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Understanding fleet behaviour to reduce uncertainty in tuna fisheries management

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Declaration of originality

This dissertation is the result of my own work and includes nothing which is the outcome of work done by or in collaboration with others, except where specifically indicated in the text.

Tim Davies, April 2014

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Abstract

The behaviour of a fishing fleet is a critical, but all too often overlooked, uncertainty in the implementation of fisheries management. Unexpected responses by fishers to management controls, such as effort restrictions or spatial closures, can result in unintended and potentially undesirable outcomes. Whilst this uncertainty can be reduced by anticipating the behavioural response of a fishing fleet, it is first necessary to understand the characteristics and drivers of fleet behaviour. The aim of this thesis was to address gaps in knowledge of the behaviour of offshore tuna fleets, using the Indian Ocean tropical tuna purse seine fishery as a case study example.

I used statistical modelling to examine the factors that influence the spatial behaviour of the purse seine fleet at broad spatiotemporal scales. This analysis revealed consistency in the use of seasonal fishing grounds by the fleet, as well as a forcing influence of biophysical ocean conditions on the allocation of effort. These findings, which suggested strong inertia in fleet spatial behaviour, have important implications for predicting the response of the fleet to certain natural events or management measures (e.g. spatial closures).

To better understand the impact of spatial closures on purse seine fleet dynamics, I used the statistical model of fleet behaviour to isolate the policy effect of two recent closures on fleet behaviour. By comparing the observed behaviour of the fleet against a model-generated counterfactual scenario I revealed, in the case of one of the closures, a policy effect that was inconsistent between years, and that the absence of fishing effort in the closed area was explained primarily by biophysical ocean conditions. These findings demonstrate the importance of using a counterfactual approach to evaluate spatial closures in open ocean systems where fleet behaviour is influenced by highly variable biophysical conditions.

Fish aggregating devices (FADs) have become a dominant fishing practice in tuna purse seine fisheries worldwide, and I examined the influence of the use of FADs on purse seine fleet dynamics in the Indian Ocean. I reviewed historical catch trends and spatiotemporal patterns of fleet behaviour and linked this to the use of FADs. I also reviewed the existing management of FAD-fishing and speculated at the influence of possible future management measures on the behaviour of the fleet.

Finally, I used a scenario planning approach to think about how the main drivers of purse seine fleet behaviour might change in the future, and how this might affect fleet dynamics. This analysis served to highlight aspects of purse seine fleet behaviour that should be a priority consideration of tuna fishery managers and policy makers.

This thesis showed fleet behaviour to be a dynamic aspect of tuna fisheries management, and stressed the importance of anticipating the response of fleets to management measures in order to avoid unintentional outcomes. The understanding of purse seine fleet behaviour developed throughout this thesis provides a good basis for building the anticipation of fleet behaviour into existing management tools and processes.

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He who hurries stubs his toe.

A Swahili proverb.

Abbreviations and acronyms

AIC	Akaike information criterion
AUC	Receiver operating characteristic area under curve
BIOT	British Indian Ocean Territory
CMM	Conservation and management measure
EU	European Union
FAD	Fish aggregating device
FAO	United Nations Food and Agriculture Organisation
FCO	UK Foreign and Commonwealth Office
FOB	Floating object
FPA	EU fisheries partnership agreement
FSC	Free school
GAM	Generalised additive model
IFD	Ideal Free Distribution
IOTC	Indian Ocean Tuna Commission
ISSF	International Seafood Sustainability Foundation
MPA	Marine protected area
MSC	Marine Stewardship Council
MSE	Management Strategy Evaluation
NATO	North Atlantic Treaty Organisation
RFMO	Regional Fisheries Management Organisation
RUM	Random utility model
SC	Science committee
SES	Socio-ecological system
SFA	Seychelles Fishing Authority
SLA	Sea level anomaly
SRS	Satellite remote sensing
SSC	Sea surface chlorophyll-a
SST	Sea surface temperature

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Chapter 1

1 Introduction

1.1 Background

The poor state of the world's fisheries has been the focus of scientific and public debate for at least two decades (McGoodwin 1995; Pauly et al. 1998; Hutchings 2000; Myers and Worm 2003; Essington et al. 2006; Grafton et al. 2008). The United Nations Food and Agriculture Organisation (FAO), which monitors the state of world fisheries, has estimated that since 1990 roughly one-quarter of fish stocks have been overexploited, depleted or are in the process of recovering from overfishing (FAO 2010). The situation is particularly grim in certain regions (e.g. northeast and northwest Atlantic, Mediterranean, Black Sea; Garcia and Grainger 2005), and for shared stocks and those on the high seas (Lodge 2007). In addition to the undesirable ecological and economic consequences of overfishing the sustainability of fisheries production has important implications for global food security, with fish and shellfish constituting the primary source of protein for an estimated 950 million people worldwide (Porter 2001).

In seeking sustainability, fishery managers are constantly confronted with the challenges of uncertainty, and management outcomes can be influenced by factors that are overlooked or difficult to account for (Hilborn and Walters 1992; Harwood and Stokes 2003; Beddington et al. 2007; Holland and Herrera 2009; Fulton et al. 2011). For example, variability in ecosystem dynamics, mistakes and omission in the collection and interpretation of fisheries data, and errors in stock assessment models can undermine the scientific advice that underpins management decisions (Mace

1997; Abella et al. 2008; Agnew et al. 2009). Even where scientific advice is sound, ineffectual implementation and enforcement of management controls, and unexpected behaviour of resource users, can result in management outcomes that deviate from those originally intended (Dinmore et al. 2003; Dichmont et al. 2006). Failing to acknowledge and account for these uncertainties in the design and implementation of interventions can fatally undermine the outcomes of management (Punt and Donovan 2007; Hilborn et al. 2007).

Fishers are the key linkage between policymakers and the resource, and the outcomes of management are contingent on their behaviour. As the purpose of fishery management is to regulate and control fishing activities, it should not be unexpected that fishers respond to protect their livelihoods, including in ways that result in undesirable management outcomes (Salas and Gaertner 2004; Fulton et al. 2011). For example, where fishing seasons have been implemented as a means to restrict fishing effort, fishers have responded by intensifying effort, such as by investing in larger vessels or more sophisticated fishing technologies. At the extreme this can lead to situations such as the Bristol Bay red king crab, where although the fishing season was reduced to just four days, total catch exceeded pre-season guidelines by 65% (Briand et al. 2004). In some cases the unexpected behaviour of fishers can create entirely new management problems. For instance, spatial closures (e.g. marine reserves) are often used as a means to protect vulnerable species or areas of sensitive habitat, but a consequence of closing an area to fishing is that effort is reallocated into other areas, which may simply displace the problem elsewhere (Dinmore et al. 2003; Hilborn et al. 2004).

The challenges of uncertainty are well recognised by fishery scientists and managers and much work has been directed at reducing them, although not all sources of uncertainty have received the same level of attention by scientists. In particular, considerable research has been directed at reducing and accounting for uncertainty in the resource assessment half of the management cycle, mainly through better scientific understanding of resource dynamics and improvements to stock assessment models (Kirkwood and Smith 1996; Beddington et al. 2007). However, far less attention has been directed at reducing uncertainty in implementation half of the management cycle (Fulton et al. 2011).

1.2 Research context, aim and objectives

Fisheries for tropical and temperate tunas operate on an industrial scale in the Indian, Atlantic and Pacific Oceans, landing more than 4.2 million tonnes in 2011. Of the 23 commercially exploited tuna stocks worldwide, 9 are currently considered to be in an overfished state (ISSF 2013). Overcapacity in tuna fleets, both in terms of the number of vessels and their ability to catch and store fish, is a serious concern in the conservation and management of tuna stocks, resulting in overfishing and significant economic waste (Joseph et al. 2010). Tuna fishing also has negative ecosystem impacts, primarily bycatch of vulnerable species including sharks, cetaceans and seabirds (Amandè et al. 2008, 2010; Gilman 2011). These concerns over sustainability and impact have prompted a critical look at the way in which tuna fisheries exploit the resource, in particular the techniques used and the design of fishing gears employed to catch tunas (Gilman et al. 2005; Dagorn et al. 2012b). There has also been increasing scrutiny of how fisheries are managed, with many tuna RFMOs criticised for a notable absence of 'modern' philosophies such as the precautionary and ecosystem-based approaches to management (Grafton et al. 2006; Cullis-Suzuki and Pauly 2010).

An important factor in the success or failure of tuna fisheries management is the behaviour of fishers and fishing fleets, yet to date there has been little research directed at understanding and anticipating the human dimension of tuna fisheries. As a result, there are many uncertainties that have the potential to undermine management. For instance, how will fleets respond to the implementation of management measures, such as spatial closures, catch limits or gear restrictions, and how will these responses affect management outcomes? Also, how might the fleet respond to change in other environmental, social, economic and political components of the fishery system, and what might the implications of this change be?

It is a tenet of this thesis that the management of tuna fisheries would be strengthened with an improved understanding of fleet behaviour. This would reduce uncertainty in the response of tuna fleets to management, in particular helping to better anticipate the possible consequences of management controls, and also to undertake more accurate retrospective evaluations of policy effects. Hence, the aim of this thesis is to improve understanding of the behaviour of tuna fleets. This aim is approached i) by developing a better understanding of the characteristics and drivers of fleet behaviour; and ii) by stimulating thinking on the future behaviour of tuna fleets, and the consequences for fishery management of possible behavioural responses.

The Indian Ocean tuna purse seine fleet is used as a case study example throughout this thesis. Although a wide range of fleet behaviours are potentially of interest to fishery managers, this work focuses primarily on two behaviours that are of relevance to contemporary issues in tuna fishery management; the allocation of fishing effort in space, in the context of area closures and marine reserves, and the use of fish aggregating devices (FADs), in the context of concerns over the fishery and ecosystem impacts of this fishing practice.

Specific objectives that contribute to the aim of this thesis include:

- To identify key drivers of the spatial behaviour of the purse seine fleet
- To examine the behavioural response of the fleet to existing spatial closures
- To examine the influence of fish aggregating devices (FADs) on fleet behaviour
- To stimulate thinking on possible behavioural responses of the fleet to social, economic, geo-political and management change

1.3 Thesis outline

The thesis is structured into the following chapters:

Chapter 2: Research background and case study description

In Chapter 2 I provide a background to the thesis. I review literature on fisher behaviour to describe strategies and tactics of fishers, explore the objectives and priorities underpinning decision making, and provide discussion on conceptual models of fisher behaviour. I also introduce the case study fishery, and describe the tools, techniques and fishing practices used by purse seine skippers to search for tunas, based on interviews undertaken during fieldwork in Victoria, Seychelles. This practical knowledge of the short term behaviour of skippers underpins analysis and interpretation of broader scale fleet behaviour throughout the rest of the thesis.

Chapter 3: The past, present and future use of drifting fish aggregating devices (FADs) in the Indian Ocean

In Chapter 5 I characterise the past and present use of FADs in the Indian Ocean tuna purse seine fishery, including historical trends in fishing practices and spatiotemporal patterns in the use of FADs. I also provide an overview of current FAD management policies in the Indian Ocean and examine the observed effects of existing FAD management measures on the fishing behavior of the purse seine fleet. Finally, I discuss the potential impact of a number of plausible FAD management options on the behaviour of the fleet and draw inferences for the future sustainability of tropical tuna purse seine fishing in the Indian Ocean.

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Chapter 4: Modelling the spatial behaviour of a tropical tuna purse seine fleet

In Chapter 3 I model the spatial behaviour of the Indian Ocean tuna purse seine fleet. I use statistical modelling to examine the factors that influence the spatial behaviour of the purse seine fleet at broad spatiotemporal scales. This analysis reveals consistency in the use of seasonal fishing grounds by the fleet, as well as a forcing g influence of biophysical ocean conditions on the distribution of fishing effort. These findings suggest strong inertia in the spatial behaviour of the fleet, which has important implications for predicting the response of the fleet to natural events or management measures (e.g. spatial closures).

Chapter 5: Examining the impact of area closures on the behaviour of a tropical tuna purse seine fleet

In Chapter 4 I examine the response of the Indian Ocean purse seine fleet to two existing spatial closures: a management time-area closure and a large marine reserve. I use the model of fleet behaviour developed in Chapter 3 to build a counterfactual scenario and disentangle the policy effects of the closures from other competing influences on the allocation of effort. By comparing the observed behaviour of the fleet against a counterfactual scenario I reveal, in the case of one of the closures, a policy effect that was inconsistent between years, and that the absence of fishing effort is explained instead by biophysical ocean conditions. These findings demonstrate the importance of using a counterfactual approach to evaluate spatial closures in open ocean systems, where fleet behaviour is influenced by highly variable biophysical conditions.

Chapter 6: Second guessing uncertainty: scenario planning for management in the Indian Ocean tuna purse seine fishery

In Chapter 6 I use scenario planning to explore uncertainties in the future of the Indian Ocean tuna purse seine fishery. This chapter stimulates thinking on how the key social, economic and environmental conditions that influence fleet behaviour may change in the future, and how these changes might affect the dynamics of fishing effort. Comparing across several possible future scenarios, I identify a number of key aspects of fleet behaviour that should be important considerations for policymakers, but which are currently poorly understood.

Chapter 7: Discussion

This chapter offers a general discussion of the main findings of this thesis and suggests how the knowledge generated on fleet behaviour can be incorporated to improve tuna fisheries management.

Chapter 2

2 Research background and case study

2.1 Literature review

2.1.1 Introduction

In the context of fisheries management, arguably more research has been directed at improving stock assessment models and methods than in understanding fishing fleet dynamics. This is despite a wide recognition that an understanding of fleet dynamics and the behaviour of fishers is critical to success in fisheries management (Wilen 1979; Fulton et al. 2011). Nevertheless, over the past thirty years research into fleet behaviour has become an increasingly important area of study. Early interest in fleet dynamics was focussed on how changes in patterns and intensity of fishing activity influenced the relationship between catch and effort, as managers needed this understanding in order to interpret accurately trends in management indicators such as catch per unit effort (Hilborn 1985). Since then, a vibrant literature has emerged that aims to explain and predict fleet behaviour, with contributions from economics, anthropology, social psychology and the natural sciences (Branch et al. 2006; van Putten et al. 2011).

Broadly defined, fleet dynamics are changes in the fishing capacity and fishing activities of groups of vessels, including fishing intensity and the allocation of effort in space and time (Hilborn 1985). Fleet dynamics are driven by the choices of decision units, usually referred to as ‘fishers’ in the literature. However, the choice of where, when and what to fish can be made by a wider range of actors than individual fishers, including fishing firms managing a fleet of vessels, a collection of firms within a producer organisation acting as a coherent group, or even by countries competing for a share of a fish stock. In this way, fleet dynamics are the result of both long- and short-term decision processes, including the tactics of fishers, investment by fishing firms and national policy (Hutton et al. 2004; Tidd et al. 2011, 2012).

2.1.2 Strategies and tactics of fishers

The behaviour of fishers is governed by strategies and tactics. These terms have been discussed in the literature using several definitions, but here tactics are defined as short term actions designed to meet an immediate challenge, whereas strategies are behaviours planned in advance to achieve long term goals. Tactics can determine the way a fisher operates a vessel or uses a fishing gear, and whilst some tactics may be deliberately performed in succession to enact a strategy, others may be an immediate reaction to current events. Strategies on the other hand generally do not define a specific action, but instead dictate the manner in which a fisher behaves in the long term (Salas and Gaertner 2004; Branch et al. 2006). Fishing strategies ultimately emerge from a decision making process that considers a wide range of factors that may affect the ability to achieve a particular objective in their social, economic and political context (Béné 1996). Hence, strategies are not necessarily fixed and can be abandoned or modified as objectives are achieved or the context of decision making changes (Brown 1995).

An example of a strategy commonly used by fishers to maximise certain economic objectives, for example revenue per unit effort, is specialisation (Smith and McKelvey 1986). Specialised fishing technologies or practices can emerge as fishers seek to continually refine their approach and improve their catches. For instance, tuna purse seine fishers have learnt to exploit the natural association of tuna schools with floating debris by constructing artificial rafts, known as fish aggregating devices (FADs), in an attempt to create additional fishing opportunities and reduce time spent searching (Hall 1992). Specialist strategies that increase catch rates or facilitate the exploitation of a difficult-to-catch but valuable species can be highly profitable, although the level of investment required to operate in a singular way can carry high economic risk. In contrast, fishers that employ a generalist approach use less specialised technologies and consequently may be able to switch more easily between target species, or even engage in activities unrelated to fishing, such as tourism (Hilborn et al. 2001). For example, many small scale coastal fisheries in UK target a suite of species using generic trawl gear, and fishers can focus on catching one or another species fish depending on relative abundance or the amount of their quota allocation remaining (Tidd et al. 2011). Although revenues may not be as high as for the specialist fisher, generalist strategies provide fishers with more flexibility to change in the fishery, such as variability in catches or the implementation of restrictive management controls (Salas and Gaertner 2004; Branch et al. 2006).

Cooperation between fishers is another common strategy for reducing variability in catches, and for minimising competitive conflicts with others (Eales and Wilen 1986; Gaertner et al. 1996; Begossi 1996). Catch variability is often related to uncertainty in the distribution of the resource, and one of the ways to reduce uncertainty is through information exchange. The existence of teams or 'code groups' is well known in some fisheries, and cooperation between fishers is especially important in fisheries targeting a highly mobile but aggregated resource, such as sardine and tuna, where search costs are high and the benefit of sharing information outweighs the cost of competition (Gaertner and Pallares 2002). Catch sharing is another form of cooperation that can reduce variability in catches and allow fishers to operate in highly uncertain environments. For example, winter storms generate high variability in catches in Dzilam Bravo, Mexico, and fishers compensate for losses during this part of the year by sharing catch with others, ensuring a minimum catch for each fisher (Salas 2000). Similarly, in quota-regulated fisheries, where catch allowances are perceived to be small, quota-pooling strategies may develop between some fishers as they attempt to maintain a profitable level of catch (Hilborn et al. 2001). The rules of cooperation and the structure of information sharing networks are defined by social norms, kinship and friendships, although unfamiliar fishers allied by company ties may also be encouraged to work cooperatively if gains can be made (Salas and Gaertner 2004; Gezelius 2007).

2.1.3 Priorities, objectives and maximisation

Commercial fishing is fundamentally an economic activity and it is often assumed that fishers prioritise economic goals over any others (Hilborn and Ledbetter 1979; Branch et al. 2006; van Putten et al. 2011). Profit maximising behaviour does not necessarily mean that the observed activity of a fisher is truly optimal, but rather that fishers adopt strategies that will increase their profitability. For example, fishers may be expected to switch between target species if the perceived benefits exceed the opportunity and actual costs associated with doing so. Robinson and Pascoe (1997) explored the motivations of fishers in an English beam trawl fleet and found decision making was consistent with profit maximising behaviour, even though the fishers themselves did not admit this directly. Similarly, Pascoe and Tingley (2006) found that most fishers in the Scottish beam trawl fleet balanced marginal revenue and cost, which is consistent with profit maximisation. Moreover, the assumption of profit maximising behaviour does not exclude the influence of other social constraints, such as leisure time or social standing (Roy 1998; Andersen et al. 2011), but assumes maximisation within these constraints.

Nevertheless, whilst financial objectives are no doubt important in most commercial situations, not all fishers may be inclined to maximise their profits (Abernethy et al. 2007; Holland 2008). Christensen and Raajjaer (2006) illustrate the diversity of fishing behaviours and the mixed desire to maximise profits in a case study of Danish demersal fisheries. Less than 10 per cent of fishers adopted profit maximisation strategies, and those that did generally owned larger vessels and invested in the newest technology to fish 24 hours a day. A second fishing strategy, used by just under half of skippers, was to minimise costs. These individuals, who came from established fishing families and did not want to accumulate debt like previous generations, avoided financial risk, accepted lower returns and often had alternative forms of income. A third strategy was to specialise in one preferred fishing method, despite potentially more lucrative alternatives. These fishers also tended to be risk averse and invested carefully, and depended on information sharing within a close network of peers to maintain an income. These last two strategies demonstrate satisficing behaviour, which is a decision making strategy that does not involve maximisation of any goal; rather than strive to maximise their output, fishers may be satisfied with meeting the costs of maintaining a constant catch rate.

Clearly, social norms and well as financial incentives are important in the development of objectives (Vignaux 1996; Salas et al. 2004; Christensen and Raakjær 2006). Decision making may be further influenced by the characteristics of a fishing vessel, which can encourage or rule out certain strategies. For example, in the

Venezuelan tuna fishery, the largest and fastest purse seiners target high value adult yellowfin tuna offshore in the eastern Pacific, and only move into the Caribbean seasonally where they fish on lower value mixed species schools. In contrast, older and slower vessels are confined to the Caribbean all year as they require and association with other vessels using pole-and-line methods to increase the probability of a successful purse seine set (Gaertner et al. 1996). These limitations on decision making may not be entirely uncontrollable, as an individual's experience can often determine the resources available to them. For instance, in some fisheries the most successful individuals are paired with newest or best equipped vessels in order to maximise to their competitive potential (Gaertner et al. 1996).

2.1.4 Conceptual models of fleet behavior

Fishing involves choosing between alternative options, whether it be to target a particular species or to fish in a certain location, and considerable attention has been directed at explaining and predicting this decision making. These conceptual models of fisher behaviour can be broadly categorised into two groups: those which draw on theory from the natural sciences and search for clues to the drivers of behaviour in observed patterns of fishing activity; and those which draw on micro-economic theory and seek to explain how individuals develop the expectations that influence their behaviour.

Foraging theory

Foraging theory was first developed in the behavioural ecology literature, where it was used to describe the foraging behaviour of organisms (MacArthur and Pianka 1966). The theory asserts that organisms behave in such a way as to maximise their energy intake with minimal energy cost. Hence, the theory is easily transferred into a fisheries context, where fishers may be viewed as foragers making decisions to maximise their intake (e.g. catch or revenue) at minimal cost (Hilborn and Kennedy 1992). Foraging theory provides the foundation for the Ideal Free Distribution (IFD), which predicts the relationship between predators (fishers) and a resource in the environment (Fretwell and Lucas 1969). In the context of fisher behaviour, the IFD postulates the null hypothesis that fishers will allocate effort to the most profitable fishing grounds as determined on the basis of their knowledge of resource abundance in different areas and costs of accessing them, including the level of competition from other vessels. If these assumptions are met, eventually the distribution of fishing effort will be proportional to resource abundance and profit rates will be equalised between vessels (Gillis et al. 1993; Gillis 2003).

The IFD uses just a few simple rules to explain the behaviour of fishers, yet the equilibrium predicted by the IFD has been observed in empirical patterns of fishing effort. For instance, Hilborn and Ledbetter (1979) identified this behaviour in their early work on the Canadian salmon purse seine fleet, showing that when salmon abundance increased in one location, fishers responded quickly to the expected increase in catch rate and moved into that area until catch rate per vessel again equalised across all areas. Similar patterns of behaviour have been found in several other fisheries (Abrahams and Healy 1990; Gillis et al. 1993, 1998; Rijnsdorp et al. 2000; Swain and Wade 2003; Vogues et al. 2005; Powers and Abeare 2009), lending support to the idea that fishers will choose to fish in areas where they expect to achieve the greatest catch rate or the highest profit.

Nevertheless, the assumptions of the IFD are unrealistic in most situations, particularly when financial factors are less important in decision making (Edwards-

Jones 2006). In a demonstration of this, Abernethy et al (2007) used IFD theory to explore the mechanisms underlying site selection in an artisanal reef fishery, finding that patterns of effort were not proportional to estimated resource abundance and thus that the IFD did not hold true. This contradiction of IFD theory was attributed to key assumptions not being met. Firstly, fishers appeared to have only limited knowledge of the resource abundance in different fishing grounds and could not necessarily choose to fish in most productive area on this basis. Secondly, not all fishers were considered to be profit maximisers and while some did attempt to maximise economic goals where possible, others instead prioritised lifestyle objectives, such as maximising their leisure time. Finally, some fishers not prepared to attempt certain risky fishing activities, for example fishing at night, which resulted in variation in the ability and freedom of movement of individual fishers.

Expected utility theory

The most common approach to studying the decision making of fishers is based on micro-economic theory, and assumes that fishers are analogous with firms. The theory asserts that firms (fishers) act so as to maximise profit, broadly defined as the difference between revenue and costs, and that micro-economic decision making is driven by expectations of the costs and revenues associated with alternative choices. In fisheries, empirical applications of this theory have mainly sought to explain how fishers develop expectations associated with different choices, and how these expectations subsequently influence their behaviour.

Whilst these questions have been explored using a wide range of approaches, discreet choice models, sometimes called random utility models (RUMs), have proven to be very popular in studies of fisher behaviour (Bockstael and Opaluch 1983; Eales and

Wilen 1986; Holland and Sutinen 1999, 2000; Wilen et al. 2002; Hutton et al. 2004; Pradhan and Leung 2004; Marchal et al. 2009; Tidd et al. 2011). RUMs model the probability of an individual making a particular choice from amongst a set of alternatives, where the characteristic of each choice is described by a number of variables. These can describe not only the choice being made, but also the individual decision maker, thus offering insight into which type of individuals make which type of choice. This flexibility offered by RUMs has allowed researchers to construct more realistic models of behaviour than those based on the IFD, which include social as well as financial influences on decision making. However, in practice RUMs require a limited and clearly defined choice set in order for the model algorithms to converge, which can limit their usefulness in situations characterised by a wide range of similar but nevertheless distinct choices (e.g. choice of fishing location in the open ocean; see Chapter 3). Furthermore, despite the relative creativity offered by RUMs in terms of how decision making can be modelled, economic variables describing expected revenue or profitability have dominated and normative influences have been side-lined (Table 2.1). This is in part due to the reliance of RUMs on quantitative datasets, which can be problematic when dealing with predominantly qualitative social or normative influences, but also due to the inherent bias by researchers towards an economic perspective (Jentoft 2006).

Table 2.1 Factors identified as important in influencing fisher decision making with respect to the allocation of effort, including choice of fishing location, target species or fishing gear. Factors are grouped into four influence themes and for each theme the number of references that found a factor to be significant or important is given. The references are grouped into three methodological approaches (IFD, RUMs and other approaches).

Factors influencing decision making	Ideal free distribution (IFD)	Random utility models (RUM)	Other statistical methods and social surveys
Profitability	10	19	10
Expected catch or profit at location; expected catch or value per unit effort; species price	Hilborn and Ledbetter 1979; Abrahams and Healey 1990; Begossi 1992; Gillis et al. 1993 1998; Vignaux 1996 Rijnsdorp et al. 2000; Swain and Wade 2003; Vogues et al. 2005; Powers and Abeare 2009	Eales and Wilen 1986; Dupont 1993; Dorn 1997; Campbell and Hand 1999; Holland and Sutinen 1999; Curtis and Hicks 2000 Curtis and McConnell 2004; Mistiaen and Strand 2000; Smith 2002; Hutton et al. 2004; Pradhan and Leung 2004; Strand 2004; Smith 2005; Anderson and Christensen 2006; Berman 2007; Smith and Zhang 2007; Prellezo et al. 2009; Valcic 2009; Venables et al 2009; Tidd et al. 2012)	Durrenberger and Palsson 1986; Lane 1989; Béné 1996; Robinson and Pascoe 1999; 2001; Béné and Tewfik 2001; Bertrand et al. 2004; Murawski et al. 2005; Christensen and Raakjaer 2006; Guillotreau et al. 2011; Wise et al. 2012
Risk	5	15	7
Uncertainty of revenue at location; habits/inertia to change; fishing activity of others; recent catches	Hilborn and Ledbetter 1979; Rijnsdorp et al. 2000; Swain and Wade 2003; Powers and Abeare 2009; Abernethy et al. 2007	Eales and Wilen 1986; Dupont 1993; Campbell and Hand; 1999; Holland and Suitinen 1999; Curtis and Hicks 2000 Curtis and McConnell 2004; Mistiaen and Strand 2000; Smith 2002; Smith 2005; Anderson and Christensen 2006; Berman 2007; Smith and Zhang 2007; Prellezo et al. 2009; Valcic 2009	Allen and McGlade 1986; Durrenberger and Palsson 1986; Béné 1996; van Oostenbrugge et al. 2001; Murawski et al. 2005; Christensen and Raakjaer 2006; Guillotreau et al. 2011)
Information/knowledge	4	6	7
Presence of other vessels; knowledge gained from other fishers; stock status	Dorn 1997; Vignaux 1996; Begossi 1992; Abernethy et al. 2007	Holland and Suitinen 1999; Campbell and Hand 1999; Curtis and Hicks 2000 Curtis and McConnell 2004; Pradhan and Leung 2004; Anderson and Christensen 2006	Allen and McGlade 1986; Durrenberger and Palsson 1986; Robinson and Pascoe 1999; van Oostenbrugge et al. 2001; Christensen and Raakjaer 2006; Guillotreau et al. 2011; Wise et al. 2012
Characteristics of the decision maker	2	4	7
Skipper ability/ experience/ preference; vessel age/ power	Abrahams and Healey 1990; Rijnsdorp et al. 2000	Mistiaen and Strand 2000; Pradhan and Leung 2004; Smith and Zhang 2007; Prellezo et al 2009; Tidd et al. 2012	Gatewood 1984; Durrenberger and Palsson 1986; Gaertner et al. 1996; van Oostenbrugge et al. 2001; Murawski et al. 2005; Christensen and Raakjaer 2006; Guillotreau et al. 2011

2.1.5 Limitations of fleet behaviour research

Although the study of fleet behaviour has become a major strand of research in the fisheries sciences, some authors have expressed concern over the general perspective taken to investigate decision making. In a recent review of the drivers underlying models of fisher decision making, van Putten et al. (2011) argue that models based on standard models of economic production alone tend to produce unrealistic and potentially unreliable predictions of fishing effort dynamics. This is largely because many fishers may choose to balance profitability against normative priorities, meaning that their behaviour is often inconsistent with predictions based on economic theory (Abernethy et al. 2007; Holland 2008). The importance of non-monetary drivers on fisher decision making, including lifestyle preferences, social circumstance and cultural influences, is well known from the behavioural sciences (e.g. Gatewood 1984; Durrenberger and Palsson 1986; Béné 1996; van Oostenbrugge et al. 2001; Christensen and Raakjaer 2006; Guillotreau et al. 2011), yet there appears to be a general reluctance in the fisheries sciences to move beyond classical economic models of behaviour (van Putten et al. 2011).

There are several explanations for the blinkered focus on economics in fishery science, including the educational background of scientists themselves. The traditional focus in fisheries has been on quantitative interrogation of data, with methods originating from the economic or ecological disciplines, rather than practical insight generated by social scientists (Jentoft 2006). Buanes and Jentoft (2009) argue that an interdisciplinary approach is vital in modern science, but the goal of achieving meaningful collaboration between disciplines is hindered by a tangle of structural, cultural and cognitive barriers. The language spoken by scientists in one discipline often appears incompatible to that spoken in another, and social scientists in particular are often accused of being ‘fuzzy’ and their work inaccessible. This difficulty in communication is often attributed to real (or perceived) methodological differences between the quantitative and qualitative sciences, which creates a negative perception of the usefulness of information generated in other scientific disciplines (Symes and Hoefnagel 2010; Pooley 2013).

Relating the study of fleet dynamics back to fishery management, in order to confront implementation uncertainty effectively, managers need to widen their understanding of fisher behaviour beyond the mainly economic objectives that have been considered to date. Whilst this does not demand a paradigm shift as such, it does require that the scientists responsible for providing advice to managers improve communication between disciplines and revise or combine methodological approaches. Fulton et al. (2011) argue that these changes are in fact a precondition to successfully developing the effective management controls that have been deemed necessary in bring about recovery in global fish stocks (see Worm et al. 2009), and that the benefits of this richer understanding of fisher behaviour will be realised through better anticipation of the consequences of management on fishing fleets and improved design of fishery management systems that are more robust to uncertainty in resource user behaviour.

2.2 Case study: tuna purse seine fishing in the western Indian Ocean

2.2.1 Historical and geographical context

Industrialised purse seine fishing for tropical tuna – skipjack *Katsuwonus pelamis*, yellowfin *Thunnus albacares*, and bigeye tuna *T. obesus* – in the Atlantic and Indian Oceans has long been a European-dominated venture. In the late 1960s, French and Spanish tuna fishing firms began to convert their vessels from pole-and-liners into mechanised purse seiners. These gear changes led to substantial advances in productivity, and during the 1960s firms invested in new, purpose-built industrial purse seiners. This class of vessel, which remains amongst the largest and most expensive in the world, offered up to 5 times the carrying capacity of the pole-and-liners (Gallick 1984), and began a new era of tuna fishing. At the same time, French and Spanish cannery owners were funding exploratory fishing in the eastern tropical Atlantic, and throughout the 1960s there was a shift in the fishing grounds of the European-owned purse seine fleet from the Bay of Biscay to the 'new commodity frontier' in the eastern Atlantic (Campling 2012). However, by the early 1970s, less than 20 years after the discovery of the eastern Atlantic tuna grounds, annual purse seine catches peaked at 70-80,000 t and production flattened out as heavy fishing pressure began to deplete tuna stocks (Miyake et al. 2004). A decline in the relative productivity of the fishery was evident in the reduction of daily catch per unit effort, and, wanting to maintain their economic growth, French and Spanish firms looked for new fishing grounds elsewhere.

