences for the management of their fisheries. A key challenge will be to distinguish whether a change in local abundance is caused by the environment, an overtly high fishing pressure resulting in local depletion, or changing emigration rates enacted through abundance-range size relationships. To adress this I will merge tools from fisheries science and marine ecology. The resulting conclusions will explicitly account for multiple scenarios of uncertainties through the application of a management strategy evaluation (MSE). The thesis will be divided as follows:

- Chapter 1: Literature review on the topic of the geographic range across disciplines, with a focus on concepts relevant to highly-mobile marine species.

- Chapter 2: Assessement of distribution dynamics in large pelagics in the last 60 years using a low-resolution fisheries catch-and-effort dataset, and impact of data resolution on inference about abundance trends.

- Chapter 3: Theoretical population modelling of range-abundance relationships given life-history features and hypotheses about dispersal dynamics.

- Chapter 4: Management strategy evaluation of pelagic predator fisheries given scenarios about dispersal dynamics, climate change and management strategies.

I have also included here two potential chapters which might serve to supplement the thesis if needed.

Chapter 1: Current understanding of species distributions

A literature review has been conducted to (1) identify key ecological and evolutionary factors that should be accounted for in the measurement and modelling of range contraction, and (2) create a framework to synthesize current understanding of the geographic range across disciplines.

Anthropogenic global change has resulted in drastic changes in the distribution of many species and, consequently, the last two decades have seen an important rise in research aimed at understanding the drivers of species' distributions. The geographic range ties in many aspects of a species' biology such that, unsurprisingly, a variety of approaches have been developed to tackle the question. Studies, however, often do not account for existing research in closely-related disciplines. For instance, there is little cross-pollinization between climate change, conservation and invasive species research, even though scientists in these fields are all focusing on some sort of range dynamics, be it shifting, expansion or contraction.

Moving our focus to marine systems, research on the geographic range in this realm has been minimal compared to terrestrial systems. A possible reason could be that species occurrence data are hard to obtain for marine species due to the nature of their habitat (e.g. museum records are not available to the extent they are for terrestrial species) (see Tyberghein et al., 2012). Range boundaries for pelagic species could also be harder to define when viewed from a terrestrial standpoint. In fisheries science, changes in species range are rarely incorporated explicitly in stock assessments, though this is made implicitly through a parameter called catchability [1] (Winters and Wheeler, 1985). Stock assesment practitioners are well aware that changes in range can happen, as some important stock collapses have occurred together with range contraction (Rose and Kulka, 1999). "Density-dependent habitat selection" is a popular but largely untested hypothesis (MacCall, 1990) which posits that intra-specific factors like competition for resources in varied habitats result in a relationship between range size and abundance (but see Shepherd and Litvak, 2004).

In light of this, the goal of this chapter was to perform a literature review on the geographic range across the following disciplines: behaviour, conservation science, ecology, evolution, fisheries science, genetics and paleobiology. A second aim was to create a framework to synthesize our understanding of this literature along three axes: environmental *vs.* biotic drivers, single *vs.* community effects, marine *vs.* terrestrial systems.

Current status: first draft 95% completed, need to format for journal submission (journal to be determined), ideally need a second author with research experience in topics related to species distributions.

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[1] Catchability assumes (usually) that a species' range size stays constant over time.

Chapter 2: Trends in species range using Pacific-wide CPUE data

This chapter aims to develop methods to detect range contraction in large pelagics using large-scale coarse resolution spatio-temporal fisheries data, as well as highlight features of commonly available datasets that could confound measurements of range contraction.

In order to detect range contraction, we need species occurence data that cover the entire distribution of a species, ideally on a long-term basis. When these data exist, however, it is often at a coarse scale. Can we make inference about changes in a species' distribution from such datasets? What are the confounding variables that are likely to bias our analysis? In this chapter I use $5 \times 5°$ aggregated catch-and-effort data of large pelagics in the Pacific since the 1950s to assess changes in range over time. I assume that catch-per-unit-effort is proportional to abundance, such that this dataset is effectively a record of large pelagics occurence in the Pacific over the last 60 years. I start by fitting a statistical model to the existing data, then use the model to predict the value in cells with years of missing data. I define a series of arbitrary abundance thresholds above which the species is considered to be present, and then use these to detect changes in range area over time. Lastly, I use high-resolution fishing trip data to verify some of the assumptions made when using the $5 \times 5°$ data. The trip data only covers a subset of the spatial and temporal extent of the $5 \times 5°$ data, so this analysis is applied where the two datasets overlap.

Throughout this thesis I will define range contraction as a decline in the area where a species' abundance used to be above a given rarity threshold. This threshold is user-defined and could be adapted based on research or management goals. This is partly for practical reasons as the available data would not allow us to demonstrate with full certainty that a species is absent from previously occupied regions. It, however, also has an ecological justification as it is informative to document instances where the species went from abundant to rare, since this abundance decline might (1) be the precursor to extirpation and (2) indicate that ecosystem dynamics in those locales are likely to be changing. CPUE data converted to an abundance index could, if used carefully, provide information about relative abundance over time and be used to assess changes in occupancy over the range.

2.1 Description of the dataset

Industrial fishing for tuna has taken place in the Pacific since the 1950s, and extensive fisheries catch data exist for this region at various degrees of spatial and temporal resolution. In its simplest expression,

spatial catch data can be used as a proxy for presence data. In order to extract additional information, a common approach in fisheries is to convert catch data to an index of species abundance by dividing them by a unit of effort (catch-per-unit-effort, CPUE) (Maunder and Punt 2004, but see Harley et al. 2001). In this chapter I use a large dataset of longline CPUE data to assess range contraction of large pelagics in the Pacific. The dataset has been collated by the Secretariat of the Pacific Communities (SPC) and covers the period 1952-present at a 5 degree resolution for a range of fishing fleets. Catch data for the following species is present: yellowfin tuna, big-eye tuna, albacore tuna, skipjack tuna, southern bluefin tuna, black marlin, blue marlin, striped marlin, sailfish and swordfish. The time period included in the dataset covers the history of all major longline fleets. The focus is on longline data for now as it is the prevalent method of fishing in the Pacific. Figure 1 gives an overview of the dataset for the 6 most commonly caught species.

2.2 Using CPUE as an index of abundance

The underlying assumption behind the use of CPUE as an abundance index is that catch rates are proportional to abundance. This assumption, however, requires a random distribution of fishing effort throughout the area where catch data come from. In reality, effort is rarely distributed randomly over a species' range as fishermen will fish where income is maximized. In addition, a number of confounding factors prevent raw CPUE data from being used without further processing (usually in the form of standardization). For instance, over long time periods, technological advances in fishing gear increase fishing efficiency, such that CPUE has a different interpretation today than 3 decades ago. Other issues associated with the use of CPUE as a measure of abundance are reviewed in Harley et al. (2001). An active field of research in fisheries science is to develop methods that yield unbiased indices of abundance from CPUE data (e.g. Campbell, 2004), but they themselves are often heavily criticized (Carruthers et al., 2010). Despite this, fishery-dependent CPUE data do contain useful information if one is careful and explicit about the assumptions made in its use. An important challenge in the current work will thus be to develop analyses that are robust to the limitations of CPUE data.
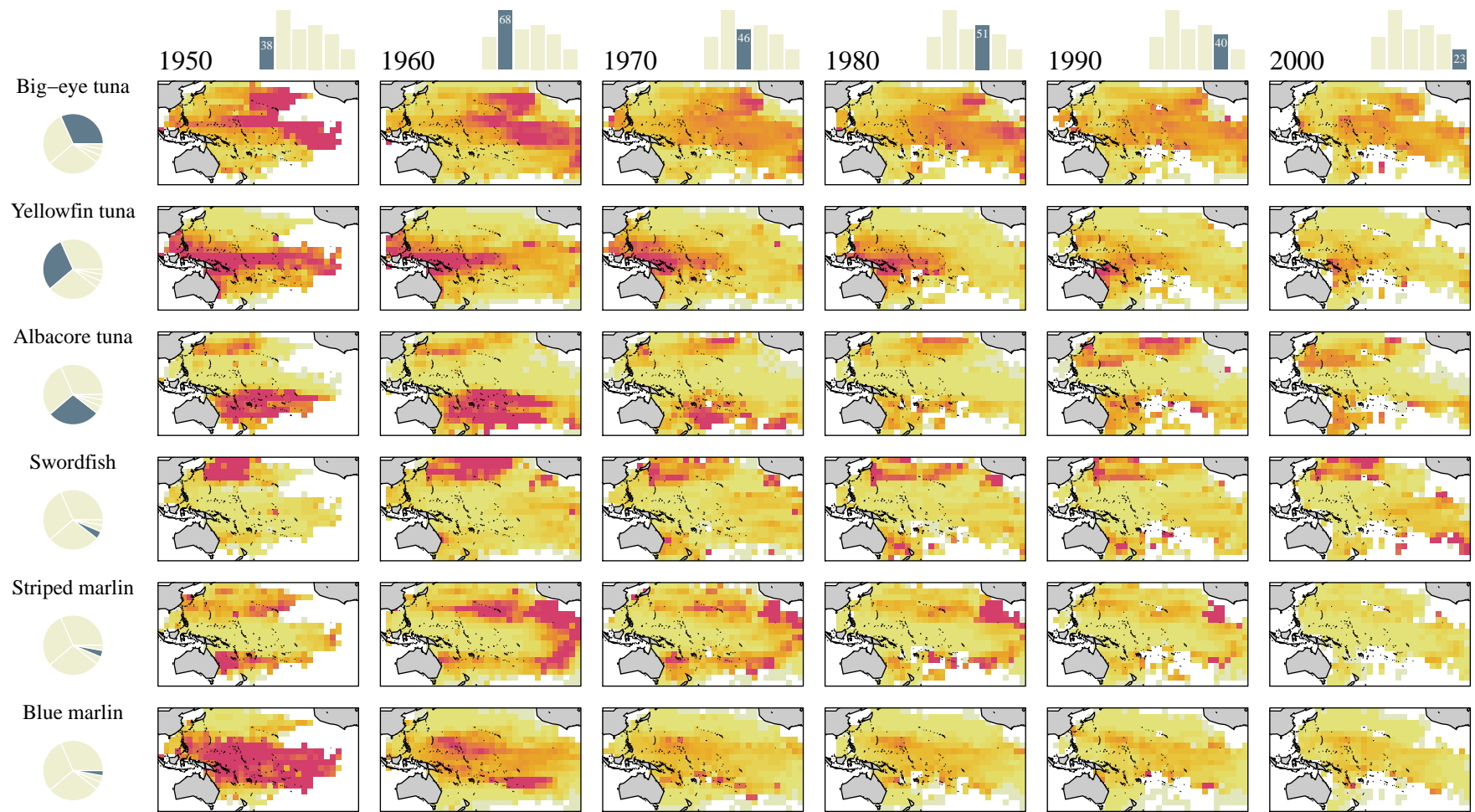
Figure 1: Summary of catch-and-effort for the 5 × 5° aggregated data from the SPC for the 6 most frequently caught species: Map of relative catch-per-unit-effort aggregated over decade and standardized for each species; proportion of each species in the total catch (left); total catch across species by decade (in million individuals) (top).

2.3 Predicting CPUE in space and time

The $5 \times 5°$ longline dataset available through the SPC has the largest spatial and temporal coverage for marine species in the Pacific. Nonetheless, there remain many cells with missing catch-and-effort data, either for a section or the entirety of the time-series. As pointed out by Walters (2003), the failure to explicitly consider cells with no fisheries data is a common error made in CPUE analyses and can lead to wrong inferences about abundance trends. For instance Myers and Worm (2003) assumed that trends in CPUE data for a subset of cells in the Pacific were representative of overall stock trends and predicted a decline in abundance much higher than that measured in subsequent, more involved analyses (Sibert et al., 2006). Special attention must thus be provided to filling cells with missing data so that the $5 \times 5°$ dataset can serve as an unbiased proxy for abundance over the Pacific. Current approaches to filling in abundance are rule-based. For example Carruthers et al. (2011), following suggestions by Walters (2003), used simulated data to test a rule-based approach to fill-in missing CPUE cell data based on data existing for that cell in subsequent years and found that the resulting abundance indices were more accurate. One important advantage with the rule-based approach is that it is straight-forward to understand and apply. However, for the approach to be practical, we are restricted to one dimension: the value of a cell can only be affected by values of that same cell in future years, even though data from neighbouring cells in the current year might be available. In addition, with varying oceanographic conditions, abundance in future years may or may not be representative of abundance in the current year. I propose to use a statistical approach to fit spatio-temporal splines to the existing abundance index and predict the value for missing cells from the resulting model. The advantage of using splines is that the relationship of catch over space and time need not be linear (or a complicated polynomial), and we can retain high degrees of freedom since longitude and latitude are not treated as fixed effects.

For the purpose of the current analysis, the main issue to address with the CPUE dataset is the need to distinguish between an absence of a species in a cell due to the fishery not having gotten there yet (i.e. spatial expansion of fishing effort), or due to the disappearance of the species from a cell where it was present in the past. The use of oceanography data as a covariate could address this by providing indication of the likely stock abundance expected in cells with no effort data given the environmental suitability. A quick exploration showed that sea temperature and time on their own explained 45% of the variance in the $5 \times 5°$ CPUE dataset, supporting the assertion that oceanographic variables would be good candidates to inform abundance levels in unobserved cells.