In the early 1980s, French firms identified the western Indian Ocean as a new (and probably the last) tuna commodity frontier (Campling 2012). Exploratory fishing in the region showed high catch rates for both yellowfin and skipjack tunas (Miyake et al. 2004), and unlike in the eastern Atlantic, higher-value yellowfin made up the greater proportion of the catch (Joseph 2005). French and later Spanish firms began to operate commercially in the western Indian Ocean from the mid 1980s, based our of port Victoria, Seychelles (Figure 2.1). This port, which is ideally situated at the geographic centre of the fishery region, allowed vessel owners to minimise steaming time and maximise fishing days, and by this virtue remains one of the most important tuna hubs in the world (Robinson et al. 2010). In the late 1980s, encouraged by growth in the European canned tuna market, French manufacturers established canning factories in port Victoria (owned by Indian Ocean Tuna Ltd), and also in Antsiranana, Madagascar (owned by Pêche et Froid Océan Indien; Campling 2012).

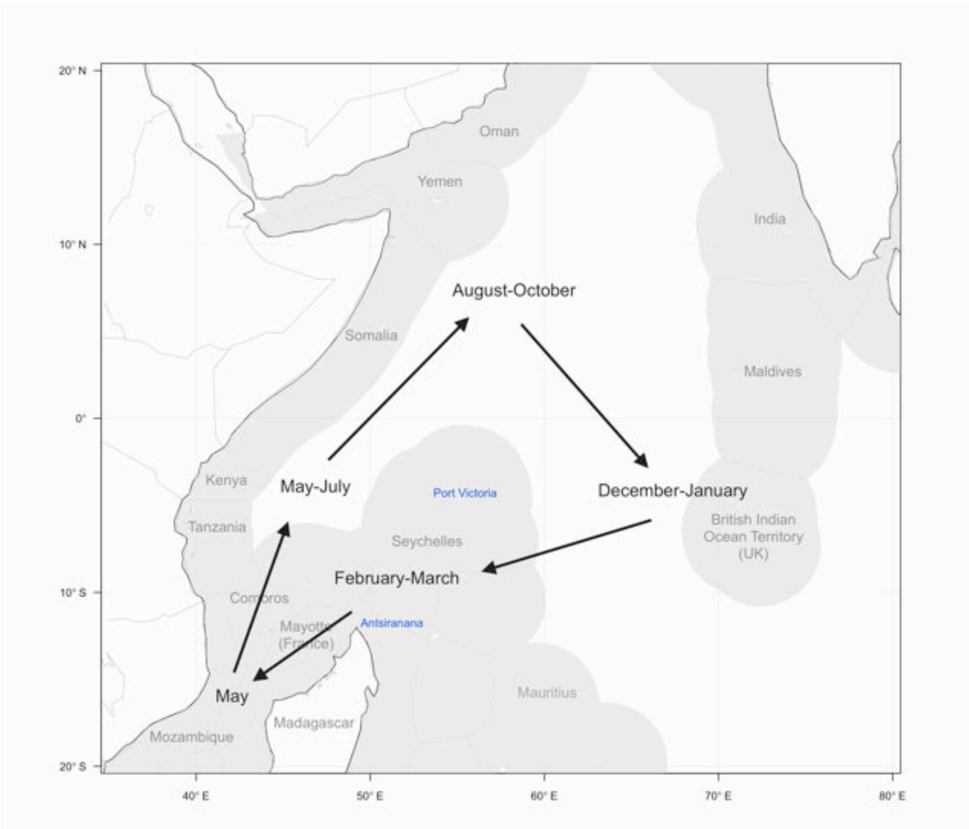

Figure 2.1 Stylised annual cycle of movement of the purse seine fleet around the western Indian Ocean, showing coastal and island nation exclusive economic zones and the two major tuna ports (blue).

2.2.2 Composition and fishing capacity of the fleet

The European-owned distant water fishing fleet continues to dominate the tuna purse seine fishery in the western Indian Ocean. Whilst most vessels are flagged to their home nations (France or Spain), some elements of the fleet have at times registered their vessels under non-EU flags, known as flags of convenience, and employed a smaller proportion of European crew. This is a business strategy intended to reduce costs and, in the case of the Spanish firms, to avoid EU regulation on the size of distant water fishing fleets (DeSombre 2010; Campling 2012). Since 2008, French firms have not used flags of convenience, although Spanish firms have used them widely, with a number of Spanish-owned vessels in the western Indian Ocean flagged to Seychelles (Table 2.2; Campling 2012).

The fishing capacity of the European-owned fleet has grown considerably since its beginnings in the 1980s. Throughout the 1990s and early 2000s French and Spanish fishing companies invested in bigger and faster purse seine vessels - at an estimated cost of US$20 million per vessel - which offered numerous commercial advantages, including the ability to make extended fishing trips further from port (Campling 2012). The development of the fleet included the construction of several 'super-seiners' (>2,000 gross tonnage; GT) and even 'super super-seiners' (> 3,500 GT). However, because larger vessels are more sensitive to increasing operating costs (e.g. fuel price; Miyake et al. 2010) it was necessary for fishing companies to adopt increasingly competitive fishing strategies to achieve high annual catch thresholds (e.g. circa 15-20,000 t; A. Fonteneau, personal communication). Consequently, purse seine firms have become increasing reliant on the use of fish aggregating devices (FADs) to achieve the very large catches needed to remain profitable (Guillotreau et al. 2011).

Table 2.2 The European-owned distant water purse seine fleet in 2008. Based on Campling (2012), IOTC positive list of vessels and the IOTC Record of Authorised Vessels. Ocean of operation is a snapshot for 2008, as firms will occasionally move vessels between oceans.

Fishing firm (national headquarters)	Vessel flags	Industry association	Ocean of operation			Gross tonnage (GT)	
			Indian	Atlantic	Other	Average per vessel	% of EU fleet
Albacora (Spain)	Spain (6); Seychelles (3); Ecuador (3); Panama (3); Netherlands Antilles (1)	Opagac	6	3	7	2,919	25
Calvo Group (Spain)	El Salvador (4); Cap Verde (2)	Opagac	0	2	4	2,137	7
Garavilla Group (Spain)	Spain (2); Equador (2)	Opagac	3	2	0	2,389	5
Inpesca (Spain)	Spain (7); Seychelles (1)	Anabac	6	1	0	2,381	10
Atunsa (Spain)	Spain (5); Seychelles (1)	Anabac	4	2	0	2,582	8
Echebastar (Spain)	Spain (3); Seychelles (3)	Anabac	6	0	0	2,474	8
Pevasa (Spain)	Spain (5)	Anabac	5	0	0	2,244	6
Cobrecaf (France)	France (7); Mayotte (2); Italy (1)	Orthongel	10	0	0	2,174	11
Kühn-Ballery , France-Afrique, CBM (France)	France (7)	Orthongel	4	2	1	1,447	5
Bolton Group/Saupiquet (France)	France (5)	Orthongel	3	2	0	1,671	4
MW Brands (France)	Ghana (5)	-	3	5	0	1,050	2
Others (Spain & France)	Spain (6); France (2); Guatemala (2)	Misc.	3	5	0	1,788	6

2.2.3 Regional fisheries management

Regional fisheries management organisations (RFMOs) are international advisory and management organisations established to regulate and monitor fisheries in international waters. Membership to RFMOs is open both to countries in the region ("coastal States") and distant countries that operate fleets in the region. RFMOs can be split into two types: those that manage all the fish stocks found in a specific area (e.g. Northwest Atlantic Fisheries Organisation), and those that focus on particular highly-migratory species, notably tuna, across vast areas (e.g. Indian Ocean Tuna Commission). Whilst some RFMOs have a purely advisory role, most have powers to design and implement management controls, including catch and effort limits, technical measures, and harvest control rules. Management decision making within RFMOs is generally underpinned by scientific research, and RFMOs' scientific committees are heavily dependent on research undertaken by national scientists of contracting parties.

The industrial tuna purse seine fishing in the Indian Ocean is managed by the Indian Ocean Tuna Commission (IOTC), one of the five tuna RFMOs responsible for managing tuna stocks in international waters around the globe. Members of the IOTC include several Indian Ocean coastal and island nations, as well as a number of Asian and the European countries, both of which have a significant presence in the region in the form of distant water purse seine and longline fleets. The IOTC is ultimately responsible for setting catch limits, undertaking stock assessments and regulating fishing rights and has the power to take legally binding decisions that must be implemented by the various Contracting Parties.

In the IOTC, the production of scientific advice is organised into thematic working groups, comprising of scientists that belong to the different members (and in some cases independent scientists), which undertake research under the coordination of the Scientific Committee. Data for scientific research is supplied by the member states, including a range of catch and effort data, and to a lesser extent, data form fisheries observers programmes. As with many other RFMOs, the submission of data is often incomplete or late, which may jeopardise the provision of robust management advice. Moreover, some aspects of research are hindered because detailed operational data, which are considered highly confidential, is rarely supplied by members.

2.2.4 Fishing operations

Tuna purse seine fisheries are amongst the most highly capitalised in the world. Modern purse seiners are large industrial vessels of 40-110 m in length and, with a fish well capacity up to 3,000 m^3, are capable of making extended trips of several weeks before returning to port to land or tranship catch and resupply (Figure 2.2). A typical vessel has a crew of up to 40, including deck hands, boatswain and netmaster, kitchen staff, engineers and a bridge officer, captain and skipper. The captain has overall responsibility for the operation of the vessel, including navigation and crew safety, whereas the skipper has responsibility for fishing operations, including decisions on where and how to fish. The crew, including the captain and the skipper, work in an unsynchronised shift pattern of several months, although a vessel will be in almost continual use.

Figure 2.2 Tuna purse seiner resupplying in Victoria port, Seychelles. Photo credit: T. Davies, 2011.

In the open ocean tunas naturally aggregate in free-swimming schools (free schools) or associate with floating objects (associated schools), such as logs or branches (Dempster and Taquet 2004). Fishers have learnt to exploit this association behaviour and deploy purpose-built fish aggregating devices (FADs) into the ocean to increase and expedite catches. A distinction is usually made between the two school types due to differences in the species composition of the catch (Dagorn et al. 2012b), although skippers will generally target a mixture of free and associated schools during fishing trips. The basic purse seine fishing operation, termed a cast or a drop, involves encircling a tuna school within a long panel of net that is floated on the surface and weighted along the bottom. A steel cable running along the bottom of the net is tightened to 'purse' the net and trap the school inside. Once captured, the net is drawn up beside the vessel to form a 'bag' and fish are transferred aboard using a small grab net and sorted into fish wells, where the catch is immediately frozen in a super-chilled brine solution. This process typically lasts 2-3 hours, depending on the tonnage caught, with most of this time spent drawing the net into a bag and transferring the fish on board.

Figure 2.3 Frozen skipjack and bigeye tunas being transferred from the fish wells to the upper deck during landing of the catch in Victoria port, Seychelles. Photo credit: T. Davies, 2011.

Although the basic cast operation is similar for both school types, the techniques and skill sets used to locate and successfully catch free and associated schools can vary considerably and might be considered analogous to hunting and trapping, respectively. Setting a net around a free school is a difficult undertaking and involves a considerable amount of skill on the part of the skipper. Free schools tend to move quickly and can initially be difficult to locate and, once spotted, the speed and direction of the tuna must be judged accurately to ensure the net encircles the moving school without it escaping. In comparison, schools associated with floating objects are generally considered easier to catch, mainly because objects on the surface are easier to locate and also because schools tend to stabilise and become less mobile when associated with a floating object. Objects fitted with GPS or satellite buoys are detectable from virtually any distance and are often found in darkness and fished the next day before sunrise, partly to maximise the chance of a successful cast but also to maximise search time in daylight elsewhere (Fonteneau et al. 2000).

2.2.5 Fisher perspectives on strategies for effort allocation

The western Indian Ocean covers an enormous area but resources are not distributed evenly in space and time. Purse seine skippers exploit this heterogeneity, seeking out aggregations of tuna using a range of tools, fishing aids and fishing practices, and although skippers will attempt to fish whenever a tuna school is encountered, their fishing behaviour is directed by frequent and informed evaluations of possible opportunities.

An understanding of the fishery, the practice of purse seine fishing and the behaviour of skippers was developed through direct communication with fishers. Semi-structured interviews were held with key fishery informants in the main landing and transhipment port of Victoria, Seychelles. Informants were chosen on the basis of their practical knowledge of the fishery and included skippers of purse seine vessels, fleet representatives, fishery managers and researchers. Interviews were conducted with one representative from each of the Seychelles-based distant water fleets (French and Spanish). Fleet representatives are port-based officials who act as the liaison between foreign governments and skippers working in distant water fishing fleets and have an intimate knowledge of the fishery and many of the past and present skippers. Interviews with fleet representatives were carried out both before and after the interviews with skippers, initially to develop interview questions and subsequently to validate information generated from these interviews. These discussions were also useful in gaining a comprehensive impression of the fishery from the wider perspective of the fleet representatives, including trends in fishing practices over time.

Four skippers were interviewed, all of whom operated Spanish-owned vessels. Introduction to these skippers was made via the Spanish fleet representative (J.J. Areso). Each interview followed two lines of questioning; interviewees were first asked to describe the tactics used by skippers to generate information on the whereabouts of tuna schools, then asked how skippers evaluated this information and ultimately made decisions when information was deemed incomplete or of poor quality. The interviewing approach was based on guidelines for semi-structured interviews by Bernard (1994). In order to encourage fishers to talk openly about their behaviour and fishing experiences, interviews were conducted in the company of J.J. Areso, with whom skippers had a good relationship. J.J. Areso also provided translation from Spanish were appropriate. Skippers were also promised anonymity, although most waived this right. Questions were open and allowed for a natural conversation to take place, with answers and discussion recorded in detailed notes. Interviews lasted 1-2 hours and took place on board fishing vessels in port.

Detection technologies

Purse seine vessels are fitted with state of the art equipment to locate tuna schools. In the open ocean a number of signs can be used to locate tuna schools, including feeding sea birds, marine mammals and whale sharks and floating objects. To detect these signs on the surface, vessels are equipped with powerful binoculars, usually positioned high in a crows nest structure, although the advent of bird radar in the late 1980s has allowed feeding birds to be detected from greater distances. Until the 1990s helicopters were also used to search for schools in the Indian Ocean, although these have since become obsolete with the advent of other technologies. Various forms of radar, sonar and sounders on the bridge are also useful in locating schools or marine animals beneath the surface.

FADs are particularly useful fishing tools and their use has come to dominate purse seine fishing operations worldwide (Dagorn et al. 2012b). At any given time a skipper can track the location of many tens of FADs on a computer monitor in real time. Experienced skippers can anticipate whether or not a FAD is likely to have an associated tuna school beneath it based on where and when it was set, the length of time it has been at sea, the route it has drifted and the environmental conditions surrounding it. Furthermore, many modern FADs are fitted with a basic echosounder that produces an estimate of the biomass swimming beneath and skippers of many Spanish vessels receive information on the status of a FAD or unmarked floating object from an allied supply vessel.

Communication systems

Information sharing between skippers is regarded as the most immediate way to gather new information on the location of potential fishing opportunities. This considerably increases search efficiency, as explained by one skipper; "*The most important aspect for searching is the news sent by others boats especially if there is good fishing but also when no fishing so as to know where a boat had already* *prospected with no results or few results"*. Key information, including the location, volume and species composition of recent catches, is shared via satellite phone or email within restricted groups of 'friendly' skippers. These sharing networks are often professional and based on company ties but may also be constructed on the basis of long standing friendships. In this way the size of sharing networks can vary by individual, with skippers that have better contacts (and larger networks) potentially having access to more information. Furthermore, the quality of shared information can vary according to the structure of the network and as such may be associated with some uncertainty. For instance, one skipper described having groups of friends arranged like concentric circles: *"The information I share with my inner circle of one or two friends is maybe 99% accurate, whereas what I share with the outer groups is maybe only 50% true."* Information quality is eroded by misreporting the size of recent catches (through omission and/or underreporting) or delaying how quickly the information is shared.

Remote sensing fishing aids

The use of charts based on satellite remote sensing (SRS) measurements and oceanographic models (near real-time data commercially available from CATSAT; http://www.catsat.com) is commonplace in all tuna purse seine fisheries, including in the Indian Ocean. However, the use of SRS data when searching for schools is complex and varies with the scale of the decision making. For instance, one skipper suggested these data are useful in building a general picture of potential medium to long term opportunities (i.e. weeks to months) across the entire region; "*When I come on board from holidays one of the first thing I do is to look the satellite* *information so as to have an idea of the global situation"*. At much finer spatial and temporal scales SRS data may again be consulted, often to complement and build on shared information from other vessels; "*Then we are looking on the screens to see the interaction of the fishing ground with plankton and sea temperature.*"

There is some suggestion that SRS data are considered subordinate to other sources of information, implied in the response of one skipper; "*If the fishing is poor then the skippers are more looking for the satellite operation to help to find a good fishing ground. Because the function of skipper is to take always decisions, these maps can help them to take a route where to go.*" This quote also gives insight into the need for skippers to justify their decision making in some way. The ambivalence toward SRS data is possibly due to the perceived quality of the information provided by SRS data, as one skipper explained: *"I only use ocean charts when I am really lost* [for ideas]. *I don't think it is much good – I have seen too many unexplained patterns of tuna abundance"*. The usefulness of SRS data may also vary depending on the type of school a skipper is searching for. Whilst several skippers reported that better fishing on floating objects was associated with areas with higher plankton concentrations, particularly during the boreal summer months, when asked about searching for free-schooling tunas a skipper replied; "*In fact for free schools it is not so easy to know with maps where to find it. Very often we are finding yellowfin school in an area where nothing appears on satellite map, no front, no plankton, nothing special about subtemperature or altimetry... nothing, the big calm.*"

Acquired knowledge and experience

A skipper's personal experience is important in determining when and where to search for schools. Underpinning the choice of fishing location is a general knowledge of 'traditional' seasonal fishing areas, gained through personal experience and working alongside others. These established patterns, well known by skippers throughout the fishery, provide a general rule of thumb for where to search for tuna at any given time of year. For instance, when asked where he might fish next week, one skipper replied: *"I will try down in the Mozambique Channel because that is where the fleet are at this time of year"*. This heuristic is largely based on skippers' understanding of the seasonal movement of tunas between regions (i.e. ecological knowledge), but also the optimal time to fish in particular areas based on prior experience of catches and catch rates in a particular area at a certain time. This was illustrated by the quote; "Generally *(but not all the time) it is better to search for logs* [floating objects] *in the northern plankton area specially during months of July to November. There is more chance to find fish with logs in these zone. So for example if you go to search during these periods in the zone with low level of plankton we have great chance to find only associated fishes with 2 or 3 tons of tuna only."*

Chapter 3

3 The past, present and future use of drifting fish aggregating devices (FADs) in the Indian Ocean

3.1 Introduction

In the open ocean many species, including tunas, associate with objects drifting on the surface, such as logs or branches (Dempster and Taquet 2004). This is highly advantageous to purse seine fishing as floating objects (FOBs) aggregate sparsely distributed schools, are more easily spotted than tuna swimming freely beneath the surface, stabilise schools and reduce the speed at which they travel, making them comparatively easy to catch (Fonteneau et al. 2000; Miyake et al. 2010). In the mid-1980s skippers started experimenting with ways to maximise the potential of floating objects as fishing tools. Initially, reflectors and radio beacons were attached to logs to improve their detection over greater distances and fishers eventually started constructing purpose built fish aggregating devices (FADs; Figure 3.1) fitted with electronic buoys to simultaneously boost the number of floating objects in the ocean and further aid their detection.

The development of FADs has dramatically improved the searching efficiency of purse seiners and today approximately half of the global tuna catch comes from this fishing practice (Miyake et al. 2010). FADs can be located quickly, minimising search time and operating costs, and because they can be located using a computer screen they can be can fished on in darkness (unlike free-swimming schools which must be located in daylight hours). The most recent generation of FADs are equipped with echosounders that transmit daily or hourly estimates of biomass beneath the buoy, allowing skippers to confirm the presence of a school beneath a FAD before visiting it, and in some oceans (e.g. Atlantic and Indian oceans), auxiliary supply vessels are allied with purse seine skippers and used to deploy and monitor FADs using sonar and other fish-finding technologies (Dagorn et al. 2012b).

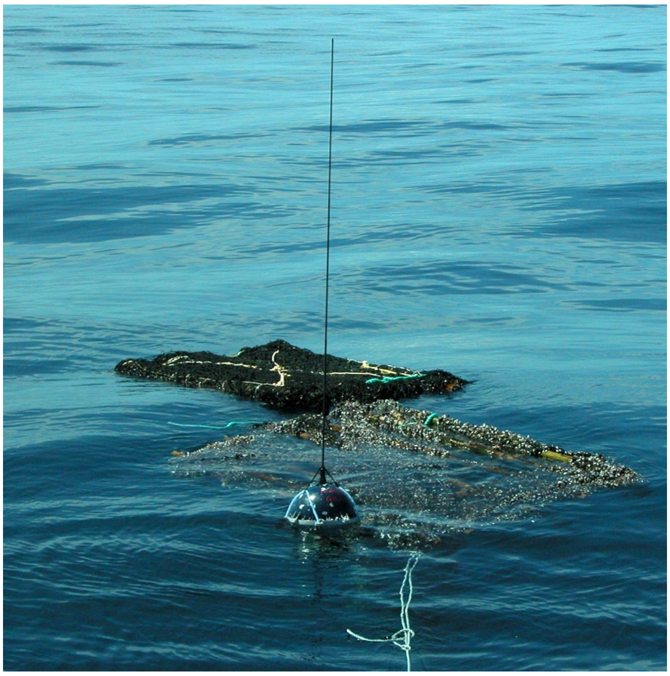

Figure 3.1 A typical FAD constructed from a bamboo raft with netting hung beneath and a buoy fitted with location-tracking technology. Photo copyright: FADIO/IRD-Ifremer/B. Wendling.

Whilst FADs are evidently useful fishing tools, their use has been associated with several potential negative ecosystem impacts, including catch of juvenile tunas and bycatch of vulnerable non-target species (Bromhead et al. 2003; Amande et al. 2008, 2010). Furthermore, there is concern that the highly efficient practice of FAD fishing, left unchecked, might exacerbate issues of overcapacity and ultimately lead to the unsustainable exploitation of tuna stocks (Fonteneau et al. 2000, 2013). There is currently little control on the use of FADs in purse seine fisheries and there has been increasing discussion within tuna Regional Fisheries Management Organisations (tRFMOs) on managing their use more strictly (Fonteneau et al. 2013). So far, this discussion has served mainly to highlight uncertainties in our understanding of the sustainability of catches on FADs and the consequences of modification of the pelagic habitat on tuna biology but has also begun tentatively to explore the impact of potential management solutions on purse seine catches (Fonteneau 2003; Martin et al. 2011; Murua et al. 2011; Fonteneau et al. 2013).

Consideration of potential management must also consider how fishers will respond to the introduction of management measures (Salas and Gaertner 2004; Branch et al. 2006). It is widely recognised that designing fisheries management with the behaviour of fishers explicitly accounted for can reduce the risk of implementation error, i.e. where management outcomes deviate from those intended (Fulton et al. 2011). In considering how purse seine fleets will respond to controls on the use of FADs it is necessary to have an understanding of the role FADs play in fleet dynamics, from long term trends in fleet characteristics to how effort is allocated in space. Yet despite the importance of understanding the role of FADs in driving these dynamics, to date this topic has received much less attention than the ecological issues associated with the use of FADs.

In this paper I characterise the past and present use of FADs in the Indian Ocean tropical tuna purse seine fishery. First I summarise the potential ecological impacts of FADs (see Dagorn et al. 2012b for a full review). I next discuss the role of FADs in the development of the Indian Ocean purse seine fishery, characterise spatio-temporal patterns in their use and examine their influence on effort allocation dynamics. Finally I discuss the potential impact of a number of plausible FAD management options on the purse seine fleet and draw inferences for the future sustainability of tropical tuna purse seine fishing in the Indian Ocean.

3.2 Ecological impacts associated with fishing on FADs

3.2.1 Impacts on tuna stocks

Floating objects have facilitated extremely high catches of tuna in every ocean, including the Indian Ocean, and potentially have two types of impact on tuna stocks (Fonteneau et al. 2000); overfishing (a reduction in spawning stock biomass) and a loss in potential yield (catching smaller fish and reducing the number of large breeding individuals in the stock). The extent of these impacts is complicated by differences in the resilience of the three main species of tropical tunas caught in purse seine fisheries. Fishing on floating objects is mainly associated with skipjack tuna *Katsuwonus pelamis*, which makes up 57-82% of the catch using this fishing practice across all four oceans (Dagorn et al 2012). Skipjack tuna is a fast growing, highly fecund species and is generally thought to be resilient to fishing (Fromentin and Fonteneau 2001) and although the use of FADs has increased dramatically since the 1990s, skipjack tuna are not currently considered to be overfished in any ocean. Whilst this suggests that the use of FADs does not in itself result in overfishing of skipjack stocks, there is concern that this situation might change with continued increase in exploitation rates using FADs into the future (Maunder 2011).

The proportions of yellowfin *Thunnus albacares* and bigeye tuna *T. obesus* in catches on floating objects are smaller (typically 14-25% and 4-28% respectively; Dagorn et al 2012), although these are mostly small or juvenile fish (Bromhead et al. 2003) and as such these species are thought to have less resilience to FAD fishing. Whilst stocks of yellowfin and bigeye have been overfished in some oceans it is difficult to assess the role of FADs in this overfishing as there is no obvious pattern between the relative magnitude of catch on floating objects and whether a stock is overfished (Anonymous 2011; Dagorn et al. 2012b). Catches of small individuals might also result in a loss of potential yield through a reduction in the number of large spawning fish in the stock (i.e. lower yield per recruit). However, again the evaluation of these negative effects is difficult due to uncertainty in growth rates and natural mortality of juvenile tunas and currently no definite conclusion can be drawn (Fonteneau et al. 2012).

3.2.2 Impacts on non-target species

A more tangible ecological impact associated with FAD fishing is bycatch of non-target species. Over time floating objects attract whole communities of non-target species that can also be taken as part of the purse seine catch (Hall 1998; Romanov 2002; Bromhead et al. 2003). Fishing on free-swimming schools is comparatively more selective, with bycatch 2.8-6.7 times lower than sets on floating objects (Dagorn et al. 2012b). The majority of non-target species caught incidentally around floating objects are small tunas and other bony fishes (Romanov 2002; Amandé et al. 2008, 2010). Many of these species are known to be fast growing and have high fecundity (see Dagorn et al. 2012b for references) and thus their vulnerability to incidental capture around FADs is likely to be low. However, sharks, rays and billfishes are also commonly taken as bycatch and are considered to have much higher vulnerability to fishing (Amandé et al. 2008, 2010). Shark bycatch on FADs is almost exclusively composed of two species; silky sharks *Carcharhinus falciformis* and oceanic white tip sharks *C. longimanus*, together comprising over 90% of shark bycatch by number (Gilman 2011). As with many sharks, these species have slow growth rates, mature late and have long reproductive cycles with few offspring, and as such are highly susceptible to population decline from excessive fishing pressure (Camhi et al. 2009). FADs in particular are also associated with the mortality of sharks and turtles through entanglement with the net hanging beneath a raft (i.e. ghost fishing) although the extent of this mortality is not usually estimated (Amandé et al. 2008).

3.2.3 Impacts on tuna habitat

The reason for the natural aggregation of tunas beneath floating objects is not entirely clear although the two most credible explanations for this behaviour are the meeting point hypothesis (Dagorn and Fréon 1999) and the indicator-log hypothesis (Hall 1992). The meeting point hypothesis suggests that fish associate with floating objects to facilitate schooling behaviour and subsequently benefit from this social interaction whilst the indicator-log hypothesis suggests that natural floating objects are indicators of productive habitat given that they originate from nutrient-rich areas (e.g. river mouths, mangrove swamps) and subsequently drift with these patches of productivity into the ocean.

Given these possible explanations for the association of tunas with floating objects there is concern that the deployment of large numbers of FADs in the pelagic ocean could change the natural environment of tunas, a theory known as the 'ecological trap hypothesis' (Marsac et al. 2000; Hallier and Gaertner 2008). Large numbers of floating objects could potentially modify the movement patterns of tunas and carry associated schools in ecologically unsuitable areas and thus affect their growth rate or increase natural mortality and/or predation (Hallier and Gaertner 2008; Jaquemet et al. 2011). Although this subject has received considerable research attention it is difficult to evaluate the impacts of FADs on the ecology of tunas, largely due to uncertainty in how tunas interact with floating objects (e.g. length of association, reasons for joining/leaving an objects etc.). Consequently the ecological trap hypothesis remains open to discussion (Dagorn et al. 2012b; Fonteneau et al. 2013).

3.3 FAD fishing in the Indian Ocean

3.3.1 Spatiotemporal patterns of FAD fishing

FADs have had a strong influence in shaping the spatial dynamics of the purse seine fishery. Floating objects are not distributed evenly throughout the western Indian Ocean and their location at any given time is determined largely by surface currents and winds. Floating logs and branches generally originate from large rivers and mangrove systems and drift with the currents throughout coastal waters and potentially further offshore. This natural flotsam, which has always been a part of the ocean habitat of tuna, accumulates at particularly high densities in the Mozambique Channel where numerous river systems wash debris into the ocean (Fauvel et al. 2009). Logs also occur in certain offshore regions of the western Indian Ocean, particularly within the large ocean gyres to the east of Somalia, but typically at lower densities (Fauvel et al. 2009). It is into these areas where natural floating objects are less abundant that fishers have subsequently deployed the greatest number of numbers of artificial objects. FADs have a short life time (generally < 6 months; Moreno et al. 2007) and can sink or be appropriated by other vessels. Thus skippers constantly deploy new FADs or relocate older FADs (e.g. objects that have drifted into areas with poor fishing opportunities) and in doing so have effectively created a perpetual artificial floating object habitat across much of the northwest Indian Ocean.

Seasonal patterns of fishing activity by the purse seine fleet follow a roughly cyclical movement around the western Indian Ocean that is largely influenced by the distribution of floating objects and by seasonal changes in fishing opportunities (T. Davies; unpublished data). The main FAD-fishing season extends from August to November and the fleet fishes predominantly in the northwest Indian Ocean to the east of Somalia. Although this northwest region is reasonably small, catches are high and almost exclusively made on floating objects. The use of FADs in particular has consistently been high in this sector with a northwards extension of the fleet in the Arabian Sea region during the mid-1990s. It is interesting to note that these new northerly fishing grounds were discovered by FADs fitted with satellite buoys drifting into previously unfished (but productive) areas (Moreno et al. 2007).

As primary productivity levels fall from November, catch rate on FADs decreases and the fleet moves into the equatorial Indian Ocean (southeast Seychelles and Chagos regions) in search of free-swimming schools. At this time schools of yellowfin and bigeye tunas are generally feeding or spawning near the surface and thus easier to find and catch (Marsac 2008). However, the spatial distribution of schools can vary considerably and as a result there is marked variation in the proportion of catches on free schools in the Chagos region during this period; vessels enter the region to search for free schools but will also fish on FADs where available, resulting in a higher proportion of FAD catches when free schools are scarce.

From March to July the fleet fishes mainly in the Mozambique Channel and northwest Seychelles region using a mixed strategy of floating objects (both natural and artificial) and free school sets. As there has always been an abundance of natural floating objects in this region (Dagorn et al. 2013) the proportion of catch on floating objects has always been reasonably high and the deployment of FADs has been more limited than further north in the Somali region.

3.3.2 Historical trends in FAD fishing

Although no distinction is made in the data, up until the late 1980s ‘floating objects’ are generally considered to be have been natural flotsam (Miyake et al. 2010). In this early period of the fishery the proportion of total catch from sets on free schooling tuna and floating objects was roughly equal (Figure 3.2a). However, skippers were making a considerably higher number of sets on free schools (Figure 3.2b) but with a much lower success rate than sets on floating objects (46% versus 89% success rate respectively during the period 1984-1990; data from Floch et al. 2012). The advantages of fishing on floating objects were obvious to skippers and fishing companies, yet opportunities to fish using this setting method were limited by the number of floating objects in the ocean. In order to continue the growth of the fishery it was necessary to generate more fishing opportunities and skippers realised that, whilst they could not influence the number of free-swimming schools, they could feasibly provide a greater number of floating objects for schools to associate with. Thus, the intensive use of purpose-built FADs began in the early 1990s and catches on floating objects increased steadily through the 1990s and 2000s.