One of the main challenges in fitting a spatio-temporal spline model to the Pacific-wide CPUE data will be to find an adequate strategy to account for spatial autocorrelation between the cells and temporal autocorrelation between the years. So far computing power has limited the application of conventional

methods, since the dataset is quite large.

Lastly, I will have to account for the different properties that target and by-catch species have in catch datasets to apply this method to all large pelagics. For instance, effort is not always linked to abundance for by-catch species such that a CPUE derived from effort targeted at another species might not yield a representative index of abundance (see Ortiz and Arocha, 2004). A way to address this could be to focus the analysis on target species only, which would be identified either through the use of a separate dataset of covariates informative of the species being targeted (e.g. historical expert opinion, hooks-per-basket, see Ward and Myers, 2005), or a formal cluster analysis using disaggregated fleet data that could be used to split the catch data into subsets where a single species is being targeted.

2.4   Impact of data resolution on measured trends

A second component of this chapter will be to investigate the sensitivity of results to the scale of data aggregation. $5 \times 5°$ cells have an area between 230 000 and 310 000 km^2 – the assumption that aggregated CPUE rates are representative of CPUE rates experienced by individual boats is thus an important one. I have access to two datasets that provide catch-and-effort data at a finer resolution for the Pacific: (1) operational fisheries data (catch reports by individual boats); (2) $1 \times 1°$ fisheries data for the Japanese fleet. Both of these only cover a subset of the spatial and temporal extent of the $5 \times 5°$ dataset, but can still be used to test the impact of scale where the datasets overlap.

Overall patterns in catch rates over space and time will be investigated to see if they match those obtained at a coarse resolution. In addition I will try to detect patterns of spatial expansion of fishing within $5 \times 5°$ cells. The latter would tell us whether declines might be due to serial depletion of fishing grounds. This additional work will highlight features of data resolution that can confound the detection of range contraction, and also provide support (or not) for patterns detected at the Pacific basin scale [2]. Another option would be to use trip data to estimate targeting and see whether the cessation of fishing effort in a cell is due to a depletion of the ressource or to a change in targeting strategy by the fishermen.

Lastly, spatial resolution can also affect the measured area of the geographic range (Hurlbert and Jetz, 2007) and bias perceived rates of change in space or in time (Rahbek, 2005, see also Figure 4). The trip dataset could be used to investigate how spatial resolution affects rates of range change. In addition to making the analysis more robust, this will be useful preparatory work for Chapter 3 which will require measurement of range as part of the modelling of range-abundance relationships.

Current status: Analysis 95% done on $5 \times 5°$ for sample species yellowfin tuna, starting on other species and fine resolution data, short paper presented to Pacific Islands Forum Fisheries Agency.

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[2]if we assume that differences between fine and coarse dataset for the overlap are representative of what they would be at the scale of the Pacific

Chapter 3: Population modelling

A spatially-explicit population model will be built to explore the impact of dispersal behaviour and life-history characteristics on (1) the relationship between geographic range and population size and (2) the distribution of biomass in the range as abundance declines.

The interpretation of observed spatial trends in the abundance of large pelagics can be complicated due to (1) the high-mobility of these species; (2) the prevalence of dynamic oceanographic conditions in the Pacific; and (3) evolving patterns of fishing effort. Explicitly including these processes in a theoretical population model would improve our understanding of the driving factors behind observed abundance-range size relationships.

In this chapter I will explore the impact of movement, dispersal and migration behaviour on the range dynamics of large pelagics. A spatial, environmentally-explicit population dynamics model will be developed. This model will first be used in a theoretical framework to understand how assumptions about movement, dispersal and migration affect observed range dynamics in heterogeneous environments. The model will then be parameterized using a set of tropical tunas with different life histories as case-studies (e.g. skipjack vs. yellowfin vs. bigeye tuna), and accounting for various spatio-temporal trends in fishing mortality. This will be used to generate predictions of biomass distribution in the range as abundance declines, which could then be compared to observed patterns of abundance in space and time obtained in Chapter 2. The impact of the contraction behaviour on the regional management of these fisheries will be considered in the next chapter.

3.1 Movement, dispersal and migration *vs.* abundance-range size relationships

The mechanism that links habitat use by individuals and local or total abundance could have a strong impact on geographic range dynamics. It is obvious that the range occupied by a critically endangered species with 10 individuals would be less than that originally occupied by the population when it was abundant. But what are the dynamics that drive the geographic range from its initial extent to the very restricted one expected for a small population? Dispersal behaviour is a main candidate to explain how some aspects of this contraction would occur. For instance, if individuals are sedentary we would expect that geographic contraction would occur first where mortality is highest. If they are mobile (like large pelagics), then a process like *density-dependent habitat selection* could occur, whereby individual immigration towards optimal, core habitats increases as overall population abundance declines and the effective suitability of these high-quality habitats increases, possibly due to a lessening of intra-specific

competition (MacCall, 1990).

The relationship between the abundance of a species and the extent of its distribution implies that some component of the way invididuals, groups or populations use their environment is density-dependent. For instance, consider the case where individuals are randomly distributed throughout their range (Figure 2, left column). If abundance declines and home range stays constant, then the area of the range will decline as well, though not as much as if individuals tend to aggregate (right column). In order for range size to stay constant as abundance declines, the home range of individuals has to increase to compensate (left column, bottom). Density-dependent dispersal has been documented in a number of species (Matthysen, 2005) and could be a mechanism through which such range-abundance dynamics emerge.

In the current chapter I propose to use large pelagics as a model system to explore how/whether range dynamics can emerge in mobile species. Large pelagics are a good case-study to address this question for the following reasons:

– Large pelagics are highly-mobile *and* migratory. These two behaviours are hard to tell apart when analyzing occurrence data. Modelling these features will allow us to isolate in a controlled environment the effect each behaviour has on range dynamics.

– They represent a range of life-histories while belonging to similar ecological functional groups, such that the model could represent a range of species by tweaking a set of key parameters.

– A simple spatial model structure would be justifiable since they are thought to track smooth gradients in the environment.

– From a practical perspective, most stocks show an important decline due to fishing pressure but not so much that their populations are threatened, i.e. they cover a range of intermediate values of abundance and, from a management perspective, better understanding of their range dynamics would be useful *now*.

3.2   The role of fishing in shaping abundance-range size relationships of highly-mobile large pelagics

Fishing pressure is an important driver behind the decline of tropical tuna biomass and additional mortality incurred through fishing is not spread evenly throughout the range. Changes in range size with abundance are thus likely to be affected by both intrinsic ecological factors and spatial trends in fishing effort. The model needs to account for this in order to be useful in the analysis of real-life
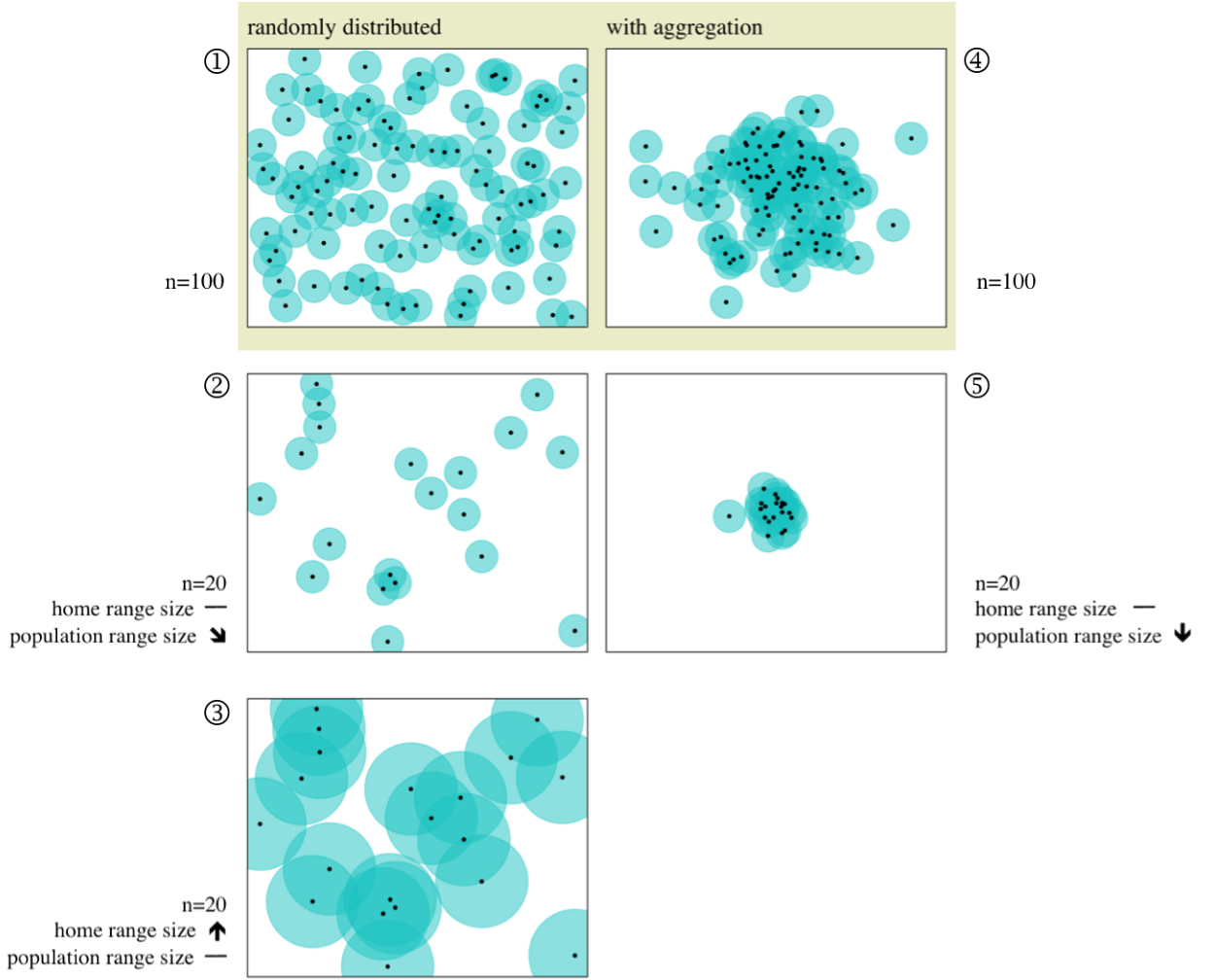
Figure 2: Effects on the range of a reduction of abundance of one fifth from initial conditions (top, in yellow rectangle), given individuals that are randomly dispersed (left column) or aggregated in space. The home range of each individuals is represented by the blue circles. In cases (2) and (4) home range stays constant as abundance diminishes. In the former this results in small reduction in range while in the latter the reduction in range is high. In case (3) home range size increases such that population range size stays the same despite the one fifth decline in abundance.

abundance data from large pelagics in the Pacific. As an example, Figure 3 shows how abundance patterns for a mobile fish changes from unfished to fished conditions depending on whether fish move in a non-random way throughout the range (e.g. migration towards preferred core habitats) or whether fishing mortality is higher in locales with higher abundance.