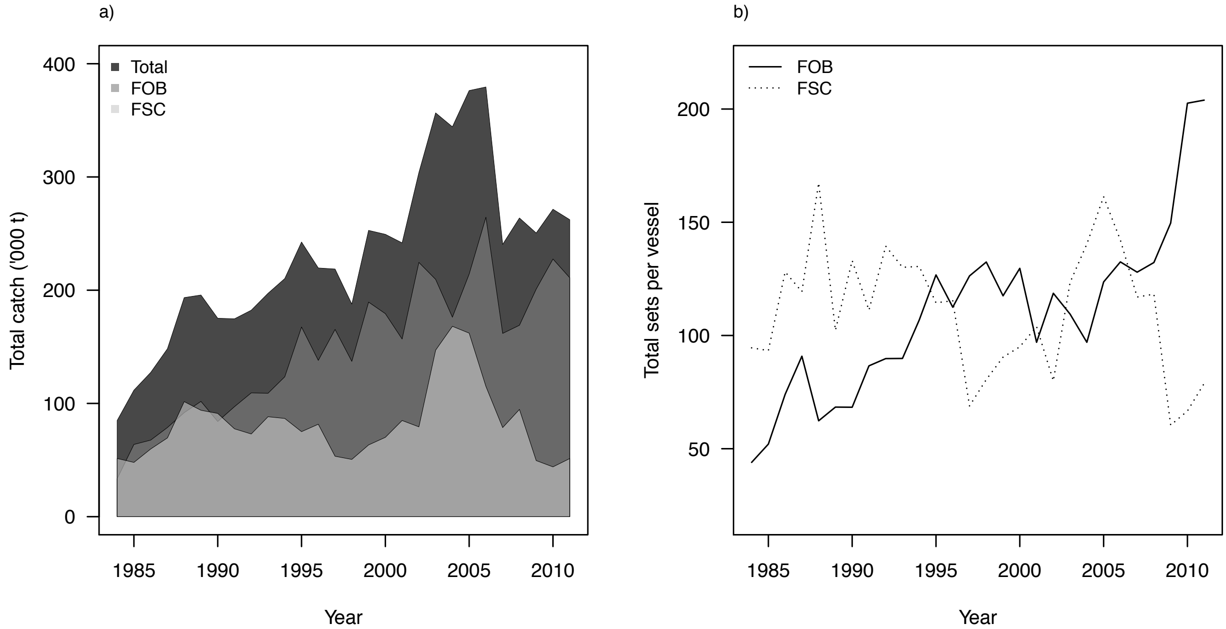

Figure 3.2 Trends in (a) total catch on floating object sets (FOB) and free school sets (FSC) of three main tropical tuna species (yellowfin, skipjack and bigeye tuna) in the Indian Ocean and (b) total number of sets per vessel by fishing practice over the history of the tuna purse seine fishery in the Indian Ocean. Data from Floch et al. 2012.

The increasing use of FADs improved catch rates and greatly enhanced the productivity of the fishery, allowing boat owners to build the capacity of their fleets in an attempt to exploit more of the resource. Throughout the 1990s and early 2000s French and Spanish fishing companies invested in larger purse seine vessels, which offered numerous commercial advantages including the ability to make extended fishing trips with larger fish-wells (Campling 2012). The development of the fleet included the construction of several 'super-seiners' (>2,000 gross tonnage; GT) and even 'super super-seiners' (> 3,500 GT) and the increasing trend in capacity matched the proliferating use of FADs (Figure 3.3). However, because larger vessels are more sensitive to increasing operating costs (e.g. fuel price; Miyake et al. 2010) it was necessary for fishing companies to adopt increasingly competitive fishing strategies to achieve high annual catch thresholds (e.g. circa 15-20,000 t; A. Fonteneau, personal communication). Consequently, the purse seine fishery has become increasing reliant on the use of FADs to achieve the very large catches needed to remain profitable (Guillotreau et al. 2011; Campling 2012).

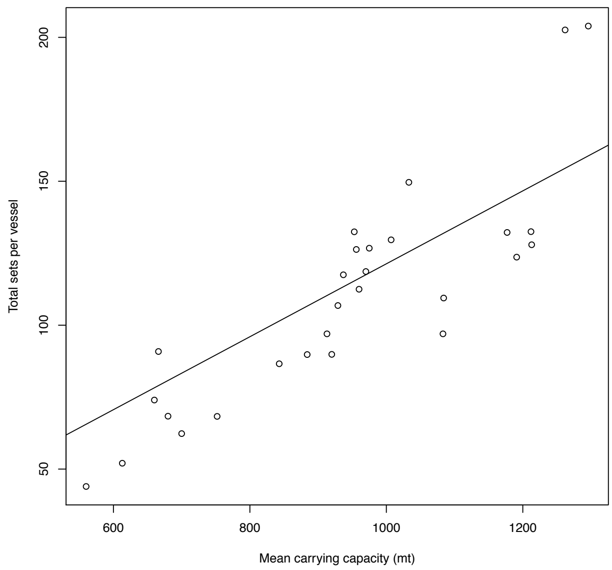

Figure 3.3 Relationship between number sets of floating objects per vessels per year and mean annual carrying capacity over the period 1984-2011. Pearson product-moment correlation, $P < 0.001$, $r=0.86$, $n=28$. Data from Floch et al. 2012.

Against the background trend in fishing capacity two episodes in particular show that other factors have an important effect on the relative use of FADs in the Indian Ocean. In the early 2000s the long-term increasing trend in the number of FOB sets flattened out and there was a clear spike in the number of sets made on free schools (Figure 3.2b). This switch in the predominant fishing practice is thought to be explained by the comparatively high abundance of free-swimming tuna schools during 2003-2005 linked to increased availability of prey species as a result of higher-than-average primary productivity in the western Indian Ocean and greater vulnerability of schools to purse seine gear due to a shoaling of the thermocline (Marsac 2008). During this period fishing companies moved vessels into the Indian

Ocean from the Atlantic to capitalise on this boom (J.J. Areso, Spanish fleet representative, personal communication), temporarily increasing both the total capacity of the fleet (Floch et al. 2012) and also the relative proportion of free schools sets (Figure 3.2b).

In the late 2000s there was a sharp increase in the number of floating object sets per vessel (Figure 3.2b) attributed largely to the impact of piracy on purse seine operations. In 2008-2010, approximately a third of the fleet, mainly comparatively smaller French vessels, moved from the Indian Ocean to the Atlantic due to the threat of piracy (Chassot et al. 2010; Floch et al. 2012), leaving behind larger vessels predisposed to target mainly FADs due to their size. Furthermore, these vessels were restricted in their activity through the requirement to carry security personnel on board (and for a short while, in the case of the French fleet, vessels were also required to fish in pairs), making it more difficult to search for free schooling tunas and ultimately increasing effort on FADs (Chassot et al. 2010).

Interesting, the relative price of skipjack, the main species caught on FADs, appears to have had had little influence on the propensity of the fleet to fish on FADs. In a study of what makes a 'FAD-fisher', Guillotreau et al. (2011) found that knowledge of yellowfin and skipjack price had little influence on a skipper‘s decision making. Instead, skippers generally aimed to fill their fish-wells as quickly and as full as possible regardless of the species.

3.3.3 Variation in FAD fishing between fleets

In the Indian Ocean there is some variation in the FAD fishing activity of the two major nationalities operating purse seine vessels in the fishery, France and Spain, largely due to different strategic standpoints regarding the use of FADs since the 1990s (Moreno et al. 2007; Guillotreau et al. 2011) and the physical characteristics of their vessels, with Spanish vessels typically much larger than those in the French fleet (e.g. 30% larger in 2008; see Campling 2012). This is apparent in the number of individual FADs deployed and monitored by the two fleets, with Spanish vessels deploying a greater number of FADs than French vessels (~100 versus ~30 per vessel respectively; Guillotreau et al. 2011). Furthermore, although FADs generally 'belong' to an individual skipper (i.e. only they can track a particular buoy), in the Spanish fleet skippers may pool FADs and thus increase their overall opportunity to fish on floating objects (Moreno et al. 2007).

In addition to the greater number of FADs available there is also a suggestion that skippers in the Spanish fleet are generally 'better' at fishing on FADs (Moreno et al. 2007). While fleets made approximately the same total number of sets on floating objects per vessel (despite differences in the number of FADs deployed), the Spanish fleet had higher catch rate using this fishing practice, which was particularly pronounced during the 1990s (Figure 3.4). This is largely due to operational differences between the fleets. Firstly, the Spanish fleet typically deploys satellite and sonar buoys (as opposed to GPS buoys) which have no antenna and are as a consequence are harder for competing vessels to find by chance. Secondly, unlike the French fleet, many Spanish vessels are assisted by supply vessels that deploy, maintain, check and often guard FADs until the catcher vessel arrives (Itano et al. 2004), considerably improving the efficiency of FAD fishing for these vessels. Lastly, as FAD and free school fishing require different knowledge and skill sets there is some suggestion that a skipper effect explains the difference between the fleet activities, with Spanish skippers appearing to have more developed FAD fishing skills (Moreno et al. 2007; Guillotreau et al. 2011).

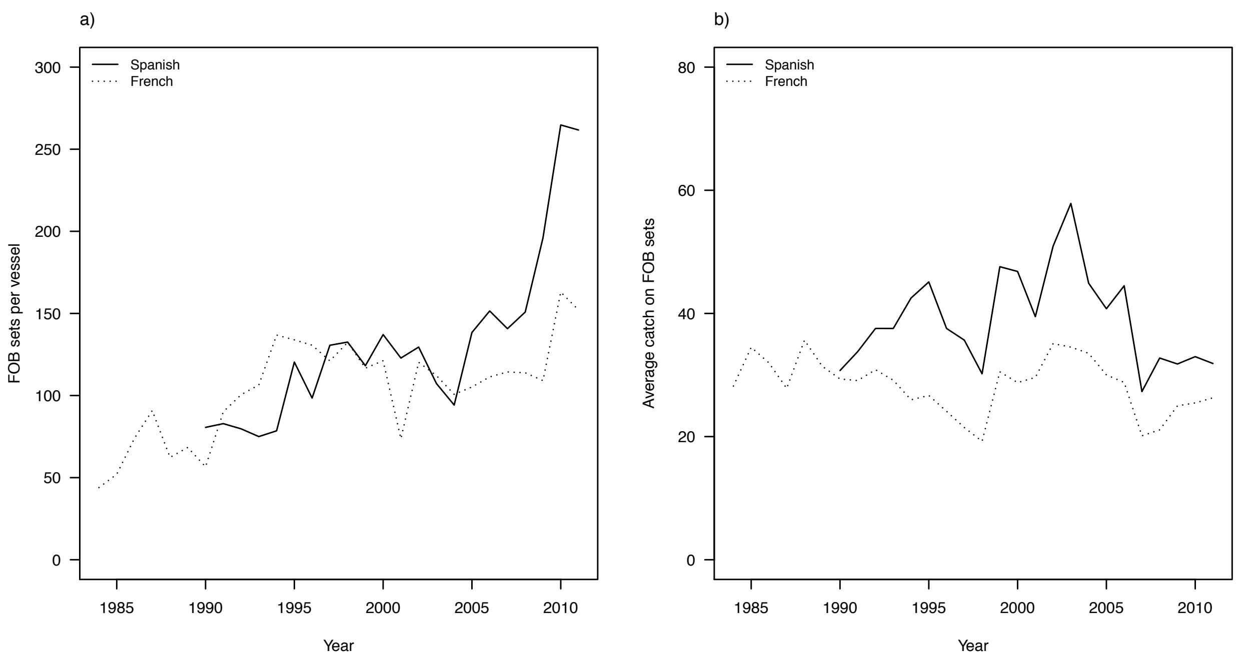

Figure 3.4 Trends in (a) the number of sets on floating objects (FOB) per vessel by the French and Spanish fleet and (b) average catch per vessel on floating object sets by fleet nationality over the history of the tuna purse seine fishery in the Indian Ocean. Data from Floch et al. 2012.

3.4 Management of FAD fishing

3.4.1 Generating more data

Much of the concern surrounding FAD fishing stems from uncertainty around their ecological impacts. In order to quantitatively assess the impact of FADs and to consider potential management options it is necessary to generate more data on how, where and why they are used. This urgent need for more data on the use of FADs in purse seine fisheries in all oceans was highlighted at the most recent joint meeting of the tRFMOs (Kobe III) in La Jolla 2011, with two types of information on FADs considered to be pertinent; an inventory and activity record of FADs ('FAD logbook') and a record of encounters with FADs by fishing and supply vessels ('fishing logbook'). In recognition of this need for better data, IOTC has recently revised and improved its reporting requirements for FADs under Resolution 10/02, which were previously considered ambiguous and insufficient to comprehensively record the practise of FAD fishing. These new and more detailed requirements include reporting the unique identifier, position, type and construction of the FAD fished on. The use of supply vessels, including the number of associated catcher vessels and number of days at sea, must also be reported. In addition, in 2012 IOTC adopted a entirely new resolution (Resolution 12/08; http://www.iotc.org/English/resolutions.php; accessed 1st June 2013) setting out the requirement for fleets to develop and submit FAD Management Plans by late 2013. This resolution, which again requires fishing companies to provide highly detailed information on their use of FADs but also apportions responsibility in managing their use, represents an important step towards regulating the practise of FAD fishing in the IOTC convention area, although it falls short of outlining any restrictions on their use.

The European tuna purse seine fishing industry appears to have a proactive attitude towards developing management plans and generating additional data on the use of FADs. Since the mid-2000s French and Spanish fishing organisations and have been by working in collaboration with their respective national scientific institutes (and independently with organisations such as the International Seafood Sustainability Foundation, ISSF) to improve the data available on FAD fishing and to also innovate FAD technologies. In particular, the European purse seine industry has been constructive in developing and deploying so-called ‘eco-FADs', which are designed using rolled nets or ropes rather than open mesh panels to minimise entanglement of sharks and turtles (Dagorn et al. 2012b). This cooperation by the industry is likely to be inspired in part by the desire to improve the public perception of purse seine fishing, with environmental organisations generally interpreting a lack of data as bad news. There has been strong pressure applied on seafood brands by the environmental lobby to source from non-FAD fisheries and several of the major seafood suppliers have already begun to move in this direction (see http://www.greenpeace.org.uk/tunaleaguetable for a league table of suppliers). Furthermore, improving data collection and adopting technical measures like eco-FADs has been relatively painless to the fishing industry and is likely to have had negligible financial cost. It is assumed that fishing companies prefer these soft measures that will improve understanding of the impact of FADs over more restrictive management measures.

3.4.2 Existing management measures

Given the uncertainty surrounding the ecological impacts of FADs there is a reasonable argument for tRFMOs to take a precautionary approach and make moves to manage the use of FADs more strictly. Whilst improvements in the design and construction of FADs can certainly play a role in reducing ghost fishing and bycatch (Gilman 2011), other measures that control fishery input are necessary to reduce the total catch taken by the purse seine fleet on FADs (Joseph et al. 2010). These measures might potentially include effort controls such as area closures, limits on the number of monitored buoys or limits on the total number of sets on FADs, although to date only area closures have been widely implemented (Davies et al. 2012).

However, a major management challenge is to achieve meaningful reductions in bycatch and catches of tuna species thought to be vulnerable to overfishing (i.e. bigeye and yellowfin tunas) whilst not significantly reducing catches of skipjack, which are not current considered overfished.

In the Indian Ocean the most significant restriction on FAD fishing has been a time-area closure, implemented in November 2011 and again in 2012, with the objective to reduce the mortality of juvenile bigeye and yellowfin tunas (Resolution 10/01; http://www.iotc.org/English/resolutions.php; accessed 1st June 2013). This no-take area covered a large proportion of the northwest Somali Basin region towards the end of the FAD-fishing season. However, a preliminary evaluation of the first year of this closure using IOTC catch data, presented in Table 3.1, suggests that it had mixed results in reducing total annual catches of bigeye and yellowfin on FADs. Taking into account reduced total fishing effort in 2011, catches of bigeye tuna on floating objects were reduced by only a small amount during the period of the closure and over the whole year, compared to the period 2008-2010, whereas catches of object-associated yellowfin actually increased. Catches of skipjack were reduced slightly during the closure period but there was no overall reduction in the annual catch (Table 3.1). This limited effect of the area closure on catches of yellowfin and bigeye tunas was largely due to the reallocation of fishing effort into adjacent areas to the south and the east of the closure where the fleet could continue to fish with reasonable efficiency using FADs. Furthermore, in the month following the closure the fleet moved back into the area and reported higher catch rates on floating objects than usual for December (15.8 versus 11.0 t fishing day^{-1} for the same period in 2008-2011; IOTC data). There is insufficient data available to be able to evaluate the effect of this closure in terms of a reduction in bycatch, although the closure area is a hotspot for bycatch of silky sharks (Amandé et al. 2011).

Table 3.1 Comparison of catches of the three principal target species taken on floating object sets during the closure period and the whole year when the closure was implemented compared to the reference period 2009-2010. Catches are expressed as catch per fishing day to account for changes in total effort. Data from the IOTC catch and effort database.

		Catch rate by species (t day^{-1})		
	Fishing effort (days)	Bigeye	Yellowfin	Skipjack
Closure period (November 2011)				
2008-2010	798	1.7	6.0	13.2
2011	666	1.3	8.3	11.3
Difference		-0.4	2.3	-2.0
Full year (2011)				
2008-2010	10,419	1.7	5.0	12.4
2011	9,718	1.6	7.8	12.4
Difference		-0.2	2.8	0.0

The displacement of effort around the boundaries of closed areas, often termed 'fishing the line', is a common harvesting tactic in many fisheries (e.g. Murwarski et al. 2005; Abbott and Haynie 2012) and in this instance the purse seine fleet could still access much of the seasonal fishing ground. As such the closure appeared to simply displace the issues associated with FAD fishing. In order to produce meaningful reductions in the catches of juvenile yellowfin and bigeye tunas using an area closure it would probably be necessary to implement closures considerably larger (and longer) than those that have been implemented to date (Kaplan et al. 2013). The creation of a massive closure in the main FAD fishing region is likely to have a disproportionate effect on catches, as it is unlikely that the fleet would be able to recoup its losses through the reallocation of effort elsewhere due to the relatively poor fishing in other regions during this season. Whilst this conservation measure would be expected to reduce overall catches of small yellowfin and bigeye tunas, it would also result in a significant reduction in catches of skipjack tuna. This loss in catches of what is currently a healthy stock would probably be an unacceptable penalty to the purse seine industry and would also have a major impact on the processing industry in Indian Ocean states, realistically limiting the possibility of such as dramatic conservation measure ever being adopted by the IOTC.

3.4.3 Potential management options

The known location of FADs is important information in determining where a skipper will choose to fish and in general a larger number of monitored FADs both improves search efficiency and fishing capacity (Fonteneau et al. 2000). A limit on the number of deployed or monitored FADs would thus curb search efficiency and decrease (or maintain, depending on where limits are set) the total number of sets made, although it is important to note the distinction between the number of FADs deployed and the number monitored; the former is relevant to modification of pelagic habitat (and issues relating to their effect on tuna biology) whereas the latter is relevant to fishing capacity and efficiency. A challenge for implementing both measures is setting an appropriate limit without a well defined reference point, which has yet to be calculated by the IOTC. Nevertheless, at least some of the industry appears to have introduced a ceiling on the use of FADs, with French fishing companies recently choosing to limit the number of FAD monitored by their vessels at any time to 150 (Dagorn et al. 2012b). Whilst this is probably close to the number of FADs French skippers have monitored in recent years (Moreno et al. 2007), and is therefore unlikely to reflect a reduction in effort by the French fleet, it might represent a future reduction when considering the increasing trend in FAD use.

A precautionary upper limit on the number of monitored FADs would go some way towards controlling fishing mortality on FADs, although this depends largely on whether a limit was set on the total number monitored or the total number monitored *at any given time* (i.e. allowing for cycling between buoys). There is some evidence that older FADs that have been in in the water for a longer period and have been colonised by other pelagic species are better at attracting tuna schools (Moreno et al. 2007). As a result, the ability to fish on a FAD that had been 'hidden' for a period of several months, assuming it has not been fished by another vessel, might lead to larger catches on a smaller number of sets and diminish any overall reduction in total catch on floating objects. Furthermore, as skippers would be permitted to fish on any floating object they encounter opportunistically, it might be considered advantageous to deploy a greater total number of FADs, with or without buoys.

Limiting the total number of sets allowed to be made by an individual vessel on floating objects (including FADs) might have a more direct effect on the practice of FAD fishing. Skippers usually fish on any floating object they come across, particularly in the absence of other opportunities, even if the associated school is relatively small. Thus, placing a finite limit on the number of FADs that can be fished might incentivise skippers to be more discriminatory in the objects they fished on, presumably by choosing to fish on those objects with large associated schools. This would be possible in practice due to the increasing use of buoys fitted with echosounders, which gives an idea of the size of the school associated with the FAD. As an additional effect to regulating effort, this selective fishing behaviour might also reduce the ecological impacts of FAD fishing on the basis that the ratio of bycatch to target catch is generally lower for larger set sizes (Dagorn et al. 2012a).

A potential challenge to implementing either quota options is the variation in the importance of FAD fishing at different times of year and also to different components of the fleet. For instance, restriction on the use of FADs may limit the ability of fleets to cushion the economic impact of poor free school opportunities at certain times of year or during anomalous climatic events (see Robinson et al. 2010). A blanket quota on FAD use may also be perceived as discriminatory against larger vessels that are reliant on FADs to maintain a profitable operation and compromise in negotiations on FAD limits within IOTC might result in high and potentially ineffectual limits. It should also be noted that to effectively implement controls on the total number of FADs fished on or deployed it would be necessary to ensure compliance with effort limits using measures such as closed circuit television or on-board observers.

3.5 The future of the fishery

In the past two decades the use of FADs has the reshaped the dynamics of purse seine fleets, particularly in the Indian Ocean. The improved catch levels made possible by this fishing practice facilitated a rapid growth of the fishery, and the subsequent development of the fleet, in particular the Spanish component, has largely been based around the use of FADs. Thus, with the use of FADs increasingly vital to the fishing operations of many vessels their use is not expected to decline under a business-as-usual scenario, potentially rekindling excess capacity observed in the fishery in the past (Joseph et al. 2010). However, any increase in the use of FADs would not necessarily mean a uniform increase in fishing effort throughout the western Indian Ocean, but rather increased intensity of effort in the main FAD fishing regions. The fishery and ecological effects of such a change in the spatial dynamics of effort are not well understood, although recent modelling work suggests that an increase in the number of FADs in a region would probably result in smaller schools distributed between the greater number of objects. Thus search costs and bycatch might increase, rather than catches (Sempo et al. 2013).

A number of external pressures might also be expected to change the face of FAD fishing in the future, although conflicting pressures have the potential to push the industry in different directions. Purse seine fishing has become an increasingly expensive operation over the past decade, particularly for the largest and most powerful vessels, due to rising fuel prices and increased fishing effort (Miyake et al. 2010). This has reduced profit margins and potentially increased the fisheries' economic vulnerability to poor fishing seasons and environmental or economic shocks. Given past trends it might be reasonable to assume that this situation would provoke an even stronger reliance on FADs, especially for those vessels that still target a relatively large proportion of free schools. Again, this might result in the saturation of the FAD fishery, potentially leading to increased costs, lower catches but high total extraction rates.

In contrast, market pressures might result in reduced effort on FADs. The majority of the skipjack caught in the Indian Ocean purse seine fishery is of canning grade and destined for markets in European Community countries (Campling 2012). Here consumer pressure for sustainably sourced fish is strong and seafood certification schemes, such as that of the Marine Stewardship Council (MSC), are popular (Jaffry et al. 2004). To date, one purse seine fishery in the Western and Central Pacific convention area has been awarded certification by the MSC, although this has been exclusively for skipjack tuna caught in free school sets (http://www.msc.org/track-a-fishery; accessed 25th July 2013). If this sets a precedent for certification of purse seine fisheries this may mark a move away from FAD fishing with renewed focus on pursuing free schools. However, it is unrealistic that a predominantly free school fishery in the Indian Ocean could exist without a major reduction in vessels numbers and an increase in stock size, requiring dramatic moves by IOTC to address overcapacity and implement rights-based management.

3.6 Final remarks

The increase in the use of FADs over the past two decades has given rise to concern over their associated ecological impacts, yet management of FAD fishing is complicated by the compromise between achieving a reduction in these impacts and allowing the sustainable exploitation of healthy tuna stocks, namely skipjack tuna. This is complicated further by the current reliance of the purse seine fishery on this highly efficient fishing practice, which is likely to only increase further under a business-as-usual scenario as fishing operations become more expensive and shrinking profit margins require an ever greater use of FADs. Yet continued growth in FAD fishing might be expected to result in diminishing returns as the relative benefit of each FAD in the fishery is diluted.

Explicit management of the use of FADs is undoubtedly a necessity to ensure the future sustainability of the fishery. Whilst there are several options available to manage the use of FADs, each option is expected to produce a different response from the purse seine fleet. Time-area closures have already been implemented but with mixed success in reducing juvenile mortality due to the flexibility of the fleet in reallocating effort. Whilst larger (and longer) closures may achieve greater reductions in juvenile catch this would be at the expense of significant reductions in skipjack catch. This has major implications for the fishing and processing industries based in the Indian Ocean, with a realistic danger that many purse seiners would choose to leave the Indian Ocean altogether. On the other hand, input controls such as limiting the number of actively monitored FADs or the number of sets made on floating objects directly address concerns about FAD fishing, if designed and implemented appropriately, but are likely to be challenging to negotiate within IOTC and difficult to enforce.

Chapter 4

4 Modelling the spatial behaviour of a tropical tuna purse seine fleet

4.1 Introduction

Failures in fisheries management can result from insufficient understanding of the biological dynamics of an exploited resource, but also from uncertainty in the behaviour of fishers (Hilborn 1985; Fulton et al. 2011). The allocation of effort by fishers in space is a key aspect of fishing fleet dynamics, with a fisher's choice of where to fish is driven by a wide range of biological, social, economic and management considerations (Salas and Gaertner 2004; see Chapter 2). Change in the dynamics of these drivers, for example variation in the distribution of a fish stock or the implementation of a new management measure, can affect how fishing effort is allocated in space, which in turn can impact upon the outcomes of fisheries management (e.g. Dinmore et al. 2003; Briand et al. 2004). Consequently, the ability to anticipate the behaviour of fishers, through a better understanding of the drivers of behaviour, has become an increasingly important focus of research in fisheries science (Wilen et al. 1979; Fulton et al. 2011).

The spatial behaviour of fishers can be considered in the short term at a fine scale, for example the day-to-day movement of an individual fisher between reefs or banks, or in the long term at a broad scale, such as the seasonal movement of a fleet of vessels (Table 4.1). The short term behaviour of an individual fisher is usually directed at meeting an immediate challenge, such as maximising the day's catch, and is influenced by personal experience and the information available (Gaertner et al.

1996; Abernethy et al. 2007). At the other end of the scale, longer term fleet-level behaviours may be the product of common strategies or coordinated behaviours that are determined by broad environmental, social or political influences (Hilborn 1985; Branch et al. 2006). Furthermore, some aggregate behaviours may not necessarily be the result of short term planning by individuals but instead emerge through cooperation or competitive interactions within the fleet (Hilborn 1985; Salas and Gaertner 2004; Branch et al. 2006).

Table 4.1 Varying units and spatiotemporal scales at which the behaviours of fishers may be observed

Scale	Short term, fine scale	Long term, broad scale
Decision unit	Individual fisher	Fishing fleet
Movements	e.g., tactical fishing manoeuvres, moving between local grounds	e.g., seasonal movement, fishing along closed area boundaries
Influences	e.g., real-time information, skill and experience, vessel characteristics, fishing preferences	e.g., environmental processes, socio-political influences, management controls

Several modelling approaches have been developed to explain and predict the spatial behaviour of fishers, with discrete choice models being particularly popular in the fisheries economics literature (see van Putten et al. 2011). An attractive feature of discrete choice modelling is that it does not assume homogeneity in the decision making of individuals, which is particularly useful when predicting behaviour in fisheries where the incentives and constraints that determine behaviour vary markedly between fishers (e.g. Vermard et al. 2008; Tidd et al. 2012). However, a potential shortcoming of discrete choice modelling is that the choices faced by individuals must be separate and clearly defined, for example the choice between distinct fishing locations or grounds, which may not be a viable assumption in some fisheries, particularly those targeting pelagic fish stocks in the open ocean. At the opposite scale, a number of conceptual models have been developed to examine the drivers of fleet-level spatial behaviour, which by definition do not consider discrete choices, and consequently may be more appropriate for modelling the general movement of a fleet in space. However, these models, which move effort between locations according to some index of suitability, necessarily require preconceptions as to what constitutes an 'attractive' location, for example the availability of the resource or competition from other vessels in the fleet (e.g. Gillis 2003; Powers and Abeare 2009; Dowling et al. 2011).

An alternative approach to investigating fleet-level behaviour is found in the ecology and conservation literature, where a number of statistical modelling approaches have been developed for investigating the spatiotemporal distribution of a species in a landscape (e.g. Milner-Gulland et al. 2011). Within the field of species distribution modelling, a subset of regression-based models have been used to characterise the distribution of a species or activity, explain the functional relationship between an organism and the environment, and to generate insight into a species' behavioural ecology or evolutionary history (see Elith and Leathwick 2009 for a review). Furthermore, regression models have been used to predict the distribution of species in space or time, which further supports their potential use in understanding and anticipating the spatial behaviour of fishers.

This study examines the drivers of the spatial behaviour of the Indian Ocean tropical tuna purse seine fleet. Focus was placed on the behaviour of the fleet at broad spatiotemporal scales, rather than on the behaviour of individual vessels, as, from a management perspective, this was considered to be the relevant scale in regards to anticipating broad changes in fleet dynamics. The distribution of tropical tunas is influenced by the biophysical ocean environment (Laurs et al. 1984; Morhi and Nishida 2000; Zainuddin and Saitoh 2008), and purse seine skippers use satellite-derived information on a number of key environmental conditions to identify promising fishing locations in the short term (see Chapter 2). We therefore ask whether environmental conditions influence the spatial behaviour of the fleet at broad spatiotemporal scales. Many previous studies of decision making by fishers have demonstrated a strong link between past and future behaviour, termed variously as habit, tradition or inertia (Holland and Sutinen 1999; Hutton et al. 2004; Vermard et al. 2008; Venables et al. 2009; Tidd et al. 2012). We therefore also examine the relationship between the past and future behaviour of the fleet, and discuss the implications of this in anticipating the behavioural response of the fleet.

4.2 Methods

4.2.1 Description of the fishery

The tropical tuna purse seine fishery targets three main tuna species (skipjack *Katsuwonus pelamis*, yellowfin *Thunnus albacares*, and bigeye tuna *T. obesus*) across the majority of the western Indian Ocean throughout the year. Tunas are targeted as free-swimming schools (free schools) or in association with floating objects, such as natural debris or purpose-built drifting fish aggregating devices (FADs; Dempster and Taquet 2004). Purse seine vessels are equipped with sophisticated navigation and fish-finding technology, and although capable of extended fishing trips lasting several weeks, vessels must return to port regularly to land or tranship catch and resupply. The size of the active fleet fluctuates with the perceived availability of fishing opportunities in the Indian Ocean and 34-52 vessels per year have operated in the fishery since 2000. The fleet is dominated by Spanish and French owned-and-operated vessels, although the fleet operates exclusively from ports within the Indian Ocean. Port Victoria, Seychelles, is the main port used by the fleet as it's position in the geographic centre of the region allows skippers to minimise steaming time and maximise fishing days (Robinson et al. 2010). Whilst most vessels are flagged to their home nations (France or Spain), some elements of the fleet have at times registered their vessels under non-EU flags, known as flags of convenience (DeSombre 2010).

At broad spatiotemporal scales the spatial behaviour of the fleet is characterised by seasonality in the use of fishing grounds, and the clustering of fishing effort in space. Throughout the year the fleet transitions between three main fishing grounds: the northwest grounds (associated with the practice of fishing around floating objects), the central equatorial grounds (associated with the practice of fishing on free schools) and the southwest grounds (associated with a mixture of both fishing practices). The timing of the movement between these grounds coincides approximately with the southwest (boreal summer) and northeast (boreal winter) monsoons (Figure 4.1). Whilst the use of these seasonal grounds is similar between the French and Spanish fleet components, the latter tends to fish in the northwest grounds for a greater part of the year due to the FAD-centric fishing strategies employed by some Spanish fishing companies (see Chapter 5). The clustering of fishing effort is partly due to the aggregated nature of the fisheries data, as during the course of month, a single vessel is likely to report effort in adjacent grid cells. This clustering is further amplified by the high levels of cooperation and information sharing in the fishery, which results in skippers fishing in close vicinity to others. However, as cooperation occurs mainly between vessels allied by fishing company or flag nationalities, this clustering of effort is mainly observed in the allocation of effort of the respective fleet components (see Figure 4.1).