The role of spatial trends in fishing could be explored by applying to the model simple patterns of fishing effort (as in, for e.g. Swain and Sinclair, 1994). Another option would be to extract effort patterns from the SPC database and use those to drive the model.
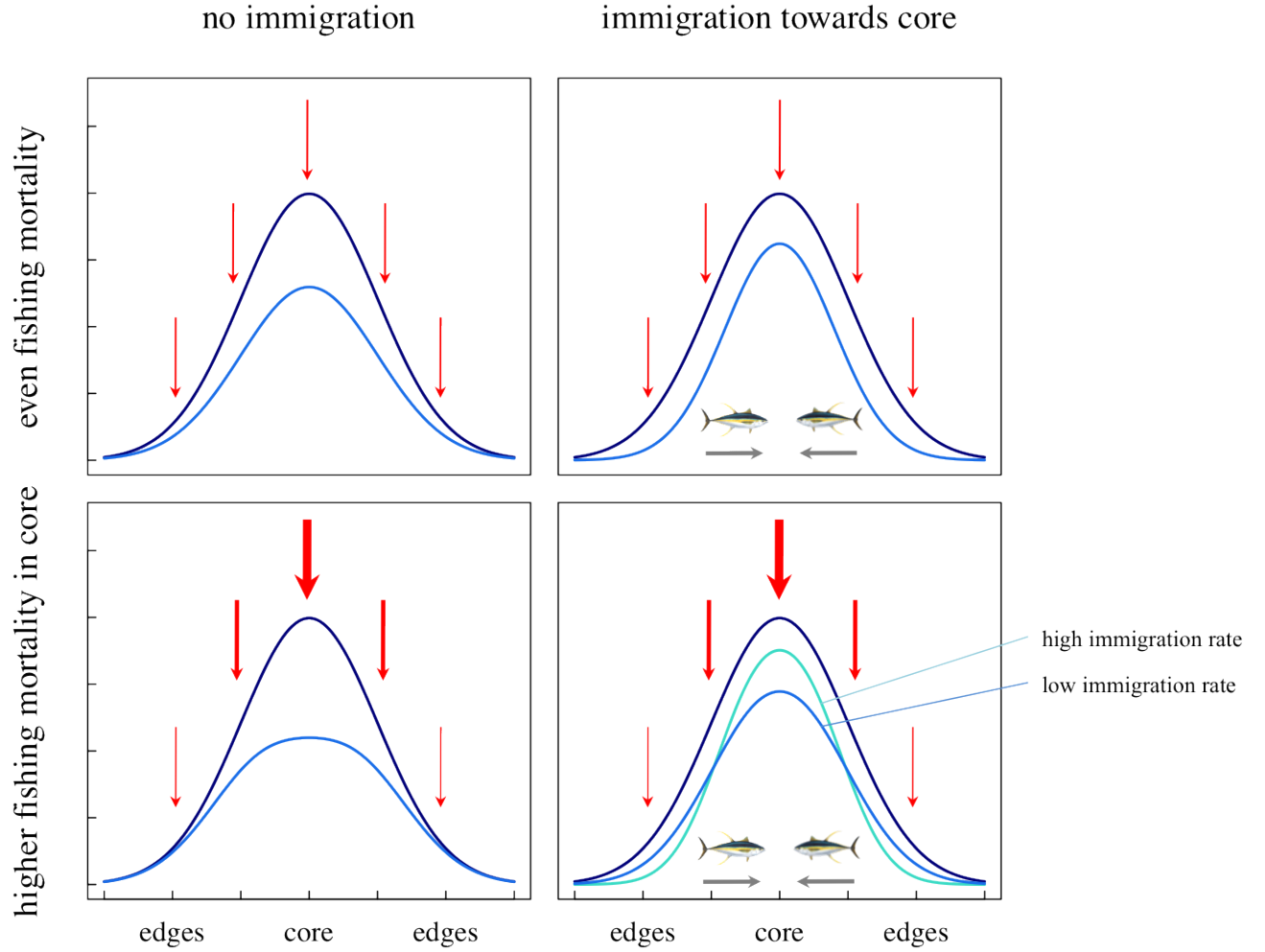
Figure 3: Schematic representation of the distribution of biomass of highly-mobile pelagics in unfished (dark blue line) vs. fished (light blue line) conditions as a function of two factors: (1) distribution of fishing mortality over the range (top, even over the range; bottom, higher at the core) and (2) relationship between immigration rates and density in core habitats (left, no relationship; right: increase immigration rate towards the core when abundance in the core declines). It is assumed here that habitat quality is higher at the range core than at the range edges. Declines in abundance at edges are more pronounced when there is increased immigration towards the core, though the effect vary as a combination of the difference in fishing mortality between the core and the edges and the impact of abundance on immigration rates (bottom-right figure).

3.3 The iSCAM model

In order to investigate links between abundance and range size I will need a population dynamics model that is explicit in space. In addition, a model compatible with a fisheries framework would be ideal as I will be comparing results to fisheries data and use the model in the next chapter to investigate management impacts. I propose to use iSCAM as a starting point for the model (Martell et al., 2012), where iSCAM stands for "integrated statistical catch at age model". It is an age-structured population model used for stock assesments that can accomodate a range of life histories and is also designed to run fast. I would have to extend the model to make it spatially explicit on a grid and include density-dependent movement/home range/migration relationships. This is likely to be one of the main challenges in model formulation and will rely on the definition of a relationship between local abundance and some form of habitat use by individuals. The advantage of starting from a model that already exists *vs.* writing one of my own is that I get to start from a robust, well-tested base and focus my energy on the spatial component, which is the one that matters the most for the questions at hand. I would still get the model developing experience as I am extending the model into space which will be a significant amount of work in itself.

3.4 Defining the range in practice

A key part of the modelling will be the assessment of geographic range size. The metric used to do so could affect perceived trends in space and time (Hurlbert and Jetz, 2007). This issue is prevalent in ecology, conservation and behaviour studies. For instance many macroecologists persist in using minimum convex polygons even though they often overestimate range size (Burgman and Fox, 2003). As the basic unit of space here will be the cell, it would be straight-forward to measure the range as the number of cells occupied (or with biomass above a given threshold). However the cell resolution could affect trends in range area over time, see Figure 4. One way to address this would be to aggregate the modelled outputs at various resolutions to see how sensitive conclusions are. Issues of results sensitivity to resolution are also addressed in the second part of Chapter 2 (see section 2.4).

3.5 Comparing model predictions to observed trends in biomass distribution

Understanding temporal changes in the spatial distribution of biomass over the range is important for the regional management of tuna stocks. One of the key modelling results of this chapter will be the predictions of patterns of biomass distribution in space and time as a function of life-history and dispersal behaviour. These predictions can be compared to the modelled abundance obtained in Chapter 2 in order
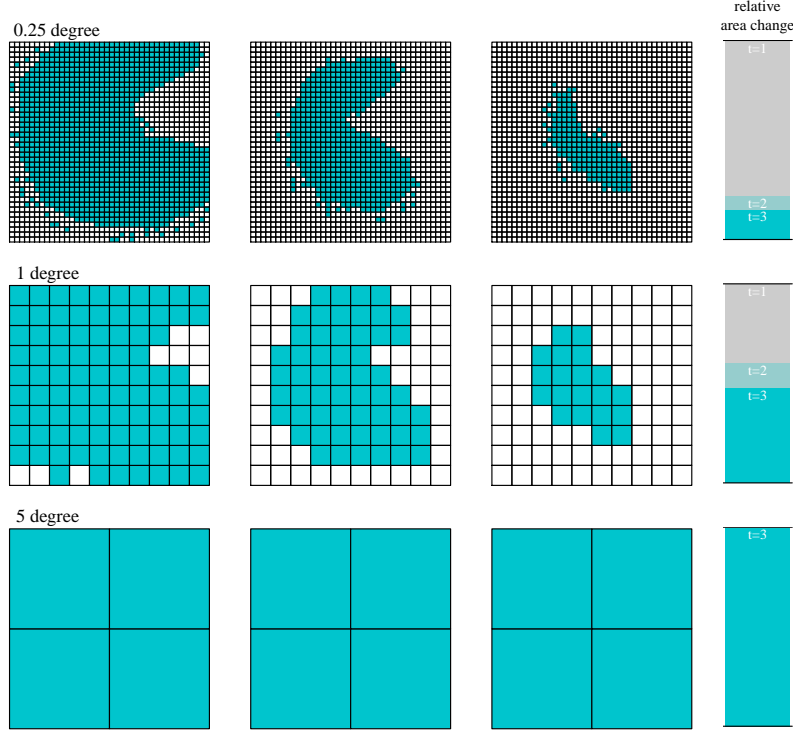
Figure 4: Decline in time of a sample geographic range viewed under three spatial resolutions. The right-column shows the relative decline in range area over time for each resolution. A coarser grid resolution results in a smaller decline and a positive bias in measured range area.

to understand which mechanisms might be at play under changes in biomass distribution as abundance declines. In addition, the model could be used to test different metrics for measuring changes in the geographic range (for example CPUE thresholds as done in Chapter 2, and other methods advocated in Swain and Sinclair, 1994).

3.6   Identifying key parameters for research prioritisation

There is considerable money invested in researching various aspects of the biology of tuna. An output of this chapter could be to identify which measurable-in-the-field model parameters have the largest impact on modelled abundance-range area relationships. An example of such a parameter is the median lifetime dispersal distance, which is measured using targeting data (see for e.g. Sibert and Hampton, 2003). This approach could be used to inform investment into tuna research and be developed into a paper on conservation/management funds prioritization.

Chapter 4: Range dynamics and the management of tropical tunas

This chapter will use management strategy evaluation to investigate the impacts of range dynamics on tropical tuna fisheries management given scenarios about the drivers of range contraction, climate-recruitment relationships and management goals.

There are uncertainties at all steps of the management of a fisheries, from the data collection to the stock assessment to the policy makers' decisions and the implementation in real-life. Given that most of these uncertainties cannot be resolved, our approach to management should strive to be robust to all possible states of the system. The goal of a management strategy evaluation (MSE) is to find a manangement strategy that fulfills the management goals independently of the uncertainties we might have about the managed system's state (Punt and Donovan, 2007). Such a procedure is especially useful in a situation where there are a lot of unknowns in the system being modelled, where shareholders have conflicting management objectives and where components important to management interact in non-intuitive ways.

The aim of this chapter is to explore the impacts of range dynamics on the recommended management strategy for tropical tuna fisheries in the Pacific. I will draw on the results from Chapters 2 and 3 to identify key uncertainties in the modelling of range contraction behaviour and population dynamics. The performance of management strategies will be assessed on a per-region basis since range contraction will have differential impacts on local fisheries based on their location in the target species' distribution. The MSE will be conceived in such a way that it renders the analyses of Chapters 2 and 3 more robust. For instance, the effects of structural uncertainty in the modelled relationship between range size and abundance will be assessed by including scenarios for various mechanisms of range contraction.

4.1   What are management strategy evaluations?

MSEs provide a framework to assess the performance of a set of management strategies while accounting for uncertainties at multiple stages of the decision-making process. It explicitly models all of the steps that go into the management of a species: modelling, decision-making based on the model's results, application of decision to real world, etc. (see Figure 5). Uncertainty can be included at any stage, in the form of a *scenario*. For instance the population model could include various mechanisms for abundance-range size relationships and population parameters could be related to temperature under a climate change scenario.

The objective of running a MSE is to identify a management strategy that performs well across all
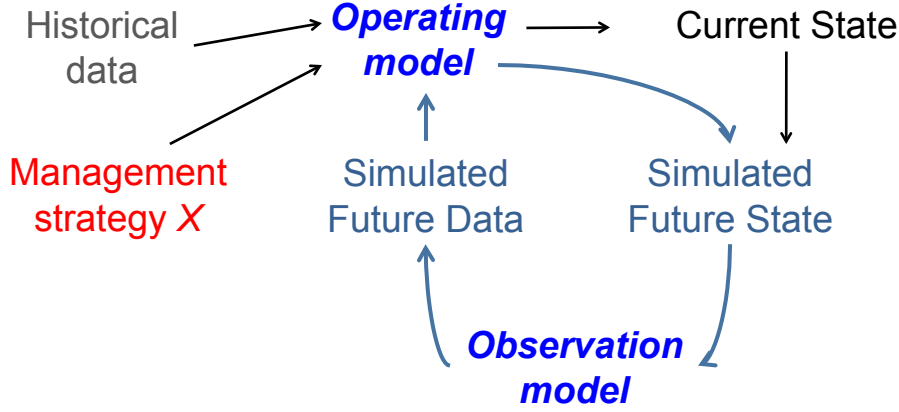
Figure 5: Flow chart of the modelling component of MSEs. The operating model represents population dynamics and is calibrated using historical data to product a prediction of what the current state of the system is. A management strategy is then applied to the system to simulate the state at t + 1. Data is collected from this state (e.g. to mimick a fisheries survey) and may include observation errors. This collected simulated future data is then used in the operating model to predict the state of the system at the next time step. This is repeated over a pre-defined time-frame for each of the candidate management strategies.

scenarios. One of the main advantages is that it requires an explicit formulation of management objectives important to stakeholders, as these are used to evaluate the success of a management strategy. In the present case for instance, the optimal strategy will likely be different based on whether an objective is to maintain high catch rates across the target's species range, since under range contraction this would (presumably) require stock biomass to be kept above B_{MSY}.

The last step of the MSE is to compare the performance of each strategy over time across all scenarios once the MSE has run for all combinations of scenario and management strategies.

4.2 Applying MSE to range contraction in tropical tunas in the Pacific

The main goal of the current MSE is to evaluate the management impacst of uncertainties about the mechanisms underlying range dynamics as well as assess how countries might be affected based on their geographic location. The process will be computationally-intensive so I will focus on a single species. Yellowfin tuna would be a good candidate here since it is an important tropical tuna fishery and my preliminary work indicates that there might be evidence of range contraction.

Scenarios: One of the key challenges in the assessment of range contraction in large pelagics is to untangle the effects of local fishing pressure from potential range-abundance relationships like DDHS. Modelling in Chapter 3 should tell us the key parameters that determine the acting mechanisms and their values could be used to formulate a set of scenarios. These scenarios are especially interesting

from a regional management perspective as they would likely result in different recommendations: in the one instance, abundance at the edges is declining because of high local fishing pressure, and the other instance abundance at the edges is declining because fishing pressure in the core is too high.

Other scenarios of interest include the degree of fish mobility, since there is an ongoing discussion on the consequences of migration of regional fisheries management, and climate change, as tuna distribution is sensitive to the environment and this question as been of interest to member countries.

Operating model: The population model from Chapter 3 would be used as an operating model.

Observation model: A simple model could be used whereby catch-and-effort data is collected and fed back to the stock assessment. It could be interesthing to explore as a scenario the effects of input catch data resolution on the recommended management strategy (e.g. $5 \times 5°$ vs. $1 \times 1°$ data).

Management objectives: The management objectives would be formulated in conjunction with the fisheries staff at the SPC as well as fisheries representatives from some of the countries, but would at least include sustainable exploitation of the stocks and some harvesting objective tied to catch or revenue. There could be some objectives tied to specific area, e.g. keep catch rates at a certain level in edge areas of the range.