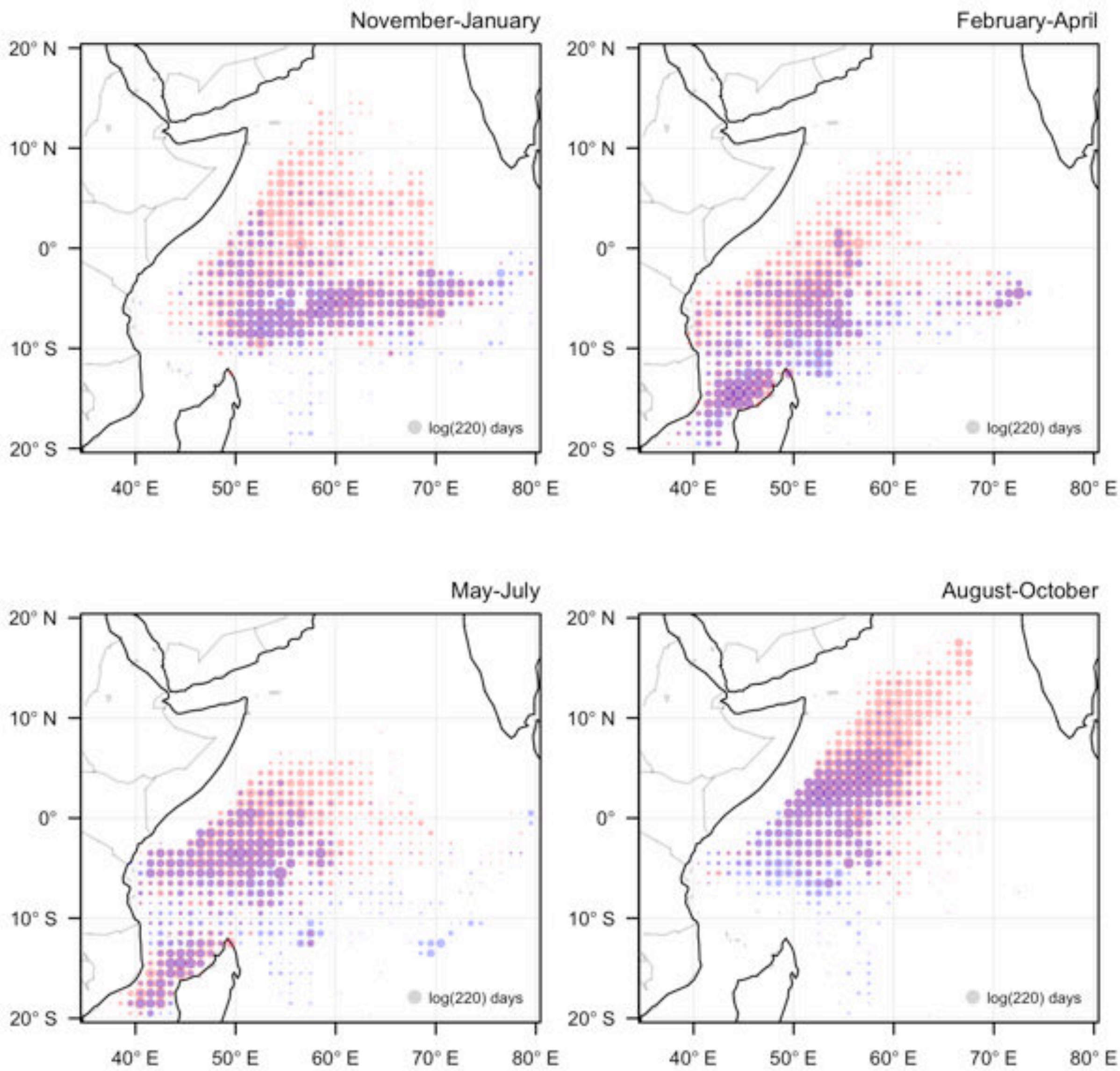

Figure 4.1 Seasonal patterns of fishing effort by the Spanish (red) and French (blue) flagged vessels in the western Indian Ocean in each of four fishing seasons: November-January and February-April (northeast monsoon), and May-July and August-October (southwest monsoon). Circle size shows the total log fishing days allocated into each grid cell in each season during 2007-2011.

4.2.2 Data

The behaviour of the fleet was considered at the spatial resolution of 1° latitude/longitude grid cells and the temporal resolution of one month. Purse seine fishing data were available from the Indian Ocean Tuna Commission (IOTC; www.iotc.org, downloaded Sept 2012). Data were disaggregated by flag nationality to distinguish between the French, including vessels flagged to French Territories (33.7% registered vessels), and Spanish, including Spanish-owned vessels flagged to Seychelles (53.1% registered vessels), components of the fleet as these had a consistent presence in the western Indian Ocean during the period analysed (2007-2011).

Data were obtained for four aspects of the biophysical ocean environment relevant to purse seine fishing; sea surface chlorophyll-*a* (SSC; mg/m^3), sea surface temperature (SST; °C), sea level anomaly (SLA; cm) and wind speed (m/s). All environmental variables were downloaded in 8-day intervals but averaged by month to correspond with fisheries data. This averaging inevitably smoothed over short term oceanographic features that may influence the fine scale allocation of effort, although basin scale environmental gradients were preserved. Data for SSC and SST were obtained from measurements produced by the MODIS sensor, made available for download by the Distributed Active Archive Centre of the Goddard Space Flight Centre/NASA (available at http://disc.sci.gsfc.nasa.gov, downloaded August 2012). SSC was log transformed to improve the spread of skewed values. SLA data were obtained from information collected by the TOPEX and Poseidon altimeters, made available for download by Aviso (available at http://www.aviso.oceanobs.com, downloaded August 2012). Data on wind speed were collected by Envisat and made available for download by MyOcean (available at http://www. myocean.eu, downloaded August 2012).

4.2.3 Statistical modelling

A series of models was fitted to the data. The response variable was binary, indicating whether or not fishing effort was observed in a location in a given month. Nine explanatory variables were chosen based on an understanding of the tools, techniques and fishing practices used by skippers to find tunas, although only variables that were relevant in explaining the behaviour of the fleet at a broad spatiotemporal scale considered (Table 4.2). Four variables described the biophysical characteristics of the location; oceanographic conditions (*SST*, sea surface temperature; *SSC*, sea surface chlorophyll-a concentration; *SLA*, height of sea level anomaly) and meteorological conditions (*wind*, wind speed over the sea surface). The variable *past use* described the past behaviour of the fleet, taking into account seasonality in the use of fishing grounds (the frequency the location had been fished in the same month in the previous five years by vessels of the same flag nationality) The variable *distance* described the described the position of a location relative to port Victoria, which for simplicity was taken to be the main port used by the fleet. In addition to the main effects, the variables *year*, *month* and *flag* were included to account for possible temporal variation in the spatial footprint of the fleet.

Table 4.2 Summary of the explanatory variables considered in the models, their predicted effect on effort allocation into an area and data sources. All variables were aggregated at monthly intervals and at a spatial resolution of 1° latitude/longitude.

Variable	Description	Range/units	Data source
Categorical variables			
Year	Calendar year	2008-2012	-
Season	Quarterly period; February-April, May-July, August-October, November-January	1-4	-
Flag	Flag nationality of reported effort	France/Spain	IOTC
Past use	Frequency with which the location was fished in the same month in the previous five years by vessels of the same flag nationality	0-5	IOTC
Continuous variables			
SSC	Log-transformed sea surface chlorophyll-*a;* proxy for primary productivity	0.02-25.8 mg/m^3	MODIS
SST	Sea surface temperature	22-32 °C	MODIS
SLA	Sea level anomaly; proxy for thermocline depth	-36-50 cm	Topex/Poseidon
Wind speed	Wind speed at 10 m above the sea surface	0-15 m/s	Envisat
Distance	Distance from port Victoria, Seychelles (calculated using the Spherical Law of Cosines)	0-3,000 km	-

A candidate set of generalised additive models (GAMs) was chosen *a priori* and fitted to the data using R 2.15 (R Development Core Team 2012) using the package *mgcv* (Wood 2006). GAMs were chosen over generalised linear models due to their ability to deal with non-linear relationships between the response and explanatory variables, which was useful for examining the potentially complicated effect of the environmental variables. Smooth functions were used to fit to the variables *SSC*, *SST*, *SLA, wind* and *distance*. Penalized cubic regression splines were used for computing efficiency due to the very large number of observation in the data. The degrees of freedom (or ‘wiggliness’) of the smooth functions was determined for each explanatory variable as part of the model fitting process, removing the subjectivity of manually determining knot locations (Wood 2006). Information Criterion (AIC) was used to rank and assign support for the competing candidate models. This selection criterion uses maximum likelihood scores as a measure of how well the model fits the data, taking into account model parsimony. The data were split randomly into a training dataset (90%) and a validation dataset (10%), with the latter used to evaluate the predictive accuracy of the models using the area under the Receiver Operating Characteristic curve (AUC), where a score of 0.5 indicates that model accuracy is no better than random and a score of 1 indicates perfect discrimination (Fawcett 2006).

4.3 Results

Model selection resulted in a single model containing 100% of the AIC weight, indicating a high degree of model selection certainty (Burnham and Anderson 2002). This AIC-best model contained all nine explanatory variables. Predictions from the best model corresponded well with the observed distribution of effort in the validation dataset (AUC = 0.868), indicating that the model could predict the spatial behaviour of the fleet with reasonable accuracy.

Average predictive comparisons illustrating the magnitude of effect of each of the predictor variables on the response are shown in Figure 4.2. The variable *past use* had the most important effect on the probability of observing fishing effort in a location, indicating that fishing was increasingly more likely to be observed in locations that had been visited more frequently in the same month in previous years by vessels of the same flag nationality. Taking into account the influence of all other variables, there was only a 5.4% mean chance of observing fishing in a location that had never been visited in the recent past, whereas fishing effort was on average 36.9% more likely to be observed in a location that had been visited consistently in the previous five years.

The distance of a location from port Victoria also had an important effect on the spatial behaviour of the fleet, with fishing 13.9% less likely to be observed in a location 2,500 km from port than a location 500km from port. This relationship between *distance* and the response was negatively exponential, with the positive influence of distance initially deteriorating gradually but becoming increasingly negative beyond 1,500km from port Victoria (Figure 4.3).

The variables *SSC* and *SST* had positive effects on the probability of fishing being observed in a location, indicating that in general the fleet was more likely to fish in warmer, more biologically productive waters. For both variables the functional relationship with the response was linear throughout low and mid-range values, but at high values the positive influence either flattened out or, in the case of SST, diminished (Figure 4.3). Average predictive comparisons indicated that for both variables the magnitude of effect on the response was reasonably small (Figure 4.2). For example, fishing was, on average, just 3.3% more likely to be observed in a location with a mid-level SSC concentration (0.11 mg m^3, global mean) than in a location with very a low SSC concentration (0.08 mg m^3, 1^{st} quartile). Similarly, fishing was only 2.8% more likely to be observed in a location with a mid-level SST (28.1 °C, global mean) than in a location with a relatively low SST (26.6 °C, 1^{st} quartile).

The variables *SLA* and *wind* had negative effects on the probability of fishing being observed in a location, although in both cases the magnitude of this effect was very small (Figure 4.2). The functional relationship between SLA and the response was slightly curvilinear and suggested that fishing was less likely to be observed in locations with either very high positive or very low negative sea surface anomalies. Similarly, the smooth for *wind speed* indicated that fishing was less likely to be observed in areas with either very low or very high wind speeds (Figure 4.3).

The effects of the variables *year*, *season* and *flag* were small but nevertheless suggested that the mean probability of fishing being observed in a location varied through time, and between the flag nationalities. Annual variation was probably explained by the differences in areas fished between years, with fishing activity most constrained in space in 2009-2010 probably due to a combination of a reduced fleet size and the influence of piracy activity on the search behaviour of vessels. Seasonal variation was probably due to differences in the geography of seasonal fishing grounds, with fishing on average more likely to be observed in any given area during the northeast monsoon months (November-April) when the fleet allocated effort over more expansive fishing grounds. Variation between flag nationalities was probably due to differences in the size of the French and Spanish fleet components, and hence the geographical dispersal of fishing activity by each respective flag in a given month.

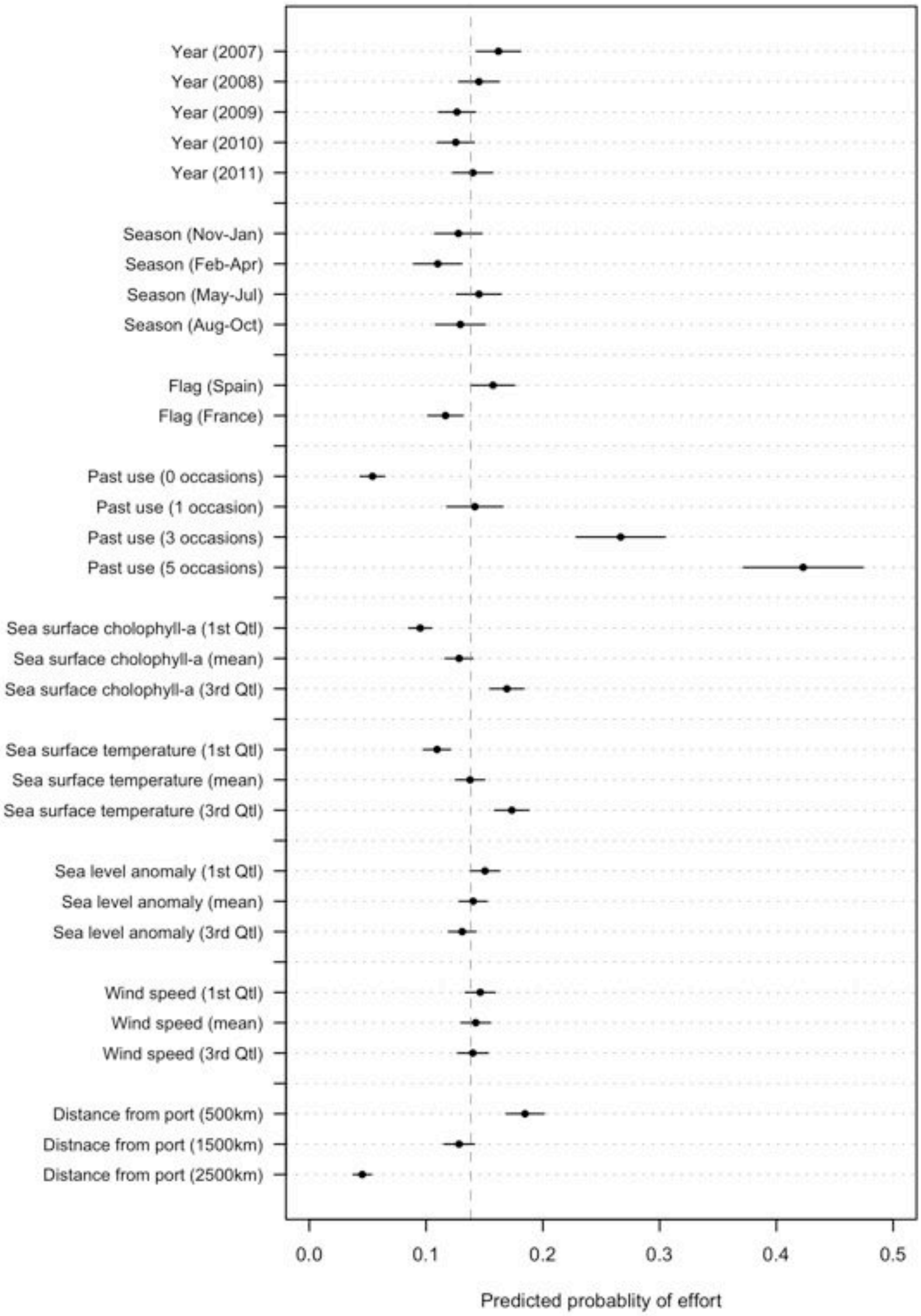

Figure 4.2 Average predicted comparison from the AIC-best model illustrating the effect of the categorical explanatory variables on the probability of observing effort in a location. The dashed vertical line indicates the predicted overall mean probability. Heavy horizontal lines through each point indicate approximate 95% confidence intervals. Note the truncated x-axis. See Table 4.2 for descriptions of the explanatory variables.

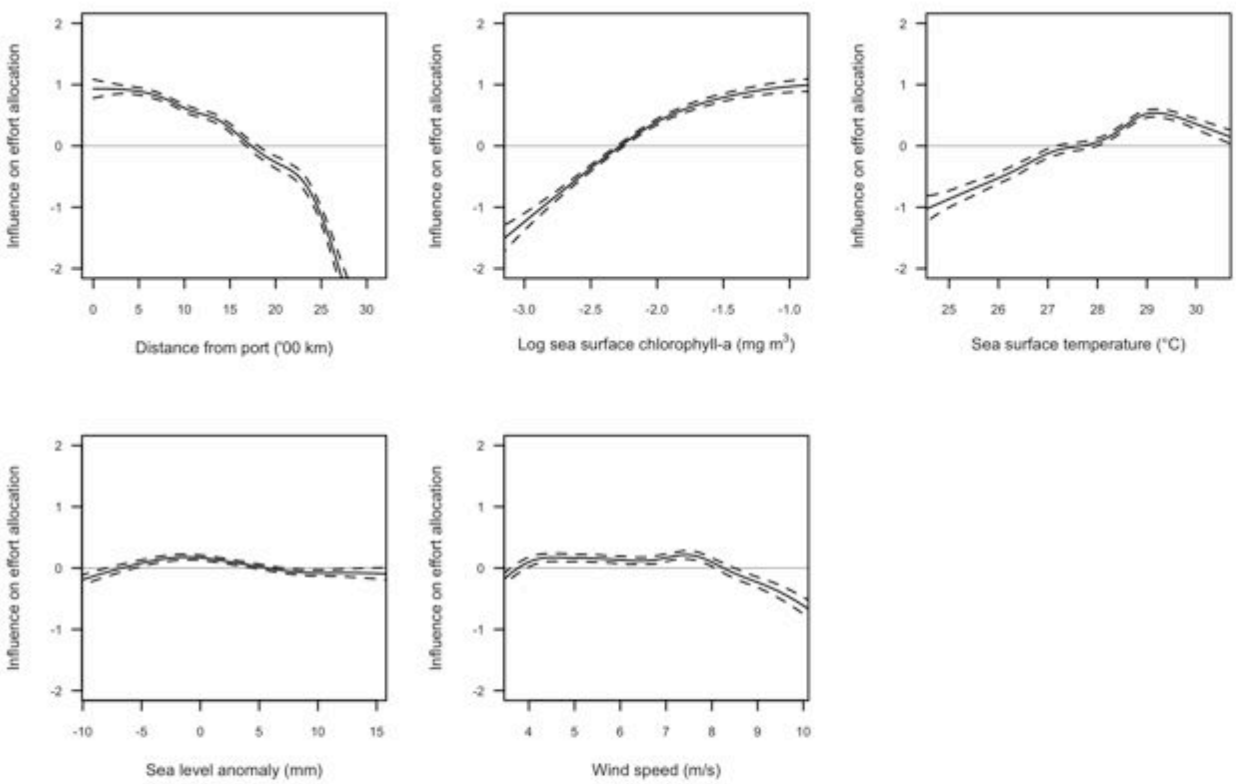

Figure 4.3 Additive components of the GAM showing the influence of the environmental variables on the probability of effort being observed in a location. The dashed lines show the standard errors. To improve interpretation, the x-axis of each panel is trimmed to show only the middle 90% of the observation. See Table 4.2 for a description of the explanatory variables.

To gain further insight into the effects of the environmental and *past use* variables on the spatial behaviour of the fleet their contribution to model accuracy was mapped in space. This was achieved by comparing for each location the accuracy of predictions generated using the AIC-best model with predictions from alternative models in which the focal variables were omitted.

Predictions from the *alternative 1* model, which was specified by dropping the four environmental variables (*SSC, SST, SLA, wind*) from the AIC-best model, showed both slight improvement and deterioration in accuracy in several regions. These changes in prediction accuracy tended to be correlated in space, corresponding with basin-scale gradients in environmental conditions. In all four seasons, prediction accuracy deteriorated in southern regions of the fishery, particularly below 10°S (Figure 4.4). When predicting from the AIC-best model, fishing had a reasonably high probability of being observed in these areas due to the close proximity to port Victoria. However, these southern grounds, which are situated along the boundary of the Indian and Southern Oceans, are characterised by biologically unproductive waters, deep thermoclines and high winds, making them unsuitable for fishing grounds for tropical tunas. In some seasons, particularly November-January and May-June, the omission of the environment variables in the *alternative 1* model resulted in improvements to prediction accuracy in the central and northern regions. The AIC-best model predicted a higher probability of observing fishing in these regions probably due to the relatively high levels of SSC observed. However, in actuality these regions received little fishing activity, despite having apparently suitable tuna habitat. Thus, the patterns of deterioration and improvement in prediction accuracy in the *alternative 1* model suggests that whilst environmental conditions are important in explaining the absence of fishing activity in certain areas, they are poor at predicting with certainty the presence of fishing effort.

Predictions from the *alternative 2* model, which was specified by dropping the *past use* variable from the AIC-best model, showed large deteriorations in accuracy throughout the fishery region, reiterating the importance of this variable in explaining the spatial behaviour of the fleet. Particularly large deteriorations in accuracy were evident in the Seychelles region (50-60°E) during May-July, and in the Somali Basin region (0-10°N) during August-October, which suggest habitual allocation of fishing effort into these seasonal grounds (Figure 4.5). During May-

July, free-swimming tuna schools are seasonally abundant in the western equatorial fishing grounds, and their surface schooling behaviour makes them especially vulnerable to purse seine gear. It is not clear to what extent this seasonal availability in the resource is coupled to environmental processes, but it appears that the location and timing of this event is well known to skippers, and this knowledge has an important influence on the spatial behaviour of the fleet. During August-October, a combination of enhanced primary productivity (reflected by high SSC concentrations) and strong ocean gyres in the Somali Basin region creates optimal conditions for fishing around floating objects (tunas tend to associate more closely with floating objects in biologically rich areas with increased forage availability; R. Bargain, skipper, personal communication). Whilst these fishing opportunities are more closely linked to environmental conditions, the very strong influence of the *past use* variable in explaining the presence of fishing in these relatively small grounds again implies habitual fleet behaviour.

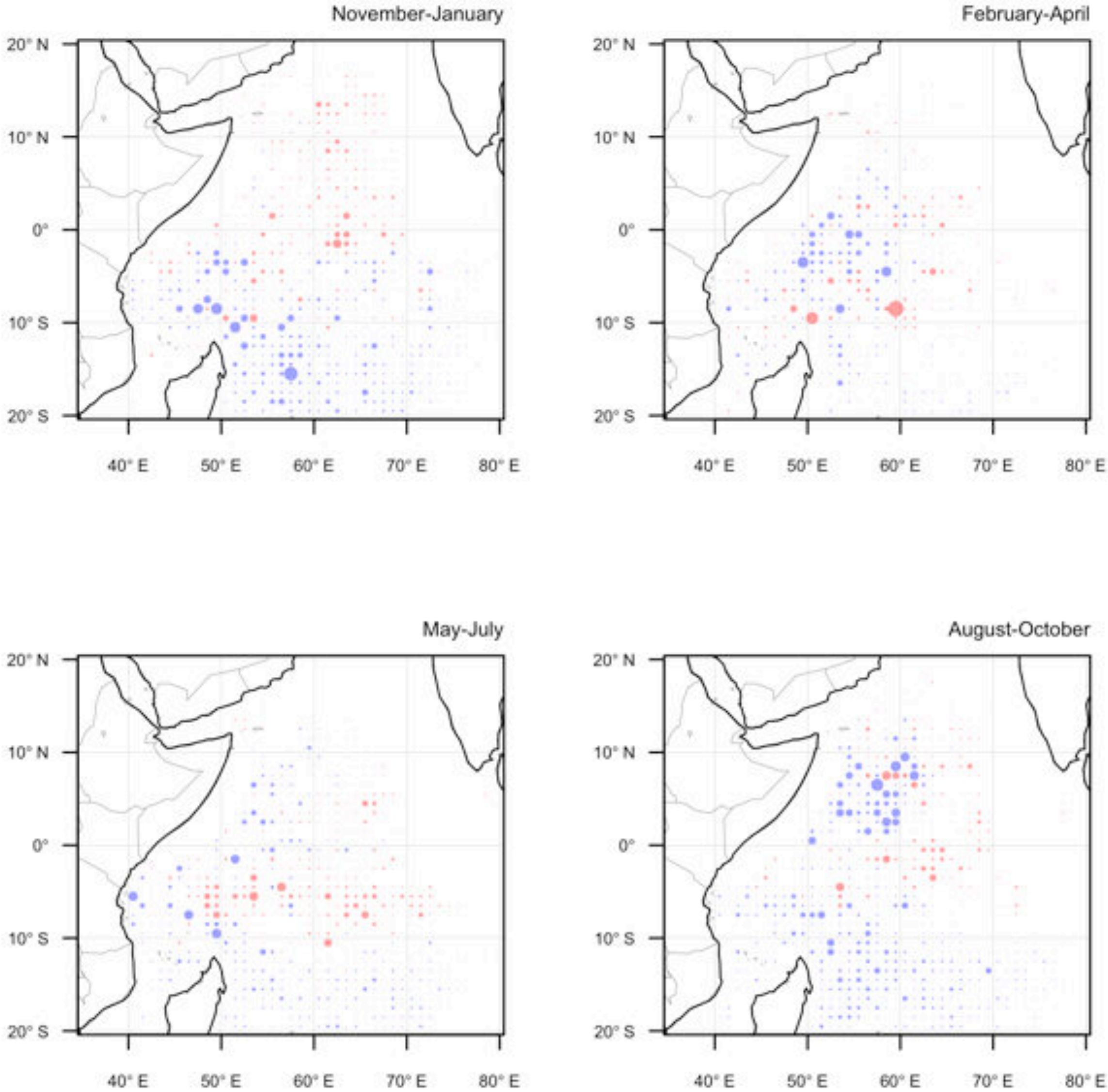

Figure 4.4 Deterioration in the accuracy of model predictions for each of the four fishing seasons when the environmental variables (*SSC, SST, SLA, wind*) were removed from the AIC-best model (*alternative 1* model). The size of the circle shows the relative magnitude of the difference in predictions and is comparable between plots. The colour indicates a more (red) or less accurate (blue) prediction.

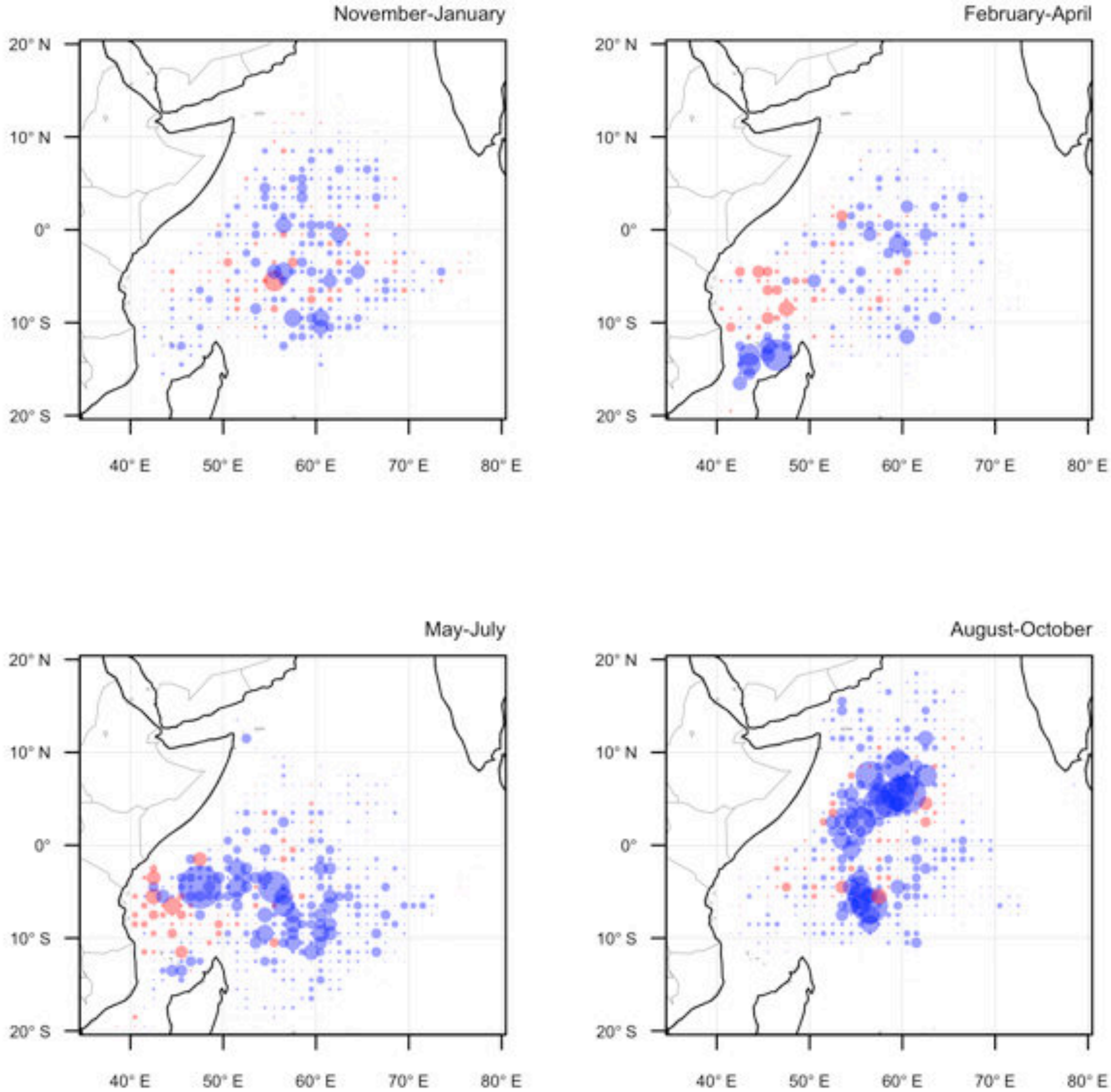

Figure 4.5 Deterioration in the accuracy of model predictions for each of the four fishing seasons when the variable *past use* was removed from the AIC-best model (*alternative 2* model). The size of the circle shows the relative magnitude of the difference in predictions and is comparable between plots. The colour indicates a more (red) or less accurate (blue) prediction.

4.4 Discussion

The ability to anticipate the spatial behaviour of fishing fleets is of increasing importance in fishery science. On the premise that an improved understanding of effort allocation will facilitate better anticipation of fleet spatial behaviour, the aim of this study was to develop a better understanding of the factors that drive the spatial behaviour of the Indian Ocean tuna purse seine fleet.

A key finding of this study was the strong inertia observed in the spatial behaviour of the purse seine fleet, characterised by consistency in the use of seasonal fishing grounds. Patterns of effort allocation were not adequately explained by biophysical ocean conditions alone but corresponded well with past fleet behaviour, suggesting that purse seine skippers tended to fish in familiar areas in which they had some previous personal or second-hand experience (i.e. learnt from others). Also, high levels of cooperation and communication between vessels, and long careers of many skippers (e.g. > 10 years; Moreno et al. 2007), have probably homogenised seasonal knowledge and experience in the fishery, which may explain the consistency in spatial behaviour at the fleet level. The indication of experience-based decision making is supported by research in the human psychology literature, which has shown that when faced with incomplete information people may not strive to make optimal decisions, but instead rely on simple heuristics (i.e. decision rules conditioned on past experience) to make decisions that achieve a satisfactory result (Tversky and Kahneman 1974; Camerer et al. 1997). Moreover, this finding echoes those from previous studies of fisher decision making that have shown uncertainty, and associated risk, to be an important influence on fishers' expectations of catch or revenue in a location, and that familiarity can lead to habitual patterns in behaviour

(Holland and Sutinen 1999; Curtis and McConnell 2004; Pradhan and Leung 2004; Smith 2005; Valcic 2009).

A second important finding from this study was the bounding influence of biophysical ocean conditions on the spatial behaviour of the fleet, with certain regions characterised by unfavourable fishing conditions at any point in time and consequently not visited by the fleet. The influence of the physical environment has rarely been considered in studies of fisher behaviour, perhaps because most previous research has focused on fisheries in which the resource is associated with the sea floor (e.g. demersal trawl fisheries; see van Putten et al. 2011). By contrast, in the open ocean, the distribution of tunas and other pelagic species is influenced by biophysical conditions near the ocean surface, which can be highly dynamic in space and time (Marsac 1999; Song et al. 2008). However, whilst these results showed that conditions associated with poor fishing conditions (e.g. cool sea surface temperatures, biologically unproductive waters) were relatively good predictors of the absence of fishing, apparently promising environmental conditions for fishing were poor predictors of the presence of fishing. This result probably reflects a limitation of using biophysical ocean conditions as a proxy for the distribution of purse seine fishing opportunities, which in reality are influenced by a variety of factors. For instance, the detectability of a tuna school is influenced by the vertical distribution of a school in the water column (which can vary by species, season and region; Marsac 2012), and also the density of floating objects around which schools often associate (which can also vary by region; see Chapters 2 and 5).

The results presented here have important management implications for anticipating the response of the purse seine fleet to events that would disrupt access to traditional fishing grounds, for example climatic anomalies, pirate activity or the implementation of spatial closures. The prediction of fleet spatial behaviour under stable fishing conditions is possible with a reasonably good level of accuracy, on the basis that strong inertia in fleet behaviour means that the distribution of effort in the past is a good predictor of where it will be allocated in the future. However, under novel conditions, such a following the closure of a significant area of fishing ground, there are likely to be considerable challenges in predicting the reallocation of fishing effort. In these situations, the past behaviour of the fleet is unlikely to be a suitable portent of where effort will be allocated, and an accurate prediction of behaviour would probably require near the same near real-time information that is available to skippers themselves. Furthermore, the prediction of behaviour would probably need to account for the influence of group-level dynamics that emerge through knowledge sharing between skippers (see Chapter 2). The influence of processes such as teamwork and competition on the distribution of fishing effort were not sufficiently considered in this study, which highlights a drawback of the statistical approach used, and hence a better understanding of cooperation and competition dynamics and their influence on fleet-level behaviour are recommended as priority topics for future research.

Chapter 5

5 Examining the impact of spatial closures on the behaviour of a tropical tuna purse seine fleet

5.1 Introduction

The use of spatial tools in fisheries management, which include marine reserves and temporary closures, has become increasingly popular in addressing problems of sustainability (Gell and Roberts 2003; Hilborn et al. 2004; Sumalia et al. 2007). In coastal regions, the reduction of fishing mortality and incidental impacts associated with fishing inside a closed area can result in ecosystem-level recovery (Halpern 2003; Hilborn et al. 2004), which in turn can directly benefit fisheries production, typically via the net emigration of fish out of the closure area (spillover) or the export of eggs into adjacent regions (recruitment subsidy; Gell and Roberts 2003). Whilst these mechanisms are less well defined in offshore regions, area closures have been used with varying success in the open ocean to reduce fishing capacity or to protect a vulnerable species or component of a fish stock (Davies et al. 2012). In all marine systems, area closures can provide management-level benefits by serving as a buffer against uncertainty, for example stock assessment error and failure of input controls, and by acting as a valuable scientific reference site where trends in recruitment and stock structure can be monitored in the absence of fishing (Hilborn et al. 2004; Gaines et al. 2010).

As with any other fisheries management tool, it is important to evaluate the performance of closed areas in achieving their objectives. Considerable work has focused on evaluating the conservation benefits to fish stocks and marine habitats within closed areas (Halpern and Warner 2002; Hart 2006; Halpern et al. 2009; Lester et al. 2009), as well as the contribution of closures to improving fishery yields (Gell and Roberts 2003; Sale et al. 2005; Gaines et al. 2010). However, far less attention has been directed at evaluating the wider management implications of closed areas and, in particular, how a closure affects the dynamics of effort allocation in a fishery. A likely consequence of closing an area to fishing is fleets reallocating fishing effort elsewhere, potentially resulting in unintended and undesirable management outcomes, including increased fishing pressure on vulnerable fish stocks or sensitive habitats in other areas (Fogarty and Murawski 1998; Dinmore et al. 2003). These displaced impacts, which can dilute the net management benefits of closed areas, have seldom been analysed and remain an important uncertainty in evaluating the effectiveness of spatial management policies (Fulton et al. 2011).

Retrospective analyses of the response of fishing fleets to closed areas are scarce, although from the handful of published examples a varied set of fleet responses has been demonstrated. Murawski et al. (2005) observed a concentration of effort by otter trawlers around the boundaries of closed areas in the northwest Atlantic, a phenomenon now widely termed 'fishing the line', and interpreted these patterns of effort reallocation as a response either to the spillover of biomass or the seasonal movement of fish out of the closures. A similar reallocation of effort was observed for the Atlantic tuna purse seine fleet around a temporary closed area, although given the short timescale considered this response was presumably linked to practical changes in where the fleet could operate rather than a response to increased tuna abundance (Torres-Irineo et al. 2011). In contrast, Wilcox and Pomery (2011) found no evidence of vessels fishing the line in a Californian rockfish fishery, due either to the lack of a real or perceived spillover effect or an informal agreement between fishers and the reserve manager not to fish the boundaries. There is also some evidence to suggest that vessels may disperse widely when fishing grounds are closed in an attempt to escape the increased competition along closure boundaries (Fogarty and Murawski 1998; Rijnsdorp et al. 2000).

In these examples, the reasons for the observed reallocation of effort around closed areas have generally been inferred and few studies have been able to disentangle the policy effect of a closure from other competing influences (Smith et al. 2006). This is because most previous evaluations of closed area effects have used observation-based before-after approaches (e.g. McClanahan and Kaunda-Arara 1996; Russ et al. 2004; Torres-Irineo et al. 2011), which although able to identify changes in behaviour, cannot ascribe such changes completely to the closure of fishing grounds given the absence of a control site or other means of accounting for changes in the environmental and socio-economic drivers of fishing behaviour. For instance, Roberts et al. (2001) show a statistically significant increase in catch rate by artisanal fishers around a marine reserve after 5 years, but without a reference site it is difficult to associate the increase in catch rate with the creation of the reserve as opposed to a period of strong recruitment or changes in fishing practices (Hilborn 2002). Therefore, alternative approaches are necessary to isolate the policy effect of closures on fishery dynamics.

A promising approach is to build up a counterfactual scenario of fleet behaviour by developing a predictive model of effort allocation that accounts for a broad range of influences on fishery dynamics. In this way, the observed response of a fleet to a closure can be compared to predictions of how the fleet would have behaved if the closure had not been implemented. This approach has been demonstrated by Smith et al. (2006), who showed it was necessary to account for a range of factors influencing catch rate, including the use of multiple gears, heterogeneity in fisher skill and the seasonal distribution of fish, to reveal the negative effect of two marine reserves on the catch of a Gulf of Mexico reef-fish fishery.

In this study we use a counterfactual approach to examine the policy effect of two closed areas on the behaviour of the tropical tuna purse seine fleet in the western Indian Ocean. The combination of a highly mobile resource and highly mobile fishing fleets presents a challenge for the effective design of spatial management policies in tuna fisheries and it is not clear to what extent area closures will impact the fishing behaviour of tuna fleets and ultimately contribute to the sustainable management of pelagic stocks (Davies et al. 2012; Kaplan et al. 2013). The counterfactual approach we use here is particularly useful for evaluating the overall contribution of closed areas to tuna fisheries management in the dynamic offshore Indian Ocean environment, where the spatial behaviour of the purse seine fleet can be highly variable and driven by a range of influences at the relatively local scales at which closures have been implemented (see Chapters 2 and 3). Thus, the focus of our analysis is understanding the causal effect of closures on fleet spatial behaviour and to characterise the reallocation of effort by the fleet in response to closed areas.

5.2 Methods

5.2.1 Description of the closed areas

The two closures examined differed in their size, position within the fishery region and intended management objectives. In November 2011 and again in 2012, the Indian Ocean Tuna Commission (IOTC) designated a one-month closure with the objective of restricting the fishing capacity of the fleet and reducing fishing pressure on stocks of yellowfin and bigeye tunas (Resolution 12/13; http://www.iotc.org/English/resolutions.php; accessed 1st June 2013). The closure extended from the Somali coast to 60°E and covered a large part of the productive northwest fishing grounds typically fished by the fleet during August-November (Figure 5.1). This region is a key fishing area for the purse seine fleet and is characterised by very high catches, mainly around floating objects (Dagorn et al. 2012b).

In late 2010 the British government designated their entire British Indian Ocean Territory (BIOT) a marine reserve. The BIOT reserve is positioned at the eastern periphery of the purse seine fishery area in a region typically fished during November-February characterised by catches of free-swimming schools (Figure 5.1). Prior to the closure of BIOT, the importance of the area in terms of purse seine fishery production varied considerably from year to year, with the average proportion of total monthly catch taken within the Territory ranging from 0-23% (MRAG Ltd; unpublished data, 1999-2008). The designation of BIOT was not linked to regional fisheries management policy and whilst no formal management plan has yet been developed, several objectives of the reserve can be inferred, including the provision of a scientific reference site and near shore and pelagic biodiversity conservation (Sheppard et al. 2012).

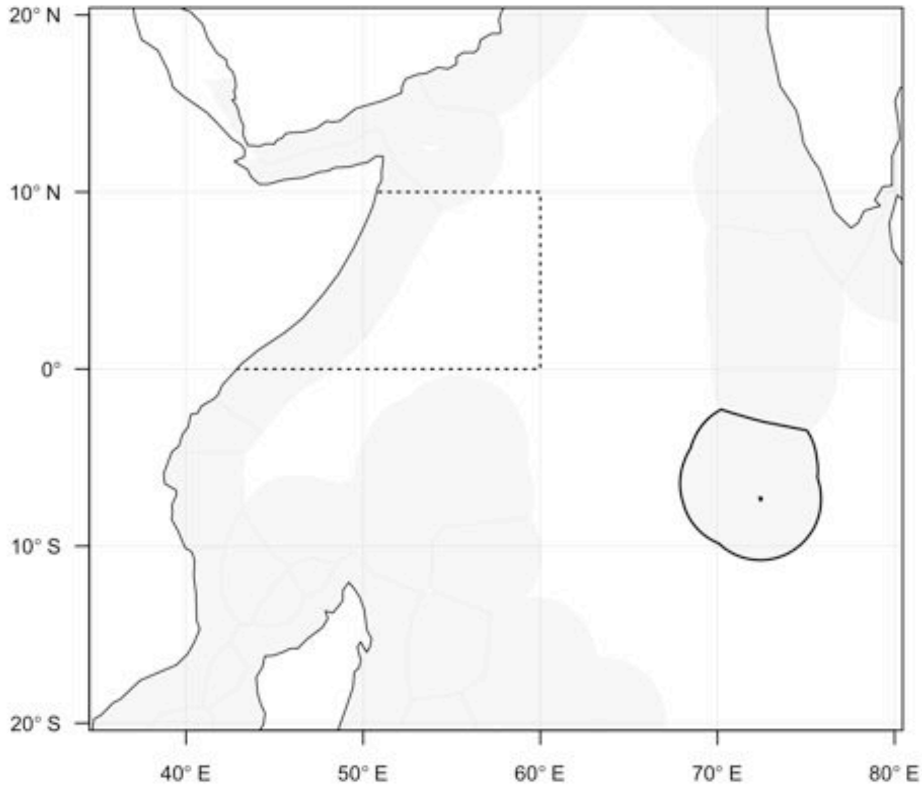

Figure 5.1 The western Indian Ocean tuna purse seine fishery region showing the position of the IOTC closure (dotted line) and British Indian Ocean Territory marine reserve (solid line). National exclusive economic zones are shown shaded grey for reference.

5.2.2 Statistical model

Due to the seasonal movement of the fleet, the impact of the two closures was examined only during relevant periods. In addition, given the temporary nature of the IOTC closure and the short period that BIOT has been designated as a reserve, our analysis was focussed on the short-term reallocation of effort rather than higher level investment and fishery participation decisions. For the IOTC closure, we focussed on the behaviour of the fleet during November, the month of the closure, in

2011 and 2012. For the BIOT reserve we focussed on the period December-January when the provision of fishing licences was historically highest (MRAG Ltd; personal communication). Fishing data were available until December 2012, allowing the analysis of two full fishing seasons.

We used the model described in Chapter 3 to generate predictions of how the fleet would have allocated effort in the absence of the closures. The model was used to predict retrospectively the probability of effort being allocated into a location based on three main drivers; the response of the fleet to the bio-physical conditions of the ocean, practical constraints on movement and inertia in the use of seasonal fishing grounds. To train the model, monthly fishing data were disaggregated by flag nationality and kept at their native spatial resolution of 1° latitude/longitude. Data were split into the periods 2006-2010 for model training and 2010-2011 for prediction.

5.3 Results

5.3.1 IOTC closure

In the absence of the closure the fleet was expected to have fished within the IOTC closure area in both years of its implementation. However, the predicted distribution of effort was markedly different for the Spanish and French components of the fleet. The Spanish fleet component was expected to have fished across a large area extending from the Seychelles plateau in the south to the Omani coast in the north, with core fishing grounds predicted within the area of the IOTC closure. In comparison, the French fleet component was expected to have fished across a comparatively small area in subequatorial waters, with core grounds predicted on the

Seychelles plateau to the south of the closure boundary (Figure 5.2). This difference in the predicted allocation of effort can be attributed to variation in fishing strategy, with Spanish vessels tending to target schools associated with floating objects at higher latitudes for a longer period during the boreal summer months and French vessels moving into subequatorial grounds earlier in the year in pursuit of free swimming schools.

In the observed scenario the fleet complied with the closure in both years of its implementation and fishing effort was allocated to the south and east of the closed area boundaries (Figure 5.3). There was some similarity in the response of the Spanish and French fleet components, with both nationalities allocating the majority of fishing effort to the south of the closure. This behaviour largely corresponded with counterfactual predictions, suggesting that vessels mainly fished in parts of the seasonal fishing grounds that remained accessible. The major difference in the response of the two flag nationalities was the allocation of effort by Spanish vessels to the east of the closure area, well beyond the eastern extent of the typical seasonal fishing grounds (Figure 5.3). This allocation of effort is probably explained by skippers searching for floating objects that had drifted eastwards out of the closure area, which would not be considered usual behaviour under typical conditions due to the reduced chance of finding and catching associated schools in this region (skipper; personal communication). This suggests that either fishing opportunities were not satisfactory in the accessible parts of the typical fishing grounds or that skippers were exploring eastern areas in an attempt to test out new fishing opportunities.

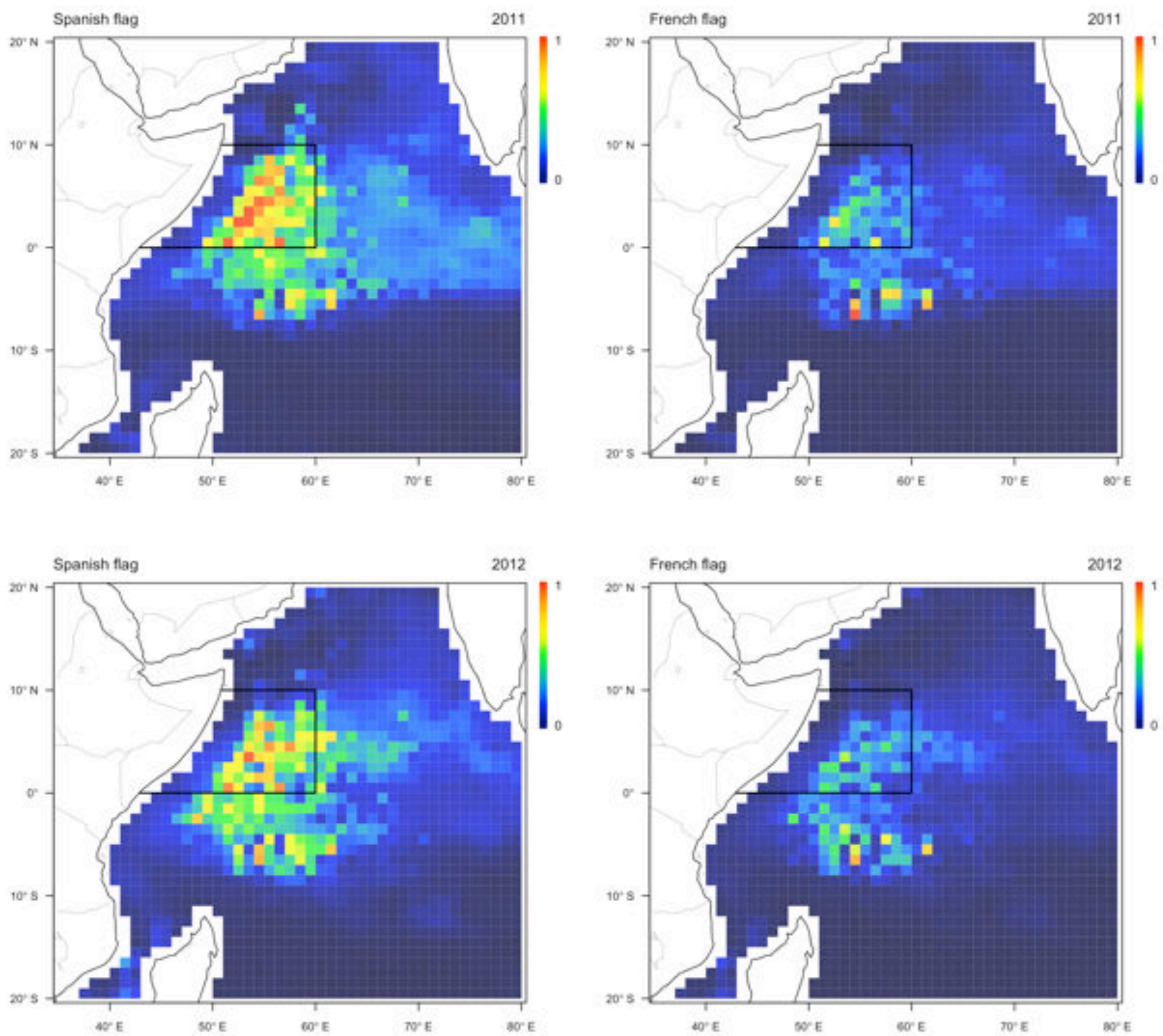

Figure 5.2 Predicted allocation of effort by the Spanish (left) and French (right) components of the fleet in the western Indian Ocean during November 2011 (upper) and 2012 (lower). The location of the IOTC area closure is shown by the solid line. Coloured cells show model predictions of probability of effort being allocated into an area.

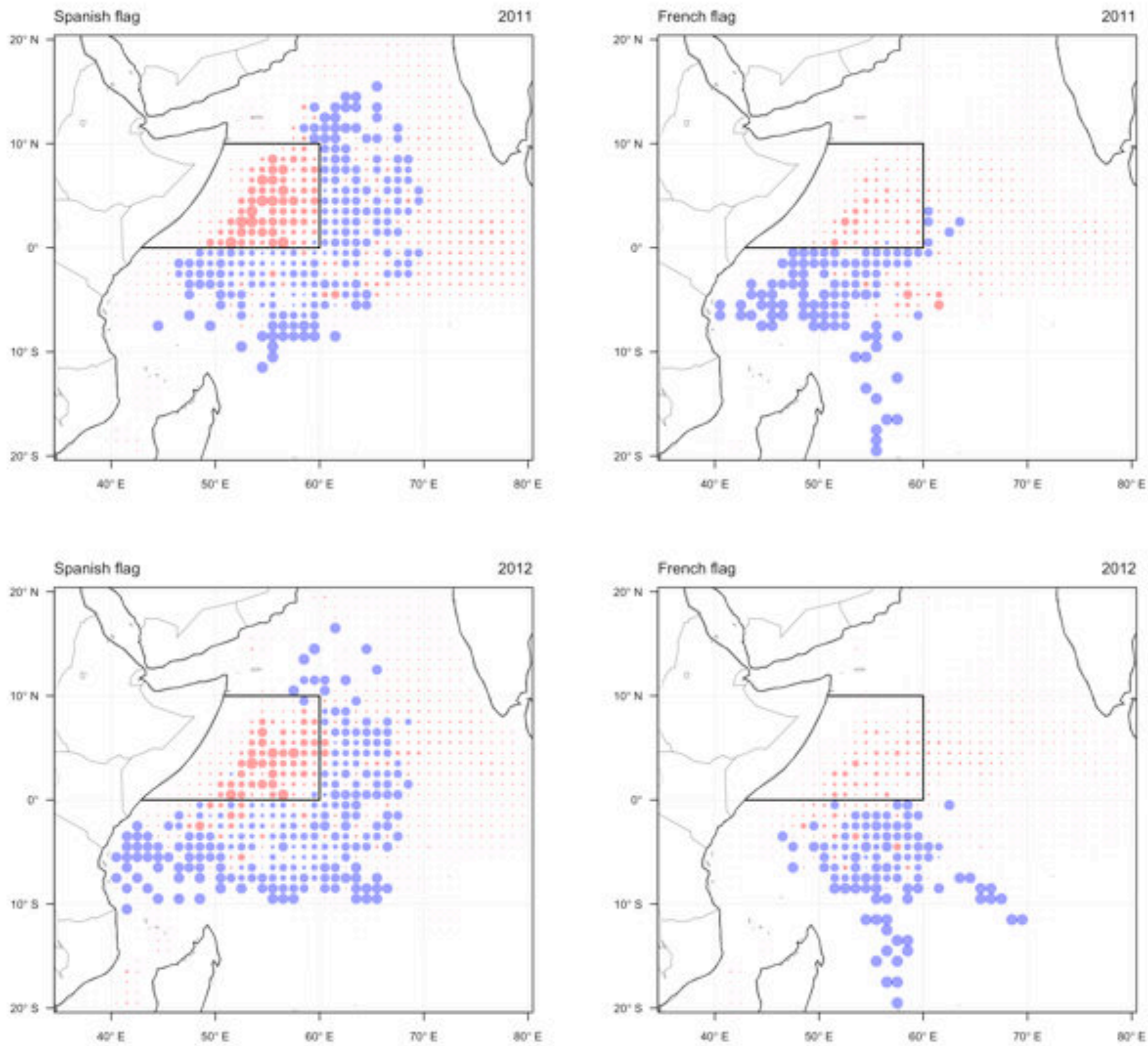

Figure 5.3 Observed allocation by the Spanish (left) and French (right) components of the fleet in the western Indian Ocean during November 2011 (upper) and 2012 (lower). Observations in each grid cell are shown as the predicted probability of effort minus observed response, where blue circles show more effort than expected and red circles show less effort than expected. Circle size indicates the relative size of the residual. The location of the IOTC area closure is shown by the solid line. Observation of French effort below 10°S is explained by passage of vessels to and from port in Mauritius.

5.3.2 BIOT reserve

In the first year of the designation of the BIOT reserve the fleet was expected to have fished across a large area of the western Indian Ocean, with core grounds for both components of the fleet predicted along a subequatorial band extending as far east as BIOT (Figure 5.4). These predictions, which take into account the influence of environmental conditions on the allocation of effort, suggest that fishing conditions were favourable throughout BIOT and the surrounding region during this season. In the second year of the closure of BIOT the expected fishing grounds of the fleet were relatively constricted, particularly for the French fleet component. The predicted southern and eastern distribution of effort was markedly different to the previous year, with a considerably lower probability of effort being allocated within and to the southeast of BIOT (Figure 5.4). This contrast in the anticipated behaviour of fleet between the two years was due to anomalous environmental conditions, characterised by a deeper-than-usual thermocline and reduced sea surface temperatures, resulting in highly unfavourable fishing conditions throughout the BIOT region in the 2011/12 season.

In the observed scenario there was a marked difference in the allocation of effort by the French and Spanish components of the fleet in the first year of closure of BIOT. In the case of the Spanish fleet component, effort was mainly allocated in the Seychelles region as predicted, although some effort was allocated in the northwest Somali basin region (Figure 5.5). This suggest that a number of vessels remained in the main FAD fishing areas out of season, although it is difficult to attribute this as a direct effect of the BIOT closure. The allocation of effort by the French fleet, whilst again mainly concentrated in the southwest Seychelles region, revealed considerable exploration around the BIOT reserve. A number of vessel travelled to the east of

BIOT into areas rarely fished by the fleet, either passing through the closure or passing to the south (Figure 5.5). This fishing behaviour may be explained by poor fishing opportunities experienced elsewhere, prompting French skippers to search in novel areas around BIOT, or may reflect the behaviour of skippers attempting to assess the lost opportunities resulting from the designation of the reserve. In the second year of closure of BIOT the fleet mainly allocated effort throughout Seychelles region (Figure 5.5). This largely corresponded with predictions of the model and thus suggests little disruption of fishing behaviour caused by the reserve. The observation of more effort than expected in the northwest regions by both fleet components may reflect the late movement of the fleet into the free school grounds due to the perceived unfavourable fishing conditions in the southeast.

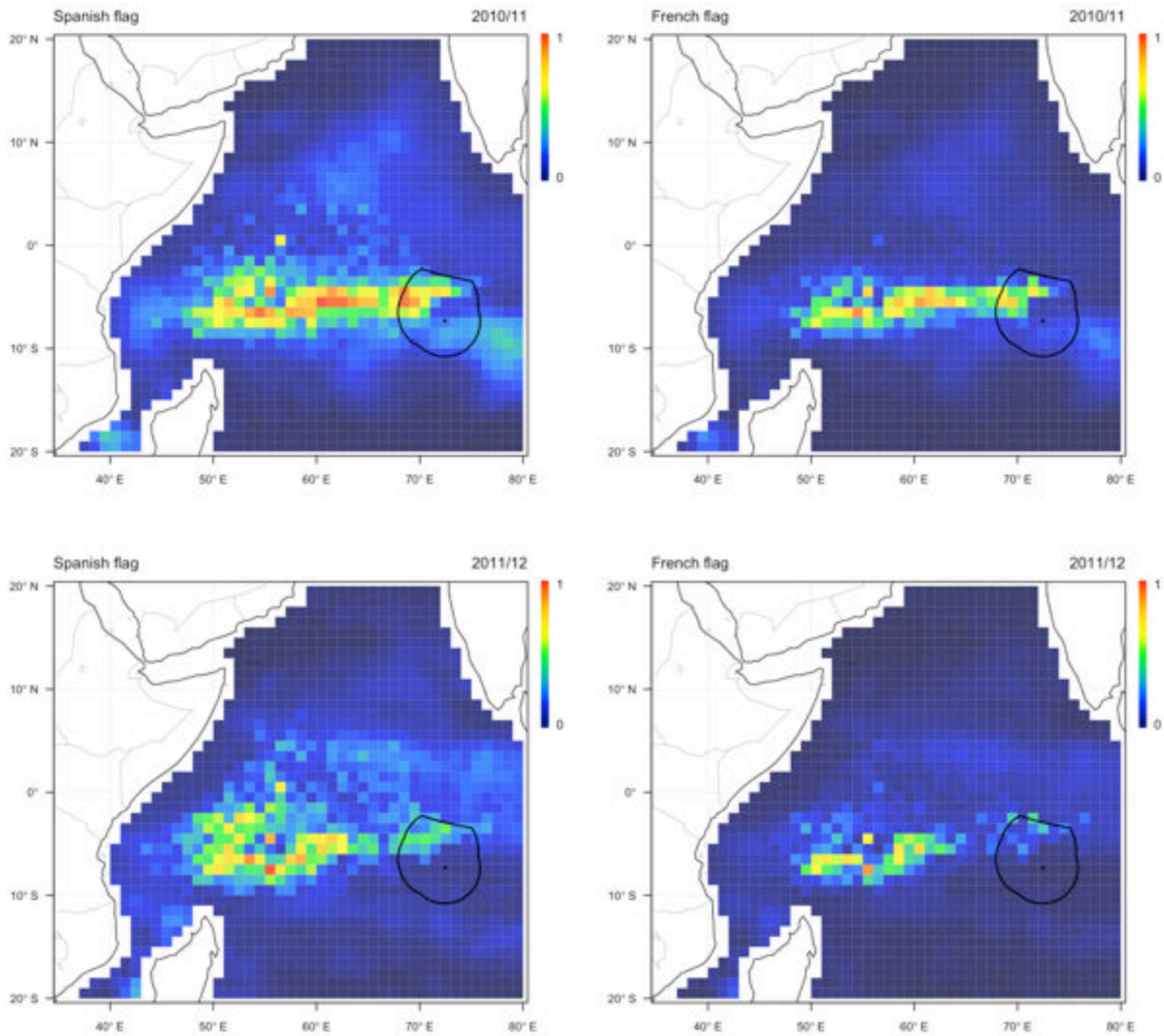

Figure 5.4 Predicted allocation of effort by the Spanish (left) and French (right) components of the fleet in the western Indian Ocean during the months December-January in 2010/2011 (upper) and 2011/2012 (lower). The location of the BIOT closure is shown by the solid line. Coloured cells show model predictions of probability of effort being allocated into an area.

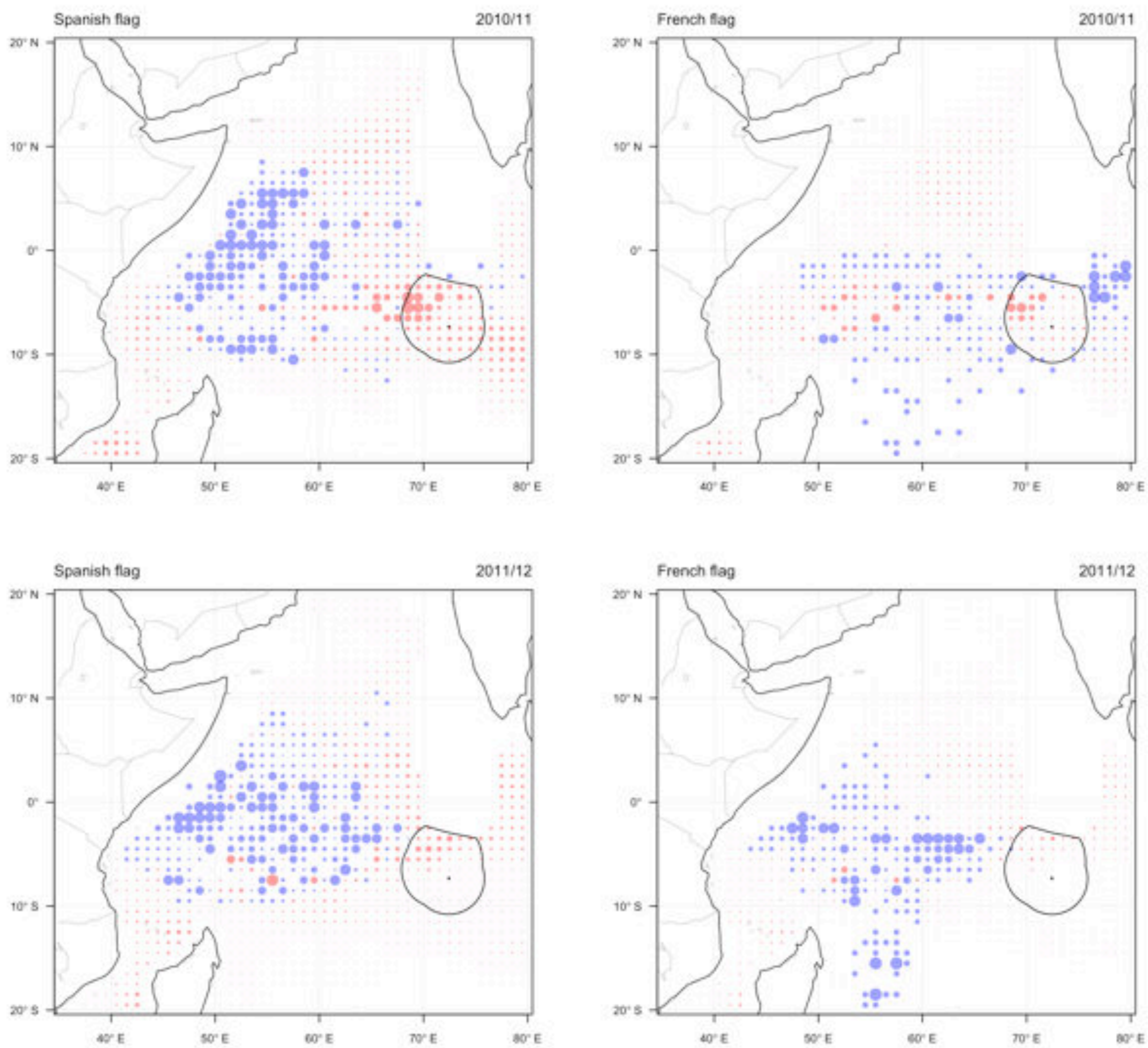

Figure 5.5 Observed allocation of effort by the Spanish (left) and French (right) components of the fleet in the western Indian Ocean during the months December-January in 2010/2011 (upper) and 2011/2012 (lower). Observations in each grid cell are shown as the predicted probability of effort minus observed response, where blue circles show more effort than expected and red circles show less effort than expected. Circle size indicates the relative size of the residual. The location of the BIOT closure is shown by the solid line. Observation of French effort below 10°S is explained by passage of vessels to and from port in Mauritius.

5.4 Discussion

In this study we examined the impact of two closed areas on the spatial behaviour of the Indian Ocean tropical tuna purse seine fleet, using a counterfactual approach to isolate the policy effect of the closures from other competing influences on fleet behaviour. We did not focus on whether the closures achieved their stated fisheries and conservation objectives but rather how and where the fleet reallocated effort in response to the closure of their former grounds. The construction of a counterfactual scenario proved to be crucial in isolating the policy effect of the closures from conflicting environmental influences on effort allocation and our results showed a mixed and inconsistent closure effect on fleet behaviour. Our results also demonstrated the flexibility of the fleet in adapting to the closures, particularly its ability to explore new areas, and furthermore we identified varied responses within the fleet, suggesting that the placement of a closure may have a varying impact on different components of the fleet.

Of particular interest in our results was the inconsistent effect of the BIOT reserve on fleet behaviour. Comparison between the observed response of the fleet and prediction of fleet behaviour under a business as usual scenario, accounting in particular for environmental influences on effort allocation, showed a response to the closure in the first year of its designation but not the second. In the 2010/11 season purse seine fishing conditions appeared to be favourable in the BIOT region and some vessels allocated effort around the boundaries of the closures, suggesting that the closure did result in the exclusion of fishing effort that would otherwise have been allocated there. In the following year, anomalous shallowing of the Seychelles-Chagos Thermocline Ridge, linked to an Indian Ocean Dipole event (Marsac 2012), affected the suitability of purse seine fishing conditions in the region and the fleet was predicted to have a considerably lower probability of fishing within BIOT. This counterfactual scenario coupled with the absence of observed effort close to the boundary of BIOT suggests that the closure in the 2011/12 season had little impact on the behaviour of the fleet. This result serves to highlight the importance of the placement of closures in fishery systems characterised by high variability, where the complex suite of influences on fleet behaviour can make it difficult to predict or evaluate the contribution of a closure to achieving management objectives.

A second key result was the varying magnitude of closure effect on the two fleet components observed for both closures. In the case of the IOTC closure, the Spanish fleet component showed the most marked change in behaviour, with a number of vessels fishing to the east of the closure in typically un-fished areas, whereas the French fleet component allocated effort mainly in traditional grounds to the south of the closure. This varied response is largely explained by differences in the seasonal movement pattern of the fleet components linked to fishing strategy, with Spanish vessels typically remaining in the northwest FAD-fishing grounds for a longer period than French vessels, which move into subequatorial free schools regions earlier. A switch in the relative impact on two fleet components was observed for the BIOT closure in 2010/11, when the French component showed a more evident response to the closure with considerable exploratory behaviour around the closure boundaries. This variation in response is probably again linked to company-level strategy and differences in the targeting of free and associated schools, with Spanish skippers belonging to FAD-orientated companies less inclined to search for free schools in the vicinity of the BIOT closure and the opposite true for French skippers.

It is important to note that in this study we have examined the short-term response of the fleet to the two closed areas. It remains unclear how these or other similar closures might affect fishing opportunities over a longer period, including how cumulative impact on catches in the long term might influence decisions at a company level to participate in the Indian Ocean fishery. For instance, whilst the operations of a fishing company might be temporarily disrupted by a short term temporary spatial management policy, such as the Resolution underpinning the recent IOTC closure, the implementation of a short term closed area for an indefinite period with an associated annual dip in production during the closure period may affect a company's ability to remain profitable, particularly where strong spatial variability in the distribution of fishing opportunities limits the ability of vessels to reallocate effort effectively and maintain adequate catch levels. In this case, effort reallocation may not occur on a regional level but instead involve the transfer of vessels into the Atlantic Ocean, where the European fleet is also active. Moreover, any strategic response may vary between fishing companies, depending on the characteristics of the company fleet and the flexibility of skippers to adjust to new fishing opportunities in the region, such as a switch in fishing practice.

In this study we focused on the behavioural response of the fleet to spatial management but did not look at overall effect of the IOTC and BIOT closures on catches of tunas or bycatch species and as such we cannot offer a conclusion as to the conservation efficacy of large offshore closures. The effect of closures on fish stocks can take years or decades to be demonstrated (Lester et al. 2009) and, as with fleet behaviour, it can be difficult to isolate the policy effect of a closure in generating reductions in catch or bycatch without accounting for other influences on production dynamics, including ecological processes, technological innovation and consumer pressures. Nevertheless, the development of a catch model that integrates with the model of fleet behaviour we employ here would be a valuable next step in the evaluation of the benefit of area closures in tuna fisheries.

Chapter 6

6 Second-guessing uncertainty: scenario planning for management of the Indian Ocean tuna purse seine fishery

6.1 Introduction

An important task of fisheries management is deciding amongst alternative policy options. In doing this, policymakers must anticipate, typically using models, how key elements and dynamics of the system are likely to change in the future, and evaluate how the outcomes of management policies might be affected by this change. However, the future is loaded with uncertainty and surprise, and generating accurate, long-range biological, economic or political forecasts is a major challenge. In some regions, improved understanding of system dynamics and breakthroughs in computing power have lead to the development of whole-of-system models (e.g. Atlantis, Fulton et al. 2004), which has gone some way to improving the accuracy of forecasts. However, this depth of understanding and complexity of modelling is still beyond reach in most fishery systems, and in complex and uncertain systems the usefulness of modelled predictions of the future is limited (Clark et al. 2001).

In all fisheries systems, resource users are the key linkage between policymakers and the resource. The success of a management policy is more often than not contingent on the behaviour of fishers, and unexpected behaviours, resulting from a response to management or change in other drivers, can potentially generate unintended and undesirable outcomes (e.g. Briand et al. 2003; Hiddink et al. 2003). Despite the importance of fisher behaviour, this linkage between implementation and outcomes of management has often been downplayed or ignored in planning (Fulton et al. 2011). This is not helped by a lack of clarity on the role of fisher behaviour in management; whilst there has been considerable work directed at characterising fisher behaviour and understanding its drivers (see Salas and Gaertner 2004; van Putten et al. 2011), there has been little focus on the role of fishers in achieving (or undermining) management outcomes. Hence, fisher behaviour remains an important source of uncertainty in fisheries systems (Fulton et al. 2011).

Scenario planning is a promising approach for aiding management decision making in complex, changeable systems. Rather than focussing on the accurate prediction of a single probable future, scenario planning involves thinking creatively about how the system might develop under a set of possible futures. In this way, policymakers can consider a range of plausible ways in which system dynamics might change, including surprise and catastrophe, and identify key uncertainties that might hinder the design and implementation of effective management policies. Scenario planning has been used extensively in business and politics to develop strategies for a range of possible futures (van der Heijden 1996). More recently, scenarios have been used in the environmental sciences to improve decision making in complex ecosystems (Wollenberg et al. 2000; Bohensky et al. 2006), to anticipate change in ecosystem services (Peterson et al. 2003) and to explore strategies for sustainable development (Rotmans et al. 2000). For instance, scenario planning was used in the Millennium Ecosystem Assessment for exploring the ways in which policy decisions may drive future ecosystem change, how ecosystem change may constrain future decision making, and ways in which ecological feedback may lead to surprise (Anon 2005).

In this study, we used scenario planning to explore uncertainty in the future of the Indian Ocean tuna purse seine fishery, focussing our attention on the behaviour of fishers. Our aim was to stimulate thinking on how the key social, economic and environmental conditions that influence fisher behaviour, which are difficult to accurately forecast, may change in the future, and how these changes might affect the dynamics of fishing effort. In our findings, we identified a number of key aspects of fishing behaviour that we believe should be important considerations for policymakers, and briefly reviewed the current state of research on these behaviours to recommend avenues for future research.

6.2 Overview of scenario planning

There are many different approaches to scenario planning, which mainly differ in emphasis rather than method due to variation in the goals of those who have created them (Wack 1985; van der Heijden 1996; Bossel 1998; Ringland 1998; Wollenberg et al. 2000). The scenario planning approach used here is adapted slightly from that described by Peterson et al. (2003), who introduce the methodology of scenario planning to the discipline of conservation science. To the best of our knowledge, there have been no scenario planning exercises published in the fisheries science literature, nor in the context of resource user behaviour. Peterson et al. describe scenario planning as consisting of six interacting stages, which, in order to incorporate wide range of perspectives, are typically carried out in a workshop format by a diverse group of, for example, research scientists, managers, policymakers, and other stakeholders. In our case, the scenario planning exercise was the culmination of three years of detailed research on tuna purse seine fisher behaviour and was carried by the author of that research (T. Davies) as a desk based study.

(1) Identification of the focal issue

Having a specific question in mind provides focus when examining possible futures, and therefore the identification of a clear focal issue is the first and arguably the most important stage in scenario planning. Here, the focal issue was uncertainty in dynamics of effort allocation in the Indian Ocean tuna purse seine fishery. These dynamics include two short term skipper-level behaviours, the allocation of effort in space and the allocation of effort between the two main fishing practices (fishing on free-swimming schools or floating objects), and two long term company-level behaviours, investment in fishing capacity and participation in the fishery.

(2) Assessment of the system

This stage should determine what is known and unknown about the forces that influence the dynamics of the fishery system. The focal issue is used to organise an assessment of the actors, institutions and ecosystems that define the fishery and identify the key linkages between them. It is also important to identify engines of external change, whether they be social, economic or environmental, that drive system dynamics. Here, this assessment was based on an understanding of the system generated during the course of this Ph.D. from review of the academic and technical literature, interviews with skippers and other fishery experts, and primary research (see Chapters 2, 3, 4 and 5).

(3) Identification of alternative futures

This stage involves the identification of alternative ways that the system could evolve in the future. How far into the future depends on the focal issue and the system; in this study we looked forward 15 years, as this was considered an appropriate length of time for both short term behaviours (e.g. patterns of effort allocation) and long term behaviours (e.g. investment in a fleet) to be influenced by the dynamics of the system. Although inherently uncertain, alternative futures should be plausible yet at the same time imaginatively push the boundaries of commonplace assumptions about the way in which the system will develop. These alternative futures should be based upon two or three uncertain or uncontrollable system drivers that have been determined in the previous assessment stage. For instance, uncertainties might arise from unknown behaviour of a group of actors, or from unknown dynamics in the natural or socio-economic components of the system.

(4) Building scenarios

The role of scenarios is to translate alternative futures into descriptive storylines, based on the understanding of the various actors and drivers in the system accumulated during the assessment stage. Scenarios should expand and challenge current thinking about the system, although they should be limited to three or four; a set of two scenarios is usually too narrow, whereas more than four may complicate or confuse the scenario planning exercise (Wack 1985; Schwartz 1991; van der Heijden 1996). In order to be plausible, scenario storylines should link present events seamlessly with hypothetical future events, and assumptions of the scenario and the differences between the storylines must be easily visible. Consequently, storylines generally begin factual and become increasingly speculative at they progress. Our storylines are constructed in three parts; first we set out the changes in the fishery systems, then we outline what these changes mean in terms of fishing opportunities, and we finish by describing the consequences on the behaviour of the fleet.

(5) Cross-cutting behaviours

In this stage, we compared the expected fisher behaviours under the different storylines. This stage allowed opportunity for discussion on the sustainability of the fishery under alternative futures, and identification of which behaviours were common under more than one scenario and which were unique to one particular future. This final stage therefore served as the basis for recommendations of the fisher behaviours that we argue should be key considerations of policymakers when planning future management policies.

6.3 Assessment of the system

6.3.1 Operational, geographical and historical context

The tuna purse seine fishery exploits the surface schooling behaviour of three principal species; skipjack *Katsuwonus pelamis*, yellowfin *Thunnus albacares*, and bigeye tuna *T. obesus*. In the open ocean tunas naturally aggregate in free-swimming schools (free schools) or associate with floating objects (associated schools), such as logs or branches (Dempster and Taquet 2004). Tuna fishers have learnt to exploit this association behaviour and deploy purpose-built fish aggregating devices (FADs) into the ocean to increase and expedite catches. A distinction is usually made between the two school types due to differences in the species composition of the catch, although skippers will generally target a mixture of free and associated schools during fishing trips (see Chapter 5). Tuna schools are found using a variety of tactics and strategies, including satellite buoys and echo sounders attached to FADs, cooperation and information-sharing between skippers and the use of meteorological forecasts and environmental 'nowcasts' based on satellite remote sensing data from which promising tuna habitat is identified (see Chapter 2).

An industrial purse seine fishery for canning-grade tropical tunas began in the Indian Ocean in the early 1980s, when French and Spanish fishing firms moved vessels into the region from the tropical eastern Atlantic in search of new fishing grounds. There is still exchange of vessels between these two oceans, orchestrated at the level of the firm and based on perceived relative fishing opportunity in either ocean (A. Fonteneau; personal communication). Early operations were based in Port Victoria, Seychelles, which has remained the primary port of call for landing and transshipping catch, refueling and resupplying and exchanging crew (Robinson et al. 2010). The European-owned distant water fishing fleet continues to dominate the fishery, although elements of the fleet have at times registered their vessels under non-EU flags of convenience. This is a business strategy intended to reduce costs and, in the case of the Spanish firms, to avoid EU regulation on the size of distant water fishing fleets (DeSombre 2010; Campling 2012).

The size of the European-owned fleet has grown considerably since its beginnings in the 1980s, largely due to the intensive use of FADs (see Chapter 5). Throughout the 1990s and early 2000s French and Spanish fishing companies invested in larger purse seine vessels, at an estimated cost of US$20 million per vessel, which offered numerous commercial advantages including the ability to make extended fishing trips with larger fish-wells (Campling 2012). However, because larger vessels are more sensitive to increasing operating costs (e.g. fuel price; Miyake et al. 2010) it was necessary for fishing companies to adopt increasingly competitive fishing strategies to achieve the high annual catch thresholds necessary to remain profitable (e.g. circa 15-20,000 t; A. Fonteneau, personal communication). Consequently, purse seine firms have become increasing reliant on the use of FADs to achieve the very large catches needed to remain profitable (Guillotreau et al. 2011; Campling 2012).

The tuna caught by the Indian Ocean tuna purse seine fishery are destined mainly for the canning industry. Canned tuna is second only to prawn/shrimp as the largest internationally traded seafood product in terms of value and volume. Appetite for tuna is particularly strong in Europe, and the EU is the largest market for canned tuna in the world, split between 5 principal consumers; Spain (21% share), Italy (20%), the UK (19%), France (19%) and Germany (9%) (Valsecchi 2007). Premium-quality yellowfin tuna, canned in olive oil, is favoured by the southern European market, especially Italy and Spain, whereas lower-value skipjack tuna, canned in brine or vegetable oil, is preferred in the northern European market, especially the UK and Germany (Campling 2012). Both of these commodities are produced using tunas caught in the Indian Ocean purse seine fishery, which are either landed in the Seychelles or Madagascar and processed in local canneries, or transshipped and sent to canneries in Europe, Asia and South America for processing (Robinson et al. 2010).

The Indian Ocean tuna purse seine fishery is managed by the Indian Ocean Tuna Commission (IOTC), one of five regional fisheries management organisations (RFMOs) responsible for managing tuna stocks in international waters around the globe. Member states that comprise the IOTC include Indian Ocean coastal and island nations, as well as the EU, due to its dominant presence in fishery. The IOTC is ultimately responsible for setting catch limits, undertaking stock assessments and regulating fishing rights and has the power to take legally binding decisions that must be implemented by the various Contracting Parties. Scientific work underpins management decision making and is conducted by national scientists from the IOTC member states and reviewed at a Scientific Committee. On the basis of this scientific advice members at the IOTC annual session consider conservation and management measures (CMMs), and if a measure is agreed to by a two-thirds majority it becomes binding.

Since the early 2000s the primary management problem facing the IOTC, as with all tuna RFMOs, has been overcapacity in the fleet. As a first step towards addressing overcapacity, in 2002 the IOTC attempted to limit access to the fishery by creating a Record of Authorized Vessels (RAV), a register of vessels of greater than 24 m length that were authorised to fish in the IOTC area of competence (Resolution 02/05; http://www.iotc.org/English/resolutions.php; accessed 1st December 2013). This Resolution has been updated and superseded on a number of occasions to include restrictions on vessel numbers and diversified to include smaller classes of vessels, although the RAV has ultimately failed in its intended purpose to maintain stocks at target levels (Aranda et al. 2012). Alternative controls on fishing effort were implemented from 2010 in an attempt to control fishing effort, in the form of temporary closed areas situated in a productive region of the fishery, although these too appear to have had little success in reducing catches in the fishery (see Chapters 4 and 5). More recently, discussions have been held in IOTC on adopting a rights-based management system, principally through the determination of total allowable catch (TAC) and quota allocation for stocks of yellowfin and bigeye tuna (Resolution 10/01; http://www.iotc.org/English/resolutions.php; accessed 1st December 2013). This is an inevitably thorny issue, as it necessarily involves developing and agreeing on criteria for allocating catches between the member states of the IOTC, and it remains to be seen how and when this fundamentally different approach to management will be implemented.

6.3.2 Fleet behaviour and fishing strategies

The behaviour of the purse seine fleet is considered in terms of three aspects of effort allocation dynamics; the allocation of effort in space, the use of free school or floating object fishing practices, and participation in the fishery. These effort dynamics are driven by the behaviour of two fundamental decision making units; the firm and the skipper. Fishing firms generally make higher-level strategic decisions, for example to invest in new vessels, to modernise equipment, or move vessels into or out of the Indian Ocean fishery. Firms may also have a direct or indirect influence on the nature of its vessels' fishing operations, such as dictating catch thresholds or encouraging certain fishing practices. Skippers are responsible for everyday fishing decisions, and ultimately decide how, where and when to fish. Each skipper's decision making is influenced by the information available to them at any given time, their personal preferences and objectives, their skill and experience and the fishing resources available to them (e.g. crew, vessel size and speed, fish-finding technology etc.).

The tuna purse seine fishery sits within a much larger socio-ecological system (SES; Figure 6.1), and the behaviour of the fleet is influenced by the dynamics of four main system components: the resource, the biophysical ocean, the IOTC and a variety of external influences (Table 6.1). External influences on behaviour include geo-political decisions (e.g. fishing access agreements), socio-political consideration (e.g. piracy), economic forces (e.g. fuel costs, port fees etc.) and market pressures (e.g. consumer preferences). The dynamism of these system elements varies considerably, and each is characterised by different levels of uncertainty. For instance, IOTC decision making tends to be slow paced and management changes are gradual and often conservative (Aranda et al. 2012; de Bruyn et al. 2013), meaning that firms may be able to anticipate the management situation some way into the future. In contrast, external socio-political and socio-economic influences can change rapidly and unexpectedly, for example the designation of British Indian Ocean Territory (BIOT) as a marine reserve in 2010 (FCO Proclamation Number 1 of 2010) and the escalation of the piracy threat to fishing vessels in the late 2000s (Chassot et al. 2010). Although there are many linkages and feedback loops within this SES, the purse seine fishing industry ultimately has little or no control over most of the influences that shape the dynamics of effort allocation.

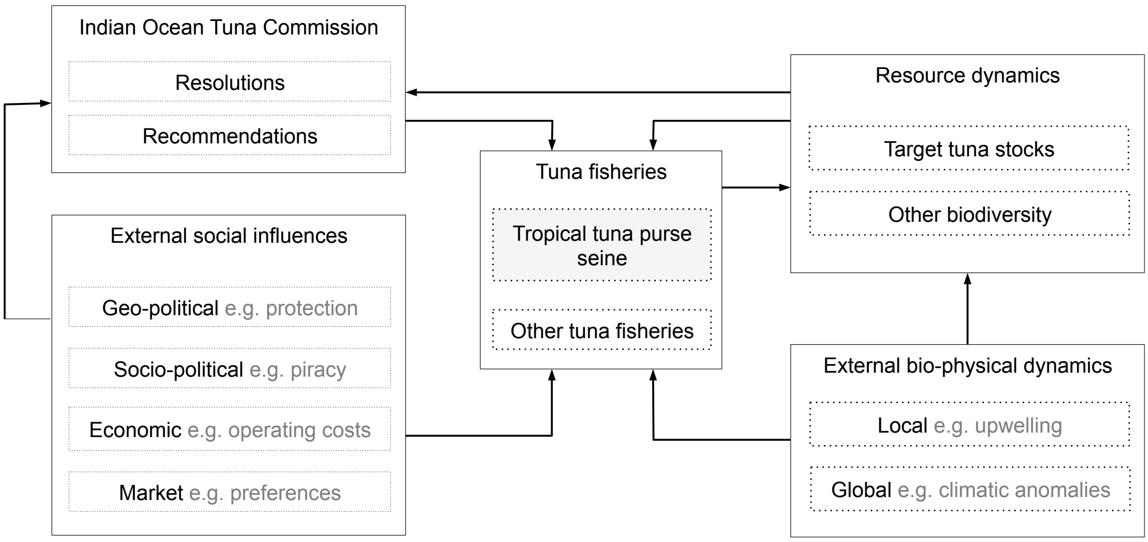

Figure 6.1 Conceptual overview of the social-ecological system that contains the western Indian Ocean tuna purse seine fishery showing the main elements of the SES and the linkages between them.

Table 6.1 Key influences on the decision making of tuna purse seine firms and skippers and examples of fishing behaviours in response to these influences. See Chapters 2, 3 and 5.

Influence	Example of behavioural response	Reference
Resource dynamics	Firms may transfer vessels from the eastern Atlantic Ocean into the Indian Ocean on the basis of perceived relatively high abundance of one or more target species	A. Fonteneau, pers. comm.
Biophysical ocean dynamics	The depth of the thermocline can affect the surface-schooling behaviour of tunas and influence choice of fishing ground, and weather and waves can determine where a vessel can fish	Marsac 2008; Chapter 2
Fisheries management	IOTC Conservation and Management Measures (e.g. area closures, prohibited species etc.) can constrain behaviour or encourage certain fishing practices	Chapters 4 and 5
Piracy	Pirate activity is associated with personal and economic risk and the threat of piracy can be a disincentive to fish in certain areas	Chassot et al. 2010
Fuel costs	Fuel costs are the single greatest variable cost in purse seine fishing and can determine how far a vessel will travel in a trip or to what extent a skipper is willing to search for free schooling tunas	Miyake et al. 2004
Market conditions	Demand for a certain species or product (i.e. sustainably sourced) can determine ex-vessel fish price and in turn influence a skipper's choice of target species or the design of fishing gears	Miyake et al. 2004; IOTC 2012

6.4 Identification of alternative futures

In considering the future of tuna purse seine fishing in the western Indian Ocean, and on the basis of current understanding of the drivers of fleet behaviour outlined in the assessment of the fishery system, three main uncertainties stand out:

1. Will more nations designate ecosystem-scale marine protected areas (MPAs) similar to the BIOT marine reserve, and how will this change access arrangements and ultimately the oceanscape of the fishery?
2. How will consumer preferences for sustainable seafood change in regard to tuna products, and how will this impact the choice of fishing practices in the purse seine fishery?
3. Will ineffective management fail to prevent overfishing of tuna stocks, and how will change in the relative abundance of the main target species affect participation in the fishery and other aspects of effort allocation dynamics?

Increase in marine protection

MPAs in one form or another are becoming increasingly popular as tools for managing and conserving marine species and ecosystems. The Convention on Biological Diversity called for 10% of the world's EEZs to be protected using some form of closed area by 2010, although the target deadline has since been pushed back to 2020. The World Parks Congress called for 20% of the oceans, including the high seas, to be protected within reserves by 2012, and the World Summit on Sustainable Development called for the creation of a global network of comprehensive, representative and effectively managed marine protected areas by 2012 (United Nations 2002).

Recently, the Pew Ocean Legacy Program has proposed ecosystem-scale MPAs ('megareserves') in a handful of EEZs around the world (Nelson and Bradner 2010). The first of these to achieve formal protection in the western Indian Ocean was BIOT in 2010. The designation of BIOT was not linked to regional fisheries management policy, as the UK government, which administers BIOT, does not have a direct interest in tuna fisheries in the region. However, whilst no formal management plan has yet been developed, several objectives of the reserve can be inferred, including the provision of a scientific reference site and near shore and pelagic biodiversity conservation (Sheppard et al. 2012).

Although the Pew Ocean Legacy Program has not identified any other potential megareserve sites in the western Indian Ocean, it is still possible that other coastal and island nations will be motivated to rescind fishing access rights and protect part or all their EEZ in the form of marine reserves. This decision would necessarily carry considerable economic consequences, as the revenue and support-in-kind gained from EU Fishing Partnership Agreements (FPAs) or private agreements with tuna fishing firms is important to many Indian Ocean coastal and island nation governments. However, examples from other parts of the world suggest that this revenue could be compensated using alternative financial mechanisms, such as the endowment fund used by the Kiribati government to fund the Phoenix Island Protected Area (PIPA; http://www.phoenixislands.org/trust.php; accessed 1st December 2013).

A change in consumer preferences for seafood

The principal market for purse seine-caught tuna is Europe (Campling 2012). Here consumer pressure for sustainably sourced fish is strong and seafood certification schemes, such as that of the Marine Stewardship Council (MSC), are popular (Jaffry et al. 2004). In this environmentally-aware social climate, becoming associated with sustainable production has business advantages, and to date one purse seine fishery in the Western and Central Pacific convention area has been awarded certification by the MSC, although this has been exclusively for free schools of skipjack tuna (http://www.msc.org/track-a-fishery; accessed 25th July 2013).

Although purse seine fishing is associated with fewer sustainability impacts than fishing for tunas using long lines or gillnets, there is growing discomfort with the practice of fishing around floating objects. This practice is associated with several potential negative ecosystem impacts, most notably catch of juvenile tunas and bycatch of non-target species, including vulnerable (and charismatic) species of sharks and turtle (Bromhead et al. 2003; Amandè et al. 2008, 2010). Furthermore, there is concern that the intensive use of FADs, if left unchecked, might exacerbate issues of overcapacity and ultimately lead to the unsustainable exploitation of tuna stocks (Fonteneau et al. 2000, 2013). There is currently little control on the use of FADs in the western Indian Ocean, although there has been increasing discussion within IOTC on managing their use more strictly (Fonteneau et al. 2013; see Chapter 5).

The 'dolphin-safe tuna' campaign in the late 1980s set a precedent for consumer-driven change in the operation of tuna fisheries. This campaign, lead by a coalition of environmental organisations in the USA, was in protest at the bycatch of large numbers of dolphin in the nets of purse seiners in the eastern tropical Pacific Ocean, and was ultimately successful in improving the management policies of the Inter American Tropical Tuna Commission (IATTC) and changing US legal standards for catching tunas in dolphin-safe practices (Wright 2007). Whilst the issues of purse seine bycatch in the western Indian Ocean are arguably less controversial in the eyes of the public than in the case of the eastern Pacific, there is still strong pressure from organisations such as Greenpeace and the WWF through the Smartfish Initiative to be cautious in buying purse seine caught tuna (http://www.panda.org/smartfishing; accessed 1st December 2013). Some organisations are already lobbying or working with the purse seine industry to reduce the environmental impacts of FADs, mainly through technological innovation (see http://iss-foundation.org/tag/bycatch-2/ISSF; accessed 1st December 2013). However, should the industry aim to achieve sustainable seafood certification through schemes such as the MSC, fishing firms would be obliged to make far bolder changes to their operations in order to address a broader range of sustainability issues.

Depletion of tuna stocks

In the western Indian Ocean the three main target species of tropical tuna – yellowfin, skipjack and bigeye tuna – are currently considered to be exploited at sustainable levels ($F/F_{MSY} < 1$; ISSF 2013). Stocks of these species are differentially susceptible to overfishing due to variation in growth rate, the age of sexual maturity and duration of spawning. For example, yellowfin tuna, which is a large and relatively slow-growing species, lives a maximum of 10 years but reaches sexual maturity relatively late (2.8 years) and spawns for only half of the year. In comparison, smaller skipjack tuna, which live for 4-5 years, grow quickly, reach sexual maturity sooner (1.8 years) and spawn all year. Consequently, stocks of skipjack are generally considered to be able to withstand greater levels of exploitation than yellowfin and the biologically similar bigeye tuna (Fromentin and Fonteneau 2001).

Although tropical tuna stocks in the western Indian Ocean are currently in a healthy state, there are a number of drivers that could potentially lead to overfishing. In the case of skipjack, investment in larger vessels by fishing firms is likely to result in an increase in the use of FADs (see Chapter 5), and in turn fishing mortality of skipjack stocks. Signs of growth overfishing in the Atlantic Ocean in the late 1990s were attributed to the intensive use of FADs (Fonteneau et al. 2000), and there is concern that unchecked expansion of FAD fishing in the eastern Pacific Ocean may ultimately lead to overexploitation of regional skipjack stocks (Maunder 2011). Also, although skipjack are caught mainly in the purse seine fishery (38% of catch share in 2010), large quantities are also caught by vessels using gillnet (36%), pole-and-line (17%) and miscellaneous gears (9%; ISSF 2013), and growth in these fisheries would be expected to increase fishing pressure on skipjack stocks.

In the case of yellowfin and bigeye stocks, fishing mortality from gillnet and longline gears (28% and 15% of catches in 2010; ISSF 2012) is expected to increase as socio-political conditions in the Indian Ocean change. Increasing pirate activity in the northwest Indian Ocean during the mid 2000s displaced fishing activity, particularly the longline fleet, into other parts of the Indian Ocean (Chassot et al. 2010; IOTC 2012), but attempts to control this threat (e.g. NATO counter-piracy operations, private security personnel etc.) has already allowed some of this fleet to return to the western Indian Ocean in 2013 (Seychelles Fishing Authority, pers. comm.). As the threat of piracy is reduced in future years, the presence of longline and gillnet vessels in the western Indian Ocean is expected to increase further, leading to a significant increase in fishing pressure on stocks of yellowfin and bigeye tuna.

6.5 Storylines

6.5.1 Protected ocean

The designation of BIOT as a marine reserve in 2010 sets a precedent for marine conservation in the Indian Ocean. International marine conservation organisations have a strong voice in the region and campaigns to protect large areas of ocean within marine reserves gain momentum. In the late 2010s, with existing fishing fleets beginning to overexploit stocks, a number of East African coastal states opt to close their EEZs to industrial tuna fisheries rather than to develop their own national offshore fleets. This decision is motivated not only by the deterioration of tuna stocks, but also because the protection of very large areas of ocean serves as a big leap forward in achieving international biodiversity conservation targets for protected areas. The closure of national EEZs to industrial fishing necessarily involves withdrawal from EU fisheries partnership agreements or privately negotiated access arrangements, although in most cases the opportunity costs associated with prohibiting fishing access are offset using alternative financing mechanisms. In the early 2020s, with existing management measures largely failing and stocks of yellowfin and bigeye in a chronically depleted state, pressure mounts within IOTC for the implementation of a robust policy of spatial management. These proposals are seen as over precautionary by some members and initial negotiations stagnate. However, coordinated awareness campaigns run by environmental organisations in Europe and Asia help to steer political opinion, and by the mid 2020s consensus is reached within the IOTC to close a large area of the high seas to the industrial fleets. This single area closure is situated in the northwest Indian Ocean and excludes fishing from a highly productive region associated mainly with fishing on FADs[1].

The implementation of marine reserves and fishery closures affects where the purse seine fleet can operate. The closure of several EEZs along the east African coast in the mid-2010s modifies the landscape of the fishery by excluding the purse seine fleet from parts of the productive spring and summer fishing grounds. In each instance of an EEZ being closed to the fishery, the immediate response of the fleet is to reallocate effort into adjacent areas. This initial reallocation of effort is exploratory, as fishers,

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1 See Chapter 5 for a review of the geographical distribution of FAD-fishing

forced to break from tradition, investigate alternative grounds[2]. After a few years, the allocation of effort settles into a new pattern as skippers become familiar with the modified landscape of the fishery. The EEZ closures mainly affect the activities of the fleet in the west and southwest regions of the fishery, although the most productive summer grounds in the northwest Indian Ocean remain accessible. However, this changes following the implementation of an IOTC high seas area closure in the mid-2020s, which denies the fleet access to a significant part of the Somali Basin fishing grounds. The response of the fleet is again to reallocate effort into adjacent areas. The size and positioning of the IOTC closure forces the majority of effort to be allocated into relatively less productive grounds in the central western Indian Ocean, many of which have already been fished intensively in previous months. Subsequently, facing a shortfall in catches and increased competition with other vessels, skippers attempt to maintain catch rates by intensifying the deployment of FADs[3], and, in some cases where fishing opportunities are perceived to be very poor, fishing firms reallocate vessels into the Atlantic Ocean[4].

6.5.2 Sustainable seafood

In the early 2010s, consumers in Europe are increasingly favouring sustainably sourced tuna. Campaigns spearheaded by influential environmental groups communicate to the public the sustainability issues associated with the use of FADs in purse seine fisheries, focusing on issues of bycatch and overfishing. The campaigns

2 This expectation is based on the observed response of the fleet to area closures implemented in 2011-2012 (see Chapter 3)

3 This expectation is based on the known FAD-fishing strategies of fishers reviewed in Chapter 5

4 This expectation is based on the observed movement of vessels by firms between the Atlantic and Indian oceans in the mid 2000s in response to perceived changes in fishing opportunities (see Chapter 5)

also pressure major supermarket brands to promote or exclusively source tunas caught using sustainable methods. The initial response by the purse seine industry to these campaigns is two-pronged. Firstly, fishing companies endeavour to supply additional data to IOTC scientists on the use of FADs in order that uncertainties in their environmental impact can be better investigated. Secondly, at a global scale, the industry begins to develop more environmentally friendly FAD-fishing methods[5]. Nevertheless, uncertainties in the ecological impact of FADs remain, and whilst technological innovation does reduce bycatch and ghost fishing by FADs, environmental groups continue to express serious concern over the contribution of FADs to overfishing.

FAD-caught tuna is unappealing to much of the European market, and free school-caught fish is regarded as the best choice. In the late 2010s, recognising the direction that the sustainable seafood movement is going, several of the smaller purse seine fishing firms invest in newer, more efficient vessels that can pursue free schooling tunas with lower operating costs. By the mid 2020s, although unable to achieve formal certification of sustainability, these companies are marketing themselves as using "clean, sustainable purse seine methods" and sell their products in the European market at a premium. In contrast, many of the larger Spanish-owned vessels, which are reliant on FADs to remain profitable, suffer as a result of the change in consumer preference. By the late 2010s, several of the largest vessels tie up in port, but, unable to transfer operations into the Atlantic, which supplies the same European market, vessels owners are forced to sell these vessels. This divergence in strategies opens up a divide in the fishery, with part of the fleet targeting mainly free schools for the premium European market and the other targeting mainly FADs and

5 These industry responses are already happening to a certain extent (see Chapter 5)

selling to the budget and non-European components of the market. Moreover, these components of the fleet fish on different grounds, with the free school-oriented fleet fishing mainly in subequatorial waters where free schools are most abundant, and the FAD-oriented fleet focusing on the northwest and southwest grounds where floating objects exist at high densities[6].

6.5.3 Depleted ocean

In the early 2010s, none of the three main target stocks is considered to be overexploited, partly as a result of the negative influence of piracy on purse seine and longline catches. On-going NATO counter-piracy operations, along with the protection provided to shipping by private security firms, are successful in reducing the pirate attack rate and many vessels feel more confident in fishing in the northwest Indian Ocean. Thus, as the threat of piracy lifts during the 2010s, longline and gillnet fleets report very high catch rates of yellowfin and bigeye. This bounty of catches prompts several nations to increase their participation in these fisheries, and the subsequent influx of additional fishing vessels into the northwest Indian Ocean rapidly exacerbates the already high fishing pressure. This increase in fishing capacity is largely unchecked due to clauses in the IOTC mechanism for regulating capacity, the RAV, that are designed to safeguard development potential of emerging fishing nations. By the mid-2020s the spawning stocks of yellowfin and bigeye are considered overexploited and catch rates fall in all fisheries, including purse seine, which in particular experiences a gradual decline in catch rates on free schooling yellowfin tuna.

6 This expectation is based on the existing divergence within the fleet in the use of these fishing grounds, driven by broad differences in fishing strategy (see Chapter 3)

In response to falling stock abundance in the late 2010s, most purse seine skippers increasingly use FADs to maintain overall catch rates. This increases the proportion of small and juvenile yellowfin and bigeye in the catch, and skippers must work harder to fill their fish wells. Moreover, as the use of FADs varies by region, this shift in fishing practice also results in a subtle adjustment in fishing grounds, with more effort allocated into western grounds where floating objects exist at higher densities[7]. By the mid-2020s the localised deployment of more FADs in these grounds results in a decrease in the average size of sets and an increase in search costs, as vessels must move between a higher number of FADs to achieve sufficient catches[8]. This impacts on the profitability of fishing firms, especially those operating larger, less fuel efficient vessels, and some choose to tie up a number of vessels in their fleets temporarily until fishing conditions improve.

6.6 Cross-cutting behaviours

The three scenarios present imaginary but not implausible futures for the western Indian Ocean tuna purse seine fishery, and describe a number of ways in which the fleet may respond to change. We do not think that any of these futures will emerge exactly as we describe, although aspects of one or more futures may occur. The *protected ocean* scenario describes a mostly positive future for the Indian Ocean tuna stocks, with fishing pressure lifted from larges areas of ocean, but changes to the system are economically undesirable from the perspective of the fishing industry. Fishing opportunities are squeezed into a small area, increasing competition between vessels and prompting an increase in the use of FADs. The *sustainable seafood*

7 This expectation is based on known FAD-fishing strategies of fishers reviewed in Chapter 5

8 This expectation is based on modelling by Sempo et al. 2013

scenario also describes a generally positive outlook for the resource, although the prognosis for the fishing industry is mixed. Some firms are able to tailor their operations to free school fishing, whereas other are less flexible and must continue to fish intensively using FADs in order to remain profitable. The *depleted resource* scenario is the only storyline that is negative for both the resource and the industry. Although overfishing of tuna stocks occurs mainly as a result of increased exploitation rates by other tuna fishing gears in the region, the consequences are keenly felt in the purse seine fishery, and skippers must increasingly use FADs in order to maintain profitable levels of catch.

Table 6.2 Cross-tabulation of fishing behaviours in the imagined future scenarios, showing commonalities or peculiarities in behaviours. The likeliness of the behaviour is represented by the + or -, where +++ indicates a very likely behavioural response.

	Scenario		
Fishing behaviour	Protected ocean	Sustainable seafood	Depleted ocean
Switch in fishing practice to/from FADs	++	+++	++
Reallocation of effort in space	+++	++	++
Investment in new vessels	-	+	-
Exit from the fishery	+	+	+

Comparison of the scenarios reveals several commonalities in possible future behaviour of the fleet, as well as a number of behaviours specific to certain changes in the system (Table 6.2). A behaviour that was likely across all scenarios was a shift in fishing practice. In the *protected ocean* and *depleted ocean* scenarios, this was observed as an increase in the use of FADs, with skippers attempting to maintain catch rates using this highly effective fishing practice in the face of shrinking fishing opportunities. However, it should be noted that in the *protected ocean* scenario there was an increase in the deployment of FADs (in areas that remained accessible to fishing), whereas in the *depleted ocean* scenario there was a spatial shift by the fleet to fish in existing high density FAD areas. These may be regarded as proactive and reactive behaviours, respectively. In comparison, in the *sustainable seafood* scenario several companies changed their focus to specialise in fishing on free schools, and this shift in fishing practice was also associated with reallocation of effort into grounds most appropriate for the fishing practice. In all instances the overriding incentive to increase the use of one practice or the other was considered to be economic: skippers favoured the fishing practice that would achieve the greatest profits. However, it should be considered that some skippers are more inclined, either through specialisation, personal preference or some other factor, to fish on FADs than on free schools, and vice versa (Moreno et al. 2007), meaning that shifts in fishing practice, if they do occur, may not be observed at the same rate for all fishing firms and individuals in the fishery.

Another common behaviour observed across the future scenarios was the reallocation of effort in space, although this varied in magnitude from subtle shifts in the areas fished in the *sustainable seafood* and *depleted ocean* scenarios, to complete displacement from former fishing grounds in the *protected ocean* scenario. As with shifts in fishing practice, these behaviours might be regarded as proactive (*sustainable seafood* and *depleted ocean*) and reactive (*protected ocean*), and consequently their drivers are likely to be very different. The subtle shifts in fishing grounds observed in the *sustainable seafood* scenario were the result of decisions made by skippers to fish in areas with known FAD or free school opportunities, depending on their preferred fishing practice, and were therefore linked to overarching fishing strategies, for example the maximisation of profit, and driven by fishers' knowledge, past experiences and attitude to risk. In contrast, the displacement of effort imagined in the *protected ocean* scenario was a forced response by the fleet, with skippers left with little option but to move into suitable grounds in other parts of the ocean that remained accessible to fishing. This reactionary behaviour therefore may not be driven by heuristics, but instead by prevailing environmental conditions, fishers' intuition and the recent activity of others (see Chapters 2 and 3).

The *sustainable seafood* scenario was the only future in which new opportunities emerged, and consequently in which some fishing companies chose to invest in new vessels. In the other scenarios, both of which painted negative pictures of fishery production, catch rates suffered and investment in new vessels was consequently unlikely. Instead, exit from the fishery was a common behaviour to these scenarios, with the largest and least economical vessels the most likely to be tied up in port or sold. This temporary or permanent decommissioning of vessels by fishing firms was imagined in the scenarios as a last remaining option, with palliative behaviours such as an increase in the use of FADs failing to achieve profitable catch rates. An alternative plausible strategy by firms might be to withdraw vessels from the fleet at an earlier time in order to reduce costs and lessen competition with remaining vessels.

6.7 Possible IOTC interventions

In addition to identifying possible fleet behaviours, it is also useful to use the storylines to consider what, if anything, the IOTC might do to change the course of the imagined scenarios. In the *protected ocean* scenario, the behaviour of the fleet is ultimately influenced by an external element of the fishery system, namely public opinion and government obligations in respect to the conservation of marine biodiversity (see Figure 6.1). The IOTC has little control over these societal influences, and consequently can probably do little to influence the *protected ocean* scenario should it emerge as imagined. In the *sustainable seafood* scenario, the main driver of behavioural change – consumer preference – is also an external social element of the fishery system. However, in this scenario, consumer backlash against unsustainable fishing is partly the result of poor management by the IOTC in respect to the use of FADs by the purse seine fleet. Hence, the course of the *sustainable seafood* storyline could to a certain extent be influenced by the implementation of timely and appropriate regulation on the use of FADs. The *depleted ocean* scenario describes a future of fishery overcapacity that cannot be effectively managed using existing controls, and hence pressure for behavioural change comes directly from the management of the fishery and the actions of the fleets. More so than the others the IOTC has the opportunity and influence to change to course of this scenario, for instance through the design and implementation of rights-based management approaches that specifically address the perverse incentives for overfishing a common resource (see Joseph et al. 2010).

6.8 Recommendations for future research

A skipper's choice of fishing strategy in the short term is a key behaviour that policymakers should aim to better understand, and some work has already been directed at this topic. This work has mostly focused on identifying the factors that determine whether a skipper is a FAD or free school fisher in the Indian Ocean purse seine fishery (see Guillotreau et al. 2011). However, there has been no work directed at understanding the drivers of change from one fishing practice to another, and indeed the flexibility of fishers to do so, and the roles of the firm and the skipper in making these decisions. This should be a priority for research. Moreover, Moreno et al. (2007), who highlight the variation in skills needed for FAD and free school fishing, suggest that research into this aspect of behaviour should consider not only economic drivers, but also the influence of culture and a skipper's knowledge, experience preference and habits on decision making.

The movement of fishers in space is another important behaviour for policymakers to consider, and has been the focus of Chapters 3 and 4 of this thesis. This work has focussed on understanding the drivers of fleet-level behaviour, which is characterised by seasonal movement between regions of the western Indian Ocean. However, the role of the firm in the spatial behaviour of vessels was not examined in this research, but should be considered in future work in order to better understand the top-down influence of firms on how and where skippers operate. Furthermore, future work should aim to better understand the link between the long term strategic decision making of firms (e.g. investment in vessels) and the short term spatial behaviour of its assets (e.g. skipper's specialisation on FADs or free schools). Similarly, investigation into the decision making of purse seine fishing firms would yield greater understanding of investment in new vessels and of entry and exit from the fishery.

6.9 Conclusion

Resource users are the key link between policymakers, as well as other social, economic and political elements of the system, and the resource. Unexpected behavioural responses to these dynamics can potentially result in unwelcome or even disastrous management outcomes, and there is considerable benefit to fishery management planning in forecasting system dynamics and anticipating the behaviour of fishers. However, uncertainty is an inherent characteristic of the future and can frustrate the task of evaluating alternative management policy options. Although reducing uncertainty in the dynamics of natural and social systems has long been a focus of fisheries science, many aspects of the future remain unpredictable using models, either because of insufficient understanding of system dynamics or through uncontrollable, irreducible uncertainty.

In this study we used scenario planning, in the absence of reliable predictive models, to peer into the future and identify key uncertainties which may change fisher behaviour. These scenarios were not intended as predictions of the future, but instead they were used to identify uncertainties in fisher behaviour that may limit the ability of policymakers to evaluate how alternative management policy options will fare in the future. Our findings suggested that some fishing behaviours are likely under several possible scenarios. These behaviours, if enacted, would be expected to alter the dynamics of fishing effort and, in some cases, affect the sustainability of the fishery. We therefore argue that these behaviours, which are currently only partially understood, should be a critical focus of research in order that robust management policies can be designed and evaluated.

Our application of scenario planning in a fisheries management context is novel, but we believe this approach has been highly constructive in stimulating thinking on system drivers of fisher behaviour, and uncertainty in the future of these system dynamics. In particular, scenario planning has served to highlight that the behaviour of fishers is not a static element of a fishery system, and that it must be afforded greater importance in management planning. There are also ways that the planning exercise presented here could be adapted, for example by extending the timeframe over which system dynamics are considered to explore the effects of climate change on tuna stocks, fishery production and fisher behaviour. Indeed, the focus of scenario planning can be directed at almost any aspect of the system where model-based forecasting is unreliable or impossible. Furthermore, as scenario planning can be carried out as a relatively rapid and inexpensive exercise, it could be undertaken by policymakers on a regular basis (e.g. every few years) to help redefine priorities and consideration of future fisheries management policy.

Chapter 7

7 Discussion

7.1 Overview

The aim of this research was to reduce uncertainty in the management of tuna fisheries by generating a better understanding of the behaviour of the Indian Ocean tropical tuna purse seine fleet. The introduction to this thesis posed several questions that policymakers might ask when considering the implementation of a management measure: how will fleets respond to the implementation of management measures, such as spatial closures, catch limits or gear restrictions; how will these behavioural responses affect management outcomes; how might the fleet respond to change in other environmental, social, economic and political components of the fishery system; and what might the implications of this change be? The work presented and discussed in this thesis goes some way to answering these questions, and discussion in the chapters also provides recommendations on the research needed to fill important knowledge gaps.

More specifically, this thesis provides important contributions to knowledge regarding the behaviour of the Indian Ocean tuna purse seine fleet: Chapters 2 and 3 provide insight into the allocation of fishing effort by the purse seine fleet, whilst Chapter 4 improves understanding of how spatial closures have influenced the allocation of fishing effort; Chapter 5 contributes to understanding of the practice of fishing on FADs, including why FADs are used in the fishery, how their use varies in space and time, and how this influences the spatial behaviour of the fleet at broad spatial and temporal scales. Furthermore, the work in this thesis has stimulated thinking on the response of the purse seine fleet to change: Chapters 3 and 4 considered how and where effort might be allocated in response to spatial closures; Chapter 5 considered how the fleet might respond to restriction on the use of FADs; and Chapter 6 explored the possible consequences of change in the social, economic and political influences on fleet behaviour.

The following discussion elaborates on the main contributions from this thesis, and explores what these findings mean for management of offshore tuna fisheries, both in the Indian Ocean and further afield.

7.2 Contributions

7.2.1 Insight into the decision making of fishers

A useful starting point in understanding the behaviour of a fishing fleet is to identify the strategies and techniques used by fishers to search for fish. To do this, interviews were held with key experts in the Indian Ocean purse seine fishery, including fleet representatives, fishery managers and skippers themselves. These interviews provided useful insight into the search choices faced by skippers, the sources of information used to inform decisions, and the spatial and temporal scales of decision making (see Chapter 2).

A key insight from interviews was that skippers' decision making on where to fish at any given time is underpinned by two main types of knowledge: that based on new information on the recent location (or probable location) of tuna schools; and that based on acquired knowledge of the location and timing of seasonal fishing opportunities (Chapter 2). In the dynamic open ocean environment, new information is essential to skippers as it allows them to respond to recent and unfolding events, for example the development of promising fishing habitat or the discovery of a large tuna aggregation by other vessels. Consequently, new information is most influential in determining precisely where a skipper might search in the coming hours or days. To improve short term search efficiency there is considerable benefit to skippers in improving the quantity, as well as the quality, of new information available to them, for example by improving detection technologies or by expanding knowledge sharing networks. In comparison, heuristic knowledge is generally most useful in planning in advance which areas will be searched in the coming weeks and months. For instance, before leaving port for a fishing trip lasting several weeks a skipper might choose a specific region in which to focus search effort, based on heuristic knowledge of the most promising region for fishing at that particular time of year. Similarly, heuristics may also help to interpret and weight new information when it is received, ensuring that short term decisions are consistent with longer term expectations of where and when to find tuna schools. A conceptualisation of a skipper's decision regarding fishing location, showing three choices leading up to making decision and examples of the key influences at each stage, is presented in Figure 7.1.

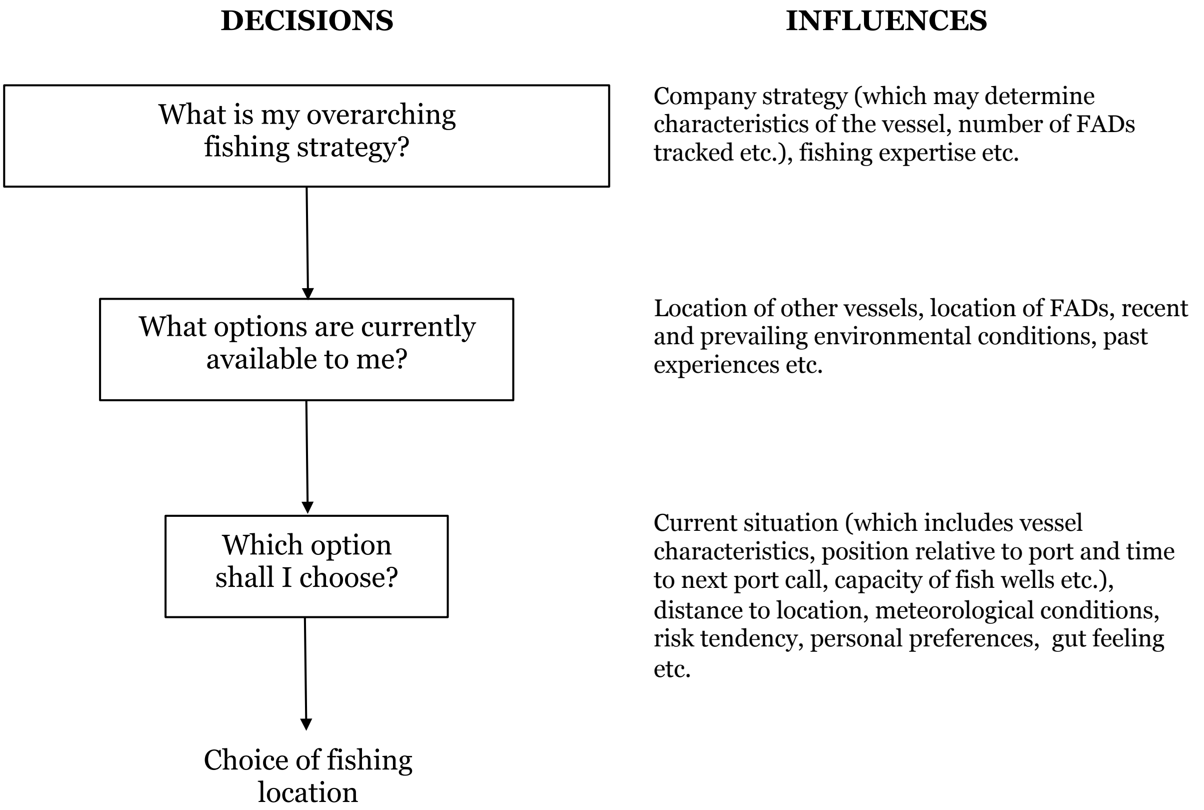

Figure 7.1 Conceptualisation of a skipper's decision process leading to the choice of a fishing location. Boxes show three hierarchical stages of making a decision; accompanying text suggests influences on each of these choice stages.

7.2.2 Insight into the drivers of fleet spatial behaviour

Many fisheries management questions relate to the spatial behaviour of fishing fleets at broad spatial and temporal scales. For example, managers may want to understand how the allocation of fishing effort will be affected by the implementation of a spatial closure, and how this might impact total annual catches. Attempting to answer these questions requires a good understanding of fishing fleet dynamics, including the factors that influence the allocation of fishing effort in space.

In Chapter 3 a statistical model was used to examine the drivers of spatial behaviour of the Indian Ocean tuna purse seine fleet at an ocean basin scale. Drawing on the understanding of skippers' short term decision making generated from interviews with fishery experts, modelling was focused on examining two possible influences on the spatial distribution of fishing effort: biophysical ocean conditions associated with tuna habitat; and the past behaviour of the fleet.

A key finding of this study was the consistency with which fishing effort was allocated into the same seasonal grounds year on year, which suggested strong inertia in the behaviour of the fleet. This ostensibly habitual allocation of effort was probably the result of the widespread use of heuristics in decision making; i.e. skippers chose to focus their search effort in well-known fishing grounds at the time of year when they expected good catches, based on their experiences of where and when they had fished before (see Chapters 2 and 3). A second finding was that biophysical conditions had an important forcing effect on the allocation of fishing effort, suggesting that the fleet is responsive to environmental variability. However, environmental variables were generally better predictors of where the fleet would not fish, rather than where it would (Chapter 3). This may be due to the very large areas of apparently suitable fishing habitat at any time weakening the influence of environmental variables in modelling. This result may also reflect the way in which skippers interpret and respond to environmental information: for instance, skippers may be confident that unfavourable conditions indicate poor fishing opportunities, but less confident that promising conditions foretell high catches.

These findings suggest that the prediction of fleet spatial behaviour under stable fishing conditions is possible with a reasonably good level of accuracy, on the basis that strong inertia in fleet behaviour means that the distribution of effort in the past is a good predictor of where it will be allocated in the future. However, under novel conditions, such as following the closure of a significant area of fishing ground, there are likely to be considerable challenges in predicting the reallocation of fishing effort. In these situations, the past behaviour of the fleet is unlikely to be suitable portent of where effort will be allocated, and accurate prediction of behaviour would probably require near the same near real-time information that is available to skippers themselves. Furthermore, the prediction of behaviour would probably need to account for the influence of group-level dynamics that emerge through knowledge sharing between skippers (see Chapter 2). The influence of processes such as teamwork and competition on the distribution of fishing effort were not sufficiently considered in this study, which highlights a drawback of the statistical approach used, and hence a better understanding of cooperation and competition dynamics and their influence on fleet-level behaviour are recommended as priority topics for future research.

7.2.3 Improved understanding of fleet response to spatial closures

Spatial closures are increasingly being proposed as management tools in tuna fisheries, and more generally as conservation tools by coastal states in RFMO convention areas (Davies et al. 2012; Pala 2013), yet there is uncertainty in how fleets respond to closed areas. A useful approach in understanding the effects of spatial management on fleet behaviour is retrospective evaluation of past spatial closures, although surprisingly such *post hoc* analyses are rare (e.g. Smith et al. 2006).

A retrospective evaluation of two recent closures in the IOTC convention area was undertaken in Chapter 4. In order to distinguish the true policy effect of the closures from other confounding influences on fleet behaviour, a counterfactual approach was used to compare the observed response of the fleet against predictions of where the fleet would have fished in the absence of the closures, using the statistical model developed in Chapter 3.

A key finding of this analysis was the inconsistent effect of the BIOT marine reserve on the allocation of fishing effort. In the first year the reserve was implemented the counterfactual scenario suggested that the purse seine fleet would have fished in the waters of the BIOT EEZ, suggesting a true policy effect of the reserve. In the following year, the observed allocation of fishing effort mainly east of 60°E potentially suggesting an MPA effect, with the fleet apparently avoiding the vicinity of BIOT. However, the counterfactual scenario in fact suggested that the fleet was unlikely to have fished in that region anyway as a result of unfavourable fishing conditions that year (Chapter 4).

The findings from Chapter 4 highlight the need for careful evaluation of the effects of spatial closures using a counterfactual approach. A key uncertainty in examining the effects of a management or conservation policy is whether an observed effect, for example a reduction in catch rate or a displacement of fishing effort, was due to the policy itself, or explained by coincidental influences (Ferraro 2009). The counterfactual approach demonstrated here reduces this uncertainty, yet the use of this approach as part of this thesis is one of only a few examples in the literature. This may be related to the paucity of research into the drivers of fisher behaviour, which is a necessary first step in developing model-based counterfactual scenarios.

More generally, these findings highlight important considerations for the design and placement of spatial closures intended to control fishing effort on highly mobile stocks. The use of space by offshore fishing fleets can be highly variable in the dynamic pelagic environment, as demonstrated by the behaviour of the Indian Ocean tuna purse seine fleet, which presents a challenge for the placement of spatial closures. Possible solutions include the implementation of very large closures, which might be robust to a certain amount of variability in the distribution of the resource, or mobile closures, which can be designed to track the predicted distribution of the resource in time and space. However, both of these potential solutions come with their own limitations and drawbacks, for example difficulty in negotiating very large closures, or the need for extensive real time datasets for predictive modelling (see Chapter 4).

7.2.4 Improved understanding of the role of FADs in fleet behaviour

The use of fish aggregating devices (FADs) has become the dominant practice in tropical tuna purse seine fishing. FADs, as fishing tools, increase fishing efficiency, but their use has been associated with negative ecosystem impacts, and moves are being made to manage the use of FADs. When evaluating the benefits and consequences of potential FAD management options it is important to consider how fishers will respond to regulation of their activities, which requires an understanding of the role FADs have played in shaping fishery dynamics. In Chapter 5 the past and present use of FADs in the Indian Ocean tropical tuna purse seine fishery was reviewed in detail, and from this understanding the response of the fleet to possible future management was considered.

A clear message from this review was the importance of FADs to modern purse seine fishing. The increasing use of FADs during the 1990s allowed boat owners to invest in the capacity of their fleets, and Spanish fishing firms in particular began to specialise in FAD-fishing, and new vessels were built that could catch and store more fish per fishing trip. To some vessels, FADs have become an essential fishing tool, without which fishing for profit would be impossible. This reliance on FADs presents a challenge for policymakers, who on one hand must take action to achieve sustainable exploitation of tuna stocks and minimise ecological fishery impacts, which may involve curbing the use of FADs, whilst on the other, they must minimise socio-economic costs to the fishing industry.

There are several plausible ways of managing the use of FADs in the Indian Ocean, although for each management option there are several ways purse seine skippers might modify their behaviour in an attempt to maintain catches. A limit on the number of deployed or monitored FADs would curb search efficiency and decrease the total number of sets made per vessel. But whilst a precautionary upper limit on the number of FADs a skipper is allowed to monitor would go some way towards controlling fishing mortality on FADs, this depends largely on whether a limit was set on the total number monitored or the total number monitored at any given time. For example, the ability to fish on a FAD that had been 'hidden' (unmonitored) for a period of several months, assuming it has not been fished by another vessel, might lead to larger catches on a smaller number of sets and diminish any overall reduction in total catch on FADs (on the basis that FADs which have been in the water for longer have larger associated tuna schools). Furthermore, as skippers would be permitted to fish on any unmonitored FAD they encounter by chance, it might be considered advantageous to deploy a greater total number of FADs, with or without monitoring buoys.

Limiting the total number of sets allowed to be made by an individual vessel on FADs might have a more direct and predictable management effect. Because skippers usually fish on any floating object they come across, even if the associated school is relatively small, placing a finite limit on the number of FADs that can be fished might incentivise skippers to be more discriminatory in the objects they fished on, presumably by choosing to fish on those objects with large associated schools. Incidentally, this selective fishing behaviour might also reduce the ecological impacts of FAD fishing on the basis that the ratio of bycatch to target catch is generally lower for larger set sizes (Dagorn et al. 2012a).

The review in Chapter 5 highlights the central role of FADs in shaping purse seine fishery dynamics in the Indian Ocean, which is also likely to be true of tuna purse seine fisheries in other regions. Yet large knowledge gaps regarding the use of FADs still exist, and this uncertainty is hindering management decision making on the use of FADs by purse seiners. This research supports the need for more data (see Dagorn et al. 2012b), although we also argue the need for better knowledge of how and why purse seine skippers deploy, visit and choose to fish on FADs. This information will help policy makers anticipate the fleet response to regulation or limits on the use of FADs, but can only come from better reporting on FAD usage by the purse seine industry.

7.3 Recommendations for management and research

7.3.1 Resolution of data available for research

The majority of the research in this thesis analysed fishing effort data aggregated by month and 1° Mercator squares, and consequently the focus was on fleet-level behaviour at broad temporal and spatial scales. Analysis at these coarse scales was appropriate with respect to the objectives of this thesis, including in understanding fleet response to spatial closures, which to date have covered large areas (e.g. over 100,000 km^2), and been implemented for a minimum of one month (see Chapter 4).

Nevertheless, access to finer scale fishery data, particularly fishing effort aggregated at daily or weekly, rather than monthly, intervals may have allowed for a more detailed understanding of the spatial behaviour of individual vessels, and groups of vessels, within the fleet. The behaviour of the fleet observed at ocean basin-scale is the product of behavioural processes operating at much finer scales, such as the group-level dynamics of the discovery and exploitation of tuna aggregations that emerge through information sharing and cooperation between skippers (Chapter 2). These dynamics are partially, if not fully obscured in monthly-aggregated fishery data, and hence could not be properly investigated as part of this PhD.

A recommendation of this thesis is that future research should focus on understanding the behavioural processes operating at the individual- and group-levels, for example how teams of vessels cooperate to locate tuna schools and how this subsequently determines fleet behaviour at broader temporal scales. In particular, this would improve understanding of how fishing effort is allocated under novel fishing conditions, such as spatial closures. However, this research will require the use of finer resolution data than that which is publically available. High resolution, set-by-set data are collected and held by the fishing industry, although these data are not made freely available to researchers outside of a handful of research institutions. Even within these institutions, access to the data, and freedom in how they are used for research, is limited. A lesson learnt in writing this thesis was that the tuna fishing industry is cautious of research into the behaviour of its vessels, partly due to confidentiality issues but also possibly because it does not perceive potential management benefits resulting from behavioural research. For instance, possible benefits to the industry might include the design of more efficient and less 'broad-brush' management measures, as well as greater consideration of the impacts of management on fishing activities in the policymaking process. Thus, it is necessary to better engage with the tuna fishing industry to communicate the aims, and potential benefits, of research into fleet behaviour, so that high resolution fishery data are made available for analysis.

7.3.2 Missing capacity for fleet research in tuna RFMOs

This thesis has highlighted the benefit to management of understanding and anticipating fleet behaviour. However, the majority of research by the tuna RFMOs has been directed at gaining better knowledge of the biology of exploited species and the dynamics of stocks, improving understanding of the ecosystem impacts of tuna fisheries, and improving the analysis and interpretation of fisheries catch data (e.g. IOTC 2013; ICCAT 2013; WCPFC 2013). In contrast, behavioural research with respect to fishers and fishing fleets has rarely featured on the scientific agendas of RFMOs.

The lack of focus may not be necessarily due to a failure of policymakers to recognise the importance of fisher behaviour *per se*, but may instead be explained by limited expertise in the national institutions contributing to tuna RFMO science (although note the limited access to high resolution data previously discussed). In fact, this problem is not peculiar to tuna RFMOs, and has been identified as a widespread weakness in fisheries science (Jentoft 2006). Fishery scientists tend to have educational backgrounds in the natural and economic sciences, and are potentially less familiar with the approaches and qualitative techniques commonly used to investigate the behaviour of resource users (e.g. Jentoft 2006; Edwards-Jones 2006; Abernethy et al. 2007). In particular, there is conspicuous absence of qualitative approaches in tuna fisheries research, such as the fisher surveys and scenario planning undertaken in this thesis (but see Moreno et al. 2007; 2008 for notable exceptions). Consequently, *ad hoc* attempts to anticipate the behavioural response of a tuna fleet to management have been based upon economic theory and published knowledge on behavioural drivers in other fisheries (Murua et al. 2011; Martin et al. 2011), rather than on primary research.

Assuming the capacity to do this research is indeed missing, or at least underdeveloped, there is a need to promote interdisciplinary research programmes that bring together scientists from a variety of quantitative and qualitative backgrounds. This is important in order to equip tuna RFMOs with the necessary empirical skills, and research perspectives, to develop a more precise understanding of the behaviour of fishers and fleets in their convention area. This may require the engagement of research institutions and universities that possess the 'missing' research expertise, but that have not participated in generating RFMOs science in the past.

7.3.3 Management strategy evaluation

It is widely acknowledged that if fishery management is to be effective, key sources of uncertainty must not only be better understood, but also considered explicitly in planning. One approach that has gained considerable momentum is management strategy evaluation (MSE), which is used to evaluate the performance of competing management strategies, and, crucially, to provide management advice in the presence of uncertainty (Butterworth and Punt 1999; Punt and Donovan 2007). The approach uses simulation to test how robust alternative management strategies are to a range of uncertainties, and allows fisheries scientists to evaluate how limited knowledge or understanding might impact on the performance of harvest rules (Holland and Herrera 2009). Unlike traditional approaches, an MSE can model the entire management system, from the dynamics of a fish stock under different harvest rules, to the gathering and analysis of data to generate a harvest rule, and further to the response of fishers to the rules imposed (Fulton et al. 2011). Given the flexibility of MSE in a wide range of natural resource systems, the approach is rapidly becoming the dominant framework for the development and evaluation of management policies for commercial fisheries (Punt and Donovan 2007; Bunnefeld et al. 2010), and steps are being taken to develop MSE in IOTC and in other tuna RFMOs (IOTC 2012).

A current challenge in MSE is to incorporate uncertainty in the human elements of management systems. Incorporating the actions and responses of fishing fleets to management and other drivers into an MSE, as one or more operating models, would allow managers to consider this important aspect of implementation uncertainty, and would widen the scope of management advice which this approach could provide (Venables et al. 2009). To this end, MSE has been extended in recent years to consider sources of uncertainty beyond those relating to resource dynamics and scientific advice, including aspects of management implementation (Little et al. 2004; Dichmont et al. 2006).

A recommendation of this thesis is that fleet behaviour should be incorporated into the MSE currently being developed for IOTC, and also into future MSEs in other tuna RFMOs. In the case of IOTC, the behaviour of the purse seine fleet could be incorporated as an operating model. This would require the development of a mechanistic model of fleet behaviour that is able to simulate the group-level behavioural processes identified, but not adequately examined, in this theses (e.g. coordination and cooperation between skippers; see Chapter 2 and 3). Similar operating models would also need to be developed for the longline fleet, and for other major semi-industrial tuna fleets operating in the IOTC convention area (e.g. the Sri Lankan inboard multiday fleet). However, the suitability and availability of the fishery data needed for modelling the behaviour of these fleets is likely to present a major challenge, as longline data are available only at very coarse spatial resolutions (5° latitude/longitude) and data for semi-industrial fleets are notoriously incomplete (IOTC 2012). Nevertheless, even simple operating models of fleet behaviour would allow for a more complete range of implementation uncertainty to be considered in the design and evaluation of management policies.

7.4 Concluding remarks

The management of fishery resources is a vital but often troublesome task, and is complicated by uncertainty in almost every part of the management process. The approaches and tools used to manage fisheries are continually being updated and improved, although these changes have often been too slow, or too limited in scope, to prevent the depletion or over-exploitation of fish stocks. Moreover, and all too frequently, management has been blindsided by an unexpected behavioural response of fishers, leading to unintended and potentially undesirable management outcomes. The importance of considering the behaviour of fishers in management planning, in order to avoid unwelcome surprises later down the line, is increasingly being recognised by fishery scientists and policymakers, including in the tuna RFMOs, yet progress in developing the necessary knowledge and approaches to reduce and account for uncertainty has been slow. Hence, there is continued need for new and multidisciplinary research of the kind presented in this thesis.

8 References

Abbott, J. K. & Haynie, A. C. (2012) What are we protecting? Fisher behavior and the unintended consequences of spatial closures as a fishery management tool. *Ecological Applications*, 22(3), 762-777.

Abella, A., Fiorentino, F., Mannini, A., & Orsi Relini, L. (2008) Exploring relationships between recruitment of European hake (*Merluccius merluccius* L. 1758) and environmental factors in the Ligurian Sea and the Strait of Sicily (Central Mediterranean). *Journal of Marine Systems*, 71(3), 279-293.

Abernethy, K. E., Allison, E. H., Molloy, P. P., & Côté, I. M. (2007) Why do fishers fish where they fish? Using the ideal free distribution to understand the behaviour of artisanal reef fishers. *Canadian Journal of Fisheries and Aquatic Sciences*, 64(11), 1595-1604.

Abrahams, M. V. & Healey, M. C. (1990) Variation in the competitive abilities of fishermen and its influence on the spatial distribution of the British Columbia salmon troll fleet. *Canadian Journal of Fisheries and Aquatic Sciences*, 47(6), 1116-1121.

Allen, P. M. & McGlade, J. M. (1986) Dynamics of discovery and exploitation: the case of the Scotian Shelf groundfish fisheries. *Canadian Journal of Fisheries and Aquatic Sciences*, 43(6), 1187-1200.

Amandè, J. M., Ariz, J., Chassot, E., Chavance, P., Delgado de Molina, A., Gaertner, D., Murua, H., Pianet, R., & Ruiz, J. (2008) By-catch and discards of the European purse seine tuna fishery in the Indian Ocean: estimation and characteristics for the

2003-2007 period. *Indian Ocean Tuna Commission document, IOTC-2008-WPEB-12*, 26.

Amandè, J. M., Bez, N., Konan, N., Murua, H., Delgado de Molina, A., Chavance, P., & Dagorn, L. (2011) Areas with high bycatch of silky sharks (*Carcharhinus falciformis*) in the Western Indian Ocean purse seine fishery. *Indian Ocean Tuna Commission document, IOTC-2008-WPEB-12*, 23.

Amandè, M. J., Ariz, J., Chassot, E., De Molina, A. D., Gaertner, D., Murua, H., Pianet, R., Ruiz, J., & Chavance, P. (2010) Bycatch of the European purse seine tuna fishery in the Atlantic Ocean for the 2003-2007 period. *Aquatic Living Resources*, 23(4), 353-362.

Amandè, M. J., Chassot, E., Chavance, P., Murua, H., de Molina, A. D., & Bez, N. (2012) Precision in bycatch estimates: the case of tuna purse-seine fisheries in the Indian Ocean. *ICES Journal of Marine Science: Journal du Conseil*, 69(8), 1501-1510.

Andersen, B.S. & Christensen, A.-S.-S. (2005) *Modelling short-term choice behaviour of Danish fishermen in a mixed fishery,* In Sumaila U.R. & Marsden, A.D. (eds) *2005 North American Association of Fisheries Economists Forum Proceedings*. Fisheries Centre Research Reports 14(1), University of British Columbia, Vancouver, Canada, pp. 13-26.

Andersen, B. S., Ulrich, C., Eigaard, O. R., & Christensen, A. S. (2011) Short-term choice behaviour in a mixed fishery: investigating metier selection in the Danish gillnet fishery. *ICES Journal of Marine Science*, 69(1), 131-143.

Anonymous (2011) *Report of the 2011 ISSF Stock Assessment Workshop, March 14-17, Rome, Italy*. ISSF Technical Report 2011-02, International Seafood Sustainability Foundation, McLean, Virginia, USA.

Aranda, M., Murua, H., & de Bruyn, P. (2012) Managing fishing capacity in tuna regional fisheries management organisations (RFMOs): Development and state of the art. *Marine Policy*, 36(5), 985-992.

Beddington, J. R., Agnew, D. J., & Clark, C. W. (2007) Current problems in the management of marine fisheries. *Science*, 316(5832), 1713-1716.

Begossi, A. (1996) Fishing Activities and Strategies at Buzios Island (Brazil). Fisheries Resource Utilization and Policy: Proceedings of the World Fisheries Congress, Theme 2. pp. 125.

Berman, M. (2006) Modeling spatial choice in ocean fisheries. *Marine Resource Economics*, 21(4), 375.

Bernard, R. (1994) *Research methods in anthropology*. Berkeley California: Sage Publications.

Bertrand, S., Díaz, E., & Ñiquen, M. (2004) Interactions between fish and fisher's spatial distribution and behaviour: an empirical study of the anchovy (*Engraulis ringens*) fishery of Peru. *ICES Journal of Marine Science: Journal du Conseil*, 61(7), 1127-1136.

Béné, C. (1996) Effects of market constraints, the remuneration system, and resource dynamics on the spatial distribution of fishing effort. *Canadian Journal of Fisheries and Aquatic Sciences*, 53(3), 563-571.

Béné, C. & Tewfik, A. (2001) Fishing effort allocation and fishermen's decision making process in a multi-species small-scale fishery: Analysis of the conch and lobster fishery in Turks and Caicos Islands. *Human Ecology*, 29(2), 157-186.

Bockstael, N. E. & Opaluch, J. J. (1983) Discrete modelling of supply response under uncertainty: The case of the fishery. *Journal of Environmental Economics and Management*, 10(2), 125-137.

Bohensky, E. L., Reyers, B., & Van Jaarsveld, A. S. (2006) Future ecosystem services in a Southern African river basin: a scenario planning approach to uncertainty. *Conservation Biology*, 20(4), 1051-1061.

Bossel, H. (1998) *Earth at a crossroads: paths to a sustainable future*. Cambridge University Press.

Branch, T. A., Hilborn, R., Haynie, A. C., Fay, G., Flynn, L., Griffiths, J., Marshall, K. N., Randall, J. K., Scheuerell, J. M., & Ward, E. J. (2006) Fleet dynamics and fishermen behavior: lessons for fisheries managers. *Canadian Journal of Fisheries and Aquatic Sciences*, 63(7), 1647-1668.

Briand, G., Heckelei, T., Matulich, S. C., & Mittelhammer, R. C. (2004) Managing fishing power: the case of Alaska red king crab (*Paralithodes camtschaticus*). *Canadian Journal of Fisheries and Aquatic Sciences*, 61(1), 43-53.

Bromhead, D., Foster, J., Attard, R., Findlay, J. & Kalish, J. (2003) *A Review of the impact of fish aggregating devices (FADs) on tuna fisheries*. Final report to Fisheries Resources Research Fund, Bureau of Rural Sciences, Canberra, Australia.

Brown, N. R. (1995) Estimation strategies and the judgment of event frequency. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 21(6), 1539.

de Bruyn, P., Murua, H., & Aranda, M. (2013) The Precautionary approach to fisheries management: How this is taken into account by Tuna regional fisheries management organisations (RFMOs). *Marine Policy*, 38, 397-406.

Buanes, A. & Jentoft, S. (2009) Building bridges: Institutional perspectives on interdisciplinarity. *Futures*, 41(7), 446-454.

Bunnefeld, N., Hoshino, E., & Milner-Gulland, E. J. (2011) Management strategy evaluation: a powerful tool for conservation? *Trends in Ecology and Evolution*, 26(9), 441 - 447.

Burham, K. P. & Anderson, D. R. (2002) Model selection and multimodel inference: a practical information-theoretic approach. Springer-Verlag, New York.

Butterworth, D. S. & Punt, A. E. (1999) Experiences in the evaluation and implementation of management procedures. *ICES Journal of Marine Science: Journal du Conseil*, 56(6), 985-998.

Camerer, C., Babcock, L., Loewenstein, G., & Thaler, R. (1997) Labor supply of New York City cabdrivers: One day at a time. *The Quarterly Journal of Economics*, 112(2), 407-441.

Camhi, M.D., SV, V., Fordham, S.V., Fowler, S.L. & Gibson, C. (2009) *The Conservation Status of Pelagic Sharks and Rays: Report of the IUCN Shark Specialist Group Pelagic Shark Red List Workshop*. IUCN Species Survival Commission Shark Specialist Group, Newbury, UK.

Campbell, H. F. & Hand, A. J. (1999) Modeling the spatial dynamics of the US purse-seine fleet operating in the western Pacific tuna fishery. *Canadian Journal of Fisheries and Aquatic Sciences*, 56(7), 1266-1277.

Campling, L. (2012) The Tuna 'Commodity Frontier': Business Strategies and Environment in the Industrial Tuna Fisheries of the Western Indian Ocean. *Journal of Agrarian Change*, 12(July), 252-278.

Chassot, E., Dewals, P., Floch, L., Lucas, V., Morales-Vargas, M., & Kaplan, D. (2010) Analysis of the effects of Somali piracy on the European tuna purse seine fisheries of the Indian Ocean. *Indian Ocean Tuna Commission document, IOTC-2010-SC-09*.

Christensen, A. S. & Raakjaer, J. (2006) Fishermen's tactical and strategic decisions: A case study of Danish demersal fisheries. *Fisheries research*, 81(2-3), 258-267.

Cullis-Suzuki, S. & Pauly, D. (2010) Failing the high seas: A global evaluation of regional fisheries management organizations. *Marine Policy*, 34(5), 1036-1042.

Curtis, R. & Hicks, R. L. (2000) The cost of sea turtle preservation: the case of Hawaii's pelagic longliners. *American Journal of Agricultural Economics*, 82, 1191-1197.

Curtis, R. E. & McConnell, K. E. (2004) Incorporating information and expectations in fishermen's spatial decisions. *Marine Resource Economics*, 19, 131-143

Dagorn, L. & Fréon, P. (1999) Tropical tuna associated with floating objects: a simulation study of the meeting point hypothesis. *Canadian Journal of Fisheries and Aquatic Sciences*, 56(6), 984-993.

Dagorn, L., Bez, N., Fauvel, T., & Walker, E. (2013) How much do fish aggregating devices (FADs) modify the floating object environment in the ocean? *Fisheries Oceanography*, 22(3), 147-153.

Dagorn, L., Filmalter, J. D., Forget, F., Amandé, J. M., Hall, M. A., Williams, P., Murua, H., Ariz, J., Chavance, P., & Bez, N. (2012a) Targeting bigger schools can reduce ecosystem impacts of fisheries. *Canadian Journal of Fisheries and Aquatic Sciences*, 69, 1463-1467.

Dagorn, L., Holland, K. N., Restrepo, V., & Moreno, G. (2012b) Is it good or bad to fish with FADs? What are the real impacts of the use of drifting FADs on pelagic marine ecosystems? *Fish and Fisheries*, 14(3), 391-415.

Davies, T.K., Martin, S., Mees, C., Chassot, E. & Kaplan, D.M. (2012) *A review of the conservation benefits of marine protected areas for pelagic species associated with fisheries*. ISSF Technical Report 2012-02, International Seafood Sustainability Foundation, McLean, Virginia, USA.

Dempster, T. & Taquet, M. (2004) Fish aggregation device (FAD) research: gaps in current knowledge and future directions for ecological studies. *Reviews in Fish Biology and Fisheries*, 14(1), 21-42.

DeSombre, E. (2010) Flags of convenience and property rights on the high seas. *Conservation and Management of Transnational Tuna Fisheries*, 269-280.

Dichmont, C. M., Deng, A. R., Punt, A. E., Venables, W., & Haddon, M. (2006) Management strategies for short-lived species: The case of Australia's Northern Prawn Fishery: 1. Accounting for multiple species, spatial structure and implementation uncertainty when evaluating risk. *Fisheries research*, 82(1), 204-220.

Dinmore, T. A., Duplisea, D. E., Rackham, B. D., Maxwell, D. L., & Jennings, S. (2003) Impact of a large-scale area closure on patterns of fishing disturbance and the consequences for benthic communities. *ICES Journal of Marine Science: Journal du Conseil*, 60(2), 371-380.

Dorn, M. (2001) Fishing behavior of factory trawlers: a hierarchical model of information processing and decision-making. *ICES Journal of Marine Science*, 58(1), 238-252.

Dowling, N. A., Wilcox, C., Mangel, M., & Pascoe, S. (2012) Assessing opportunity and relocation costs of marine protected areas using a behavioural model of longline fleet dynamics. Fish and Fisheries, 13(2), 139-157

Dupont, D. P. (1993) Price uncertainty, expectations formation and fishers' location choices. Marine Resource Economics, 8(3), 219-247.

Durrenberger, E. & Pálsson, G. (1986) Finding fish: the tactics of Icelandic skippers. *American ethnologist*, 13(2), 213-229.

Eales, J. & Wilen, J. E. (1986) An examination of fishing location choice in the pink shrimp fishery. *Marine Resource Economics*, 2(4), 331-351.

Edwards-Jones, G. (2006) Modelling farmer decision-making: concepts, progress and challenges. *Animal Science*, 82(06), 783-790.

Essington, T. E., Beaudreau, A. H., & Wiedenmann, J. (2006) Fishing through marine food webs. *Proceedings of the National Academy of Sciences of the United States of America*, 103(9), 3171-3175.

FAO (2010) *State of World Fisheries and Aquaculture*. United Nations Food and Agriculture Organisation, Rome, Italy.

Fauvel, T., Bez, N., Walker, E., Alicia, D., Murua, H., Chavance, P., & Dagorn, L. (2009) Comparative study of the distribution of natural versus artificial drifting Fish Aggregating Devices (FADs) in the Western Indian Ocean. *Indian Ocean Tuna Commission document, IOTC-2009-WPTT-19*, 17.

Fawcett, T. (2006) An introduction to ROC analysis. *Pattern recognition letters*, 27(8), 861-874.

Ferraro, P. J. (2009) Counterfactual thinking and impact evaluation in environmental policy. *New Directions for Evaluation*, 2009(122), 75-84.

Floch, L., Molina, A. D. D., Assan, C., Dewals, P., Areso, J. J., & Chassot, E. (2012) Statistics of the European purse seine fishing fleet and associated flags targeting tropical tunas in the Indian Ocean (1981-2011). *Indian Ocean Tuna Commission document, IOTC-2012-WPTT-14*, 21.

Fogarty, M. J. & Murawski, S. A. (1998) Large-scale disturbance and the structure of marine systems: fishery impacts on Georges Bank. *Ecological Applications*, 8(sp1), S6-S22.

Fonteneau, A. (2003) Prospects for the management of FAD fisheries in the Indian Ocean. *Indian Ocean Tuna Commission document, IOTC-2003-WPTT-04*, 17.

Fonteneau, A., Chassot, E., & Bodin, N. (2013) Global spatio-temporal patterns in tropical tuna purse seine fisheries on drifting fish aggregating devices (DFADs): Taking a historical perspective to inform current challenges. *Aquatic Living Resources*, 26(1), 37-48.

Fonteneau, A., Pallares, P. & Pianet, R. (2000) A worldwide review of purse seine fisheries on FADs. *In: Pêche thonière et dispositifs de concentration de poissons (proceedings of the 1st Symposium on Tuna fisheries and FADs, Martinique, October 1999).* (eds.) Le Gal JY, Cayré P, Taquet M. Actes Colloques-IFREMER 28, pp. 15-35.

Fretwell, S. D. & Lucas, H. L. (1969) On territorial behavior and other factors influencing habitat distribution in birds. *Acta biotheoretica*, 19(1), 16-36.

Fromentin, J. -M. & Fonteneau, A. (2001) Fishing effects and life history traits: a case study comparing tropical versus temperate tunas. *Fisheries Research*, 53(2), 133-150.

Fulton, E.A., Fuller, M., Smith, A.D.M. & Punt, A.E. (2004) *Ecological indicators of the ecosystem effects of fishing: final report*. CSIRO, Victoria, Australia.

Fulton, E. A., Smith, A. D. M., Smith, D. C., & van Putten, I. E. (2011) Human behaviour: the key source of uncertainty in fisheries management. *Fish and Fisheries*, 12(1), 2-17.

Gaertner, D. & Pallares, P. (2002) *Efficiency of Tuna Purse-Seiners and Effective Effort (ESTHER): Scientific report of the European Union Project*. 15th Meeting of the Standing Committee on Tuna and Billfish, 22-27 July, Honolulu, Hawai'i.

Gaertner, D., Pagavino, M., & Marcano, J. (1996) Use of generalized linear models to investigate the fishing strategies of tuna purse seiners, in presence of floating objects in the western Atlantic Ocean. Aquatic Living Resources, 56, 394-406.

Gaines, S. D., Lester, S. E., Grorud-Colvert, K., Costello, C., & Pollnac, R. (2010) Evolving science of marine reserves: new developments and emerging research frontiers. *Proceedings of the National Academy of Sciences of the United States of America*, 107(43), 18251-18255.

Garcia, S. M. & Grainger, R. J. (2005) Gloom and doom? The future of marine capture fisheries. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 360(1453), 21-46.

Gatewood, J. B. (1984) Is the skipper effect really a false ideology? *American Ethnologist*, 11(2), 378-379.

Gell, F. R. & Roberts, C. M. (2003) Benefits beyond boundaries: the fishery effects of marine reserves. *Trends in Ecology & Evolution*, 18(9), 448-455.

Gezelius, S. S. (2007) The Social Aspects of Fishing Effort. *Human Ecology*, 35(5), 587-599.

Gillis, D. M. (2003) Ideal free distributions in fleet dynamics: a behavioral perspective on vessel movement in fisheries analysis. *Canadian Journal of Zoology*, 81(2), 177-187.

Gillis, D. M. & Peterman, R. M. (1998) Implications of interference among fishing vessels and the ideal free distribution to the interpretation of CPUE. *Canadian Journal of Fisheries and Aquatic Sciences*, 55(1), 37-46.

Gillis, D. M., Peterman, R. M., & Tyler, A. V. (1993) Movement dynamics in a fishery: application of the ideal free distribution to spatial allocation of effort. *Canadian Journal of Fisheries and Aquatic Sciences*, 50(2), 323-333.

Gilman, E. L. (2011) Bycatch governance and best practice mitigation technology in global tuna fisheries. *Marine Policy*, 35(5), 590-609.

Grafton, R. Q., Arnason, R., Bjorndal, T., Campbell, D., Campbell, H. F., Clark, C. W., Connor, R., Dupont, D. P., Hannesson, R., & Hilborn, R. (2006) Incentive-based approaches to sustainable fisheries. *Canadian Journal of Fisheries and Aquatic Sciences*, 63(3), 699-710.

Grafton, R. Q., Hilborn, R., Ridgeway, L., Squires, D., Williams, M., Garcia, S., Groves, T., Joseph, J., Kelleher, K., & Kompas, T. (2008) Positioning fisheries in a changing world. *Marine Policy*, 32(4), 630-634.

Guillotreau, P., Salladarré, F., Dewals, P., & Dagorn, L. (2011) Fishing tuna around Fish Aggregating Devices (FADs) vs free swimming schools: skipper decision and other determining factors. *Fisheries Research*(109), 234-242.

Hall, M. A. (1992) The association of tunas with floating objects and dolphins in the Eastern Pacific Ocean. VII. Some hypotheses on the mechanisms governing the association of tunas with floating objects and dolphins. Background document for the International Workshop on the Ecology and Fisheries for Tunas Associated with Floating Objects. *In: International Workshop on Fishing for Tunas Associated with Floating Objects (11-14 February 1992. La Jolla, California)*. pp. 6.

Hallier, J. P. & Gaertner, D. (2008) Drifting fish aggregation devices could act as an ecological trap for tropical tuna species. *Marine Ecology Progress Series*, 353, 255-264.

Halpern, B. S. (2003) The impact of marine reserves: do reserves work and does reserve size matter? *Ecological applications*, 13(sp1), 117-137.

Halpern, B. S. & Warner, R. R. (2002) Marine reserves have rapid and lasting effects. *Ecology letters*, 5, 361-366.

Halpern, B. S., Lester, S. E., & Kellner, J. B. (2009) Spillover from marine reserves and the replenishment of fished stocks. *Environmental Conservation*, 36(04), 268-276.

Hart, D. R. (2006) When do marine reserves increase fishery yield? *Canadian Journal of Fisheries and Aquatic Sciences*, 63(7), 1445-1449.

Harwood, J. & Stokes, K. (2003) Coping with uncertainty in ecological advice: lessons from fisheries. *Trends in Ecology & Evolution*, 18(12), 617-622.

Hiddink, J. G., Hutton, T., Jennings, S., & Kaiser, M. J. (2006) Predicting the effects of area closures and fishing effort restrictions on the production, biomass, and species richness of benthic invertebrate communities. *ICES Journal of Marine Science: Journal du Conseil*, 63(5), 822-830.

Hilborn, R. (1985) Fleet dynamics and individual variation: why some people catch more fish than others. *Canadian Journal of Fisheries and Aquatic Sciences*, 42(1), 2-13.

Hilborn, R. (2002) Marine reserves and fisheries management. *Science*, 295, 1233-1235.

Hilborn, R. (2007) Managing fisheries is managing people: what has been learned? *Fish and Fisheries*, 8(4), 285-296.

Hilborn, R. & Kennedy, R. B. (1992) Spatial pattern in catch rates: a test of economic theory. *Bulletin of Mathematical Biology*, 54(2), 263-273.

Hilborn, R. & Ledbetter, M. (1979) Analysis of the British Columbia salmon purse-seine fleet: dynamics of movement. *Journal of the Fisheries Board of Canada*, 36(4), 384-391.

Hilborn, R. & Walters, C. J. (1992) Quantitative fisheries stock assessment: choice, dynamics and uncertainty. *Reviews in Fish Biology and Fisheries*, 2(2), 177-178.

Hilborn, R., Maguire, J. -J., Parma, A. M., & Rosenberg, A. A. (2001) The precautionary approach and risk management: can they increase the probability of successes in fishery management? *Canadian Journal of Fisheries and Aquatic Sciences*, 58(1), 99-107.

Hilborn, R., Stokes, K., Maguire, J. -J. -J., Smith, T., Botsford, L. W., Mangel, M., Orensanz, J., Parma, A., Rice, J., Bell, J., Cochrane, K. L., Garcia, S., Hall, S., Kirkwood, G. P., Sainsbury, K., Stefansson, G., & Walters, C. (2004) When can marine reserves improve fisheries management? *Ocean & Coastal Management*, 47(3-4), 197-205.

Holland, D. S. (2008) Are fishermen rational? A fishing expedition. *Marine Resource Economics*, 23(3), 325-344.

Holland, D. S. & Herrera, G. E. (2009) Uncertainty in the management of fisheries: contradictory implications and a new approach. *Marine Resource Economics*, 24(3), 289.

Holland, D. S. & Sutinen, J. G. (1999) An empirical model of fleet dynamics in New England trawl fisheries. *Canadian Journal of Fisheries and Aquatic Sciences*, 56(2), 253-264.

Holland, D. S. & Sutinen, J. G. (2000) Location Choice in New England Trawl Fisheries: Old Habits Die Hard. *Land Economics*, 76(1), 133-149.

Hutchings, J. A. (2000) Collapse and recovery of marine fishes. *Nature*, 406(6798), 882-885.

Hutton, T., Mardle, S., Pascoe, S., & Clark, R. A. (2004) Modelling fishing location choice within mixed fisheries: English North Sea beam trawlers in 2000 and 2001. *ICES Journal of Marine Science: Journal du Conseil*, 61(8), 1443-1452.

IOTC (2012) Report of the Fourteenth Session of the IOTC Working Party on Tropical Tunas. *IOTC Proceedings,* Victoria, Seychelles.

IOTC (2013) *Report of the the sixteenth session of the IOTC Scientific Committee.* Victoria, Seychelles.

ISSF (2013) *ISSF Tuna Stock Status Update, 2013: Status of the world fisheries for tuna*. International Seafood Sustainability Foundation, Washington, D.C., USA.

Itano, D., Fukofuka, S., & Brogan, D. (2004) The development, design and recent status of anchored and drifting FADs in the WCPO. *Standing Committee on Tuna and Billfish, Majuro, Republic of the Marshall Islands. Information Paper No. INFFTWG-3.17 TH*.

Jaffry, S., Pickering, H., Ghulam, Y., Whitmarsh, D., & Wattage, P. (2004) Consumer choices for quality and sustainability labelled seafood products in the UK. *Food Policy*, 29(3), 215-228.

Jaquemet, S., Potier, M., & Ménard, F. (2011) Do drifting and anchored fish aggregating devices (FADs) similarly influence tuna feeding habits? A case study from the western Indian Ocean. *Fisheries Research*, 107(1), 283-290.

Jentoft, S. (2006) Beyond fisheries management: The Phronetic dimension. *Marine Policy*, 30(6), 671-680.

Joseph, J., Squires, D., Bayliff, W. & Groves, T. (2010) *Addressing the problem of excess fishing capacity in tuna fisheries,* In Allen R., Joseph, J. & Squires, D. (eds)

Conservation and Management of Transnational Tuna Fisheries. Wiley-Blackwell, pp. 11-38.

Kaplan, D. M., Bach, P., Bonhommeau, S., Chassot, E., Chavance, P., Dagorn, L., Davies, T., Dueri, S., Fletcher, R., & Fonteneau, A. (2013) The true challenge of giant marine reserves. *Science (New York, NY)*, 340(6134), 810.

Kirkwood, G.P. & Smith, A.D.M. (1996) *Assessing the precautionary nature of fishery management strategies*. FAO Fisheries Technical Paper, UN Food and Agriculture Organisation, Rome, Italy.

Lane, D. E. (1989) A partially observable model of decision making by fishermen. *Operations Research*, 240-254.

Laurs, R. M., Fiedler, P. C., & Montgomery, D. R. (1984) Albacore tuna catch distributions relative to environmental features observed from satellites. *Deep Sea Research Part A. Oceanographic Research Papers*, 31(9), 1085-1099.

Lester, S., Halpern, B., Grorud-Colvert, K., Lubchenco, J., Ruttenberg, B., Gaines, S. D., Airamé, S., & Warner, R. (2009) Biological effects within no-take marine reserves: a global synthesis. *Marine Ecology Progress Series*, 384, 33-46.

Little, L., Kuikka, S., Punt, A., Pantus, F., Davies, C., & Mapstone, B. (2004) Information flow among fishing vessels modelled using a Bayesian network. *Environmental Modelling & Software*, 19(1), 27-34.

Lodge, M. (2007) Managing International Fisheries: Improving Fisheries Governance by Strengthening Regional Fisheries Management Organizations. *Chatham House, March 2007*.

Mace, P. (1997) Developing and sustaining world fisheries resources: the state of science and management. *In: Proceedings of the 2nd World Fisheries Congress, Brisbane, Australia, 1996*. (eds.) Smith A, Beumer J, Grant A, Hancock D. Victoria, Australia. pp. 1-20.

Marchal, P. M. P., Lallemand, P. L. P., & Stokes, K. S. K. (2009) The relative weight of traditions, economics, and catch plans in New Zealand fleet dynamics. *Canadian journal of fisheries and aquatic sciences*, 66(2), 291-311.

Marsac, F. (2008) Outlook of ocean climate variability in the west tropical Indian Ocean, 1997-2008. *Indian Ocean Tuna Commission document, IOTC-2008-WPTT-27*, 9.

Marsac, F. & Blanc, J. (1999) Oceanographic changes during the 1997-1998 El Niño in the Indian Ocean and their impact on the purse seine fishery. *IOTC Proceedings*, 147-157.

Marsac, F. & Eme, U. M. R. (2012) Outline of climate and oceanographic conditions in the Indian Ocean over the period 2002-2012. *IOTC Proceedings, 133-145*.

Marsac, F., Fonteneau, A. & Ménard, F. (2000) Drifting FADs used in tuna fisheries: an ecological trap? *In: Pêche thonière et dispositifs de concentration de poissons (proceedings of the 1st Symposium on Tuna fisheries and FADs, Martinique, October 1999)*. (eds.) Le Gal JY, Cayré P, Taquet M. Actes Colloques-IFREMER 28, pp. 537-552.

Martin, S., Edwards, C., & Mees, C. (2011) An analysis of the effects of the use of Fish Aggregating Devices on yellowfin tuna Thunnus albacores in the Indian Ocean. *Indian Ocean Tuna Commission document, IOTC-2011-WPTT13-57*, 7.

Maunder, M. N. (2011) Updated indicators of stock status for skipjack tuna in the eastern Pacific Ocean. *Inter-American Tropical Tuna Commission document, Stock Assessment Report*, 02-08.

McAllister, R. R. J., Tisdell, J. G., Reeson, A. F., & Gordon, I. J. (2011) Economic Behavior in the Face of Resource Variability and Uncertainty. *Ecology and Society*, 16(3).

McClanahan, T. R. & Kaunda-Arara, B. (1996) Fishery Recovery in a Coral-reef Marine Park and Its Effect on the Adjacent Fishery. *Conservation Biology*, 10(4), 1187-1199.

McGoodwin, J. (1990) *Crisis in the World's Fisheries: People, Problems, and Policies*. Chicago, Stanford University Press.

MEA (2005) *Ecosystems and human well-being*. Millennium Ecosystem Assessment, Island Press Washington, DC.

Mistiaen, J. A. & Strand, I. E. (2000) Location choice of commercial fishermen with heterogeneous risk preferences. *American Journal of Agricultural Economics*, 82(5), 1184-1190.

Miyake, M.P., Guillotreau, P., Sun, C.-H. & Ishimura, G. (2010) *Recent Developments in the Tuna Industry: Stock, Fisheries, Management, Processing, Trade and Markets*. FAO Fisheries and Aquaculture Technical Paper No. 543, Rome, Italy.

Mohri, M. & Nishida, T. (2000) Consideration on distribution of adult yellowfin tuna (Thunnus albacares) in the Indian Ocean based on Japanese tuna longline fisheries and survey information. *Journal of National Fisheries University*, 49(1), 1-11.

Moreno, G., Dagorn, L., Sancho, G., & Itano, D. (2007) Fish behaviour from fishers' knowledge: the case study of tropical tuna around drifting fish aggregating devices (DFADs). *Canadian Journal of Fisheries and Aquatic Sciences*, 64(11), 1517-1528.

Moreno, G., Dagorn, L., Sancho, G., Garcia, D., & Itano, D. (2008) Using local ecological knowledge (LEK) to provide insight on the tuna purse seine fleets of the Indian Ocean useful for management. *Aquatic Living Resources*, 376(2007), 367-376.

Murawski, S., Brown, R., Lai, H. -L., Rago, P., & Hendrickson, L. (2000) Large-scale closed areas as a fishery-management tool in temperate marine systems: the Georges Bank experience. *Bulletin of Marine Science*, 66(3), 775-798.

Murawski, S. A., Wigley, S. E., Fogarty, M. J., Rago, P. J., & Mountain, D. G. (2005) Effort distribution and catch patterns adjacent to temperate MPAs. *ICES Journal of Marine Science: Journal du Conseil*, 62(6), 1150-1167.

Murua, H., Herrera, M., Fonteneau, A., & Marsac, F. (2011) Evaluation of current and alternative time / area closures by catch reductions scenarios. *Indian Ocean Tuna Commission document, IOTC-2011-SC14-39*, 32.

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

Nelson, J. & Bradner, H. (2010) The case for establishing ecosystem-scale marine reserves. *Marine pollution bulletin*, 60(5), 635-637.

Pascoe, S. & Tingley, D. (2006) Economic capacity estimation in fisheries: A non-parametric ray approach. *Resource and Energy Economics*, 28(2), 124-138.

Pauly, D., Christensen, V., Dalsgaard, J., Froese, R., & Torres Jr, F. (1998) Fishing down marine food webs. *Science*, 279(5352), 860-863.

Peterson, G. D., Cumming, G. S., & Carpenter, S. R. (2003) Scenario Planning: a Tool for Conservation in an Uncertain World. *Conservation Biology*, 17(2), 358-366.

Pooley, S. (2013) Historians are from Venus, Ecologists are from Mars. *Conservation Biology*, 27(6), 1481-1483.

Porter, G. (2001) *Fisheries Subsidies and Overfishing: Towards a Structured Discussion*. UNEP, Nairobi.

Powers, J. & Abeare, S. (2009) Fishing effort redistribution in response to area closures. *Fisheries