Management strategies: Management options would also be formulated in consultation with the SPC and could include both Pacific-wide and region-specific harvest rules. It would also be interesting to include at least one typical "conservation" strategy, e.g. stopping fishing in certain areas/times, given that there has been a lot of high-profile debate about the potential benefits of marine reserves for the management of highly migratory tuna in the Atlantic.

Optional chapter 1: Industrial and artisanal fisheries interactions

One of the main socio-economic consequences of ecology-driven range contraction is that local catch rates could be impacted by fishing fleets far away. This is especially relevant to island nations that rely on pelagic fisheries as an important source of their daily protein intake. Often these countries have important artisanal fleets that provide seafood to the local market. The objective of this chapter would be to develop metrics to assess the interaction between industrial and artisanal fisheries in countries likely to be affected by range contraction.

I would use French Polynesia as a case study as they have fisheries data for their artisanal fleet from 1997 onwards[3]. French Polynesia consists of a set of archipelagos located in the south-east of the Pacific and distant from the core of most tropical tuna species.

Interactions between artisanal and industrial fleets can be direct and indirect. Direct interaction can occur when industrial fleets deplete ressources near islands, or prevent artisanal fishermen from fishing in certain locales. Indirect interactions can occur when industrial fleets deplete the overal stock, resulting in smaller catch rates for highly-mobily species targeted by artisanal fisheries. The former is not a result of range contraction, but is an important way by which island nations are impacted by industrial fishing.

Methods to assess interactions would vary between direct and indirect effects. In the case of direct interactions, an option could be to develop an index of species overlap (since, presumably, the interaction would be highest when targeted species are the same). This could be combined with a proxy for spatial interaction based on the location of industrial fishing effort as a function of its distance to the coast and weighted by the number of people living on the island of interest. To assess indirect interactions, local catch rates could be modelled together with Pacific-wide stock status indices in order to identify which proportion of the variation in local catch rates can be explained by signals from overall stock levels.

Current chapter status: This is a report that I am preparing for the government of French Polynesia (FP) (the project is coordinated by the SPC), to be submitted in the Fall of 2013. I have done a first exploratory trip to FP in March 2013 in which I worked with local fisheries scientists and did an extensive exploration of the artisanal catch dataset. I came back a month later to present a preliminary research strategy for the project to the fisheries department and we agreed on the future analyses suggested above (though there is some flexibility). The planned report adresses a wide array of questions but will likely not go in too much depth due to the short time-frame. The analyses would have the potential to be further developed into a full-fledged chapter, keeping in mind that the topic has to be framed in the context of the overall thesis. I have the permission from the fisheries department in French Polynesia to use this work as a chapter.

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[3]and have agreed to provide access to their dataset

Optional chapter 2: Using occupancy modelling to detect changes in species distribution

Fisheries catch records arguably constitute the most extensive set of occurrence data for marine species in space and time. A common approach in fisheries science is to use the ratio of catch over fishing effort (catch-per-unit-effort, CPUE) as an index of abundance. However, fishing trips can also be seen as monitoring surveys which collect presence data, as the occurrence of a given species in the catch shows that the species was present at that time and location.

Range contraction can be shown by measuring faster decline rates in certain parts of the range than others. Equivalently, a decline in time of the probability for a species to be present in a previously-occupied parts of its range would also indicate range contraction. Methods to detect such a change have been developed extensively in the climate change and exotic species literature, but few have been applied to marine systems (Robinson et al., 2011).

In Chapter 2 I use CPUE data as a proxy for abundance and quantify range contraction in large pelagics at the scale of the Pacific since the 1950s. There are, however, many confounding effects that hinder the use of CPUE data to infer trends in abundance over time. In addition, one of the main issues to resolve is whether contraction is caused by local depletion or ecological population-wide effects like DDHS[4]. The low spatial resolution of the $5 \times 5°$ dataset makes it hard to investigate these hypotheses more closely.

Operational data (fishing records at the scale of individual trips) are available for some regions of the Pacific, in some instances since the 1970s. These trips could be considered like individual surveys, and their catch effectively constitute presence-absence data that can be examined for trends over time. Occupancy modelling is a statistical framework recently developed in conservation science to examine presence data and calculate the probability of an absence being real given repeated surveys (MacKenzie, 2006). One of the advantages of using a presence-absence approach is that trends would be less affected by factors that usually confound CPUE analyses, as we would not be looking at how much of a species is in a given locale, but whether it is present there or not. This method would have to be adjusted to work in a fisheries context, but could provide a novel way to assess range dynamics in fished species and serve to investigate candidate mechanisms for range contraction. In addition, used together with the results of Chapter 2, it would yield more robust estimates of range dynamics in large pelagics in the Pacific.

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[4]Density-dependent habitat selection, defined in Chapter 3, occurs when individuals make choice about the habitat they occupy based on local density of conspecifics and habitat quality.

References

Allain, V., Fernandez, E., Hoyle, S. D., Caillot, S., Jurado-Molina, J., Andrefouet, S., and Nicol, S. J. (2012). Interaction between Coastal and Oceanic Ecosystems of the Western and Central Pacific Ocean through Predator-Prey Relationship Studies. *PLoS One*, 7(5):e36701.

Burgman, M. A. and Fox, J. C. (2003). Bias in species range estimates from minimum convex polygons: implications for conservation and options for improved planning. *Animal Conservation*.

Campbell, R. (2004). CPUE standardisation and the construction of indices of stock abundance in a spatially varying fishery using general linear models. *Fisheries Research*, 70(2-3):209–227.

Carruthers, T. R., Ahrens, R. N. M., McAllister, M. K., and Walters, C. J. (2011). Integrating imputation and standardization of catch rate data in the calculation of relative abundance indices. *Fisheries Research*, 109(1):157–167.

Carruthers, T. R., McAllister, M., and Ahrens, R. (2010). Simulating spatial dynamics to evaluate methods of deriving abundance indices for tropical tunas. *Canadian Journal Of Fisheries And Aquatic Sciences*, 67(9):1409–1427.

Cox, S., Essington, T., Kitchell, J., Martell, S., Walters, C., Boggs, C., and Kaplan, I. (2002). Reconstructing ecosystem dynamics in the central Pacific Ocean, 1952-1998. II. A preliminary assessment of the trophic impacts of fishing and effects on tuna dynamics. *Canadian Journal Of Fisheries And Aquatic Sciences*, 59(11):1736–1747.

Fiedler, P. and Bernard, H. (1987). Tuna aggregation and feeding near fronts observed in satellite imagery. *Continental Shelf Research*, 7(8):871–881.

Gaston, K. J., Blackburn, T. M., Greenwood, J. J. D., Gregory, R. D., Quinn, R. M., and Lawton, J. H. (2000). Abundance-occupancy relationships. *Journal Of Applied Ecology*, 37(s1):39–59.

Harley, S., Myers, R. A., and Dunn, A. (2001). Is catch-per-unit-effort proportional to abundance? *Canadian Journal Of Fisheries And Aquatic Sciences*, 58(9):1760–1772.

Hinke, J., Kaplan, I., Aydin, K., Watters, G., Olson, R., and Kitchell, J. (2004). Visualizing the food-web effects of fishing for tunas in the Pacific Ocean. *Ecology and Society*, 9(1).

Hurlbert, A. H. and Jetz, W. (2007). Species richness, hotspots, and the scale dependence of range maps in ecology and conservation. *Proceedings of the National Academy of Sciences*, 104(33):13384–13389.

Laliberte, A. and Ripple, W. (2004). Range contractions of North American carnivores and ungulates. *Bioscience*, 54(2):123–138.

Lawton, J. H. (1993). Range, population abundance and conservation. *Trends in Ecology and Evolution*, 8(11):409–413.

Lehodey, P., Bertignac, M., Hampton, J., Lewis, A., and Picaut, J. (1997). El Nino Southern Oscillation and tuna in the western Pacific. *Nature*, 389(6652):715–718.

MacCall, A. D. (1990). *Dynamic geography of marine fish populations*. Books in recruitment fishery oceanography. University of Washington Press, Seattle.

MacKenzie, D. I. (2006). *Occupancy estimation and modeling: inferring patterns and dynamics of species occurrence*. Academic Press.

Martell, S. J. D., Schweigert, J. F., Haist, V., and Cleary, J. S. (2012). Moving towards the sustainable fisheries framework for Pacific herring: data, models, and alternative assumptions; Stock Assessment and Management Advice for the British Columbia Pacific Herring Stocks: 2011 Assessment and 2012 Forecasts. *Canadian Science Advisory Secretariat*.

Matthysen, E. (2005). Density-dependent dispersal in birds and mammals. *Ecography*, 28(3):403–416.

Maunder, M. and Punt, A. (2004). Standardizing catch and effort data: a review of recent approaches. *Fisheries Research*, 70(2-3):141–159.

Myers, R. A. and Worm, B. (2003). Rapid worldwide depletion of predatory fish communities. *Nature*, 423(6937):280–283.

Ortiz, M. and Arocha, F. (2004). Alternative error distribution models for standardization of catch rates of non-target species from a pelagic longline fishery: billfish species in the Venezuelan tuna longline fishery. *Fisheries Research*, 70(2-3):275–297.

Punt, A. E. and Donovan, G. P. (2007). Developing management procedures that are robust to uncertainty: lessons from the International Whaling Commission. *ICES Journal of Marine Science*, 64(4):603–612.

Rahbek, C. (2005). The role of spatial scale and the perception of large-scale species-richness patterns. *Ecology Letters*, 8(2):224–239.

Reese, D. C., O'Malley, R. T., Brodeur, R. D., and Churnside, J. H. (2011). Epipelagic fish distributions in relation to thermal fronts in a coastal upwelling system using high-resolution remote-sensing techniques. *ICES Journal of Marine Science*, 68(9):1865–1874.

Reygondeau, G., Maury, O., Beaugrand, G., Fromentin, J.-M., Fonteneau, A., and Cury, P. (2012). Biogeography of tuna and billfish communities. *Journal Of Biogeography*, 39(1):114–129.

Robinson, L., Elith, J., Hobday, A. J., Pearson, R. G., Kendall, B. E., Possingham, H. P., and Richardson, A. J. (2011). Pushing the limits in marine species distribution modelling: lessons from the land present challenges and opportunities. *Global Ecology and Biogeography*, 20:789–802.

Rose, G. and Kulka, D. (1999). Hyperaggregation of fish and fisheries: how catch-per-unit-effort increased as the northern cod (Gadus morhua) declined. *Canadian Journal Of Fisheries And Aquatic Sciences*, 56:118–127.

Schaefer, K. and Fuller, D. (2009). Vertical movements and habitat utilization of skipjack (Katsuwonus pelamis), yellowfin (Thunnus albacares), and bigeye (Thunnus obesus) tunas in the Equatorial Eastern Pacific Ocean, ascertained through archival tag data. In Nielsen, J., Arrizabalaga, H., Fragoso, N., Hobday, A. J., and Lutcavage, M., editors, *Tagging and Tracking of Marine Animals with Electronic Devices*. Springer.

Shepherd, T. and Litvak, M. (2004). Density-dependent habitat selection and the ideal free distribution in marine fish spatial dynamics: considerations and cautions. *Fish and Fisheries*, 5(2):141–152.

Sibert, J. and Hampton, J. (2003). Mobility of tropical tunas and the implications for fisheries management. *MARINE POLICY*, 27(1):87–95.

Sibert, J., Hampton, J., Kleiber, P., and Maunder, M. (2006). Biomass, size, and trophic status of top predators in the Pacific Ocean. *Science*, 314(5806):1773–1776.

Swain, D. P. and Sinclair, A. F. (1994). Fish distribution and catchability: What is the appropriate measure of distribution? *Canadian Journal Of Fisheries And Aquatic Sciences*, 51(5):1046–1054.

Tyberghein, L., Verbruggen, H., Pauly, K., Troupin, C., Mineur, F., and De Clerck, O. (2012). Bio-ORACLE: a global environmental dataset for marine species distribution modelling. *Global Ecology and Biogeography*, 21(2):272–281.

Walters, C. (2003). Folly and fantasy in the analysis of spatial catch rate data. *Canadian Journal Of Fisheries And Aquatic Sciences*, 60(12):1433–1436.

Ward, P. and Myers, R. A. (2005). Inferring the depth distribution of catchability for pelagic fishes and correcting for variations in the depth of longline fishing gear. *Canadian Journal Of Fisheries And Aquatic Sciences*, 62(5):1130–1142.

Williams, P. and Terawasi, P. (2012). Overview of tuna fisheries in the Western and Central Pacific ocean, including economic conditions – 2011. *WCPFC-Scientific Committee*.

Winters, G. H. and Wheeler, J. P. (1985). Interaction Between Stock Area, Stock Abundance, and Catchability Coefficient. *Canadian Journal Of Fisheries And Aquatic Sciences*, 42(5):989–998.

Worm, B. and Tittensor, D. P. (2011). Range contraction in large pelagic predators. *Proceedings of the National Academy of Sciences*, 108(29):11942–11947.

Young, J., Lansdell, M., Campbell, R., and Cooper, S. (2010). Feeding ecology and niche segregation in oceanic top predators off eastern Australia. *Marine Biology*, 157(11):2347–2368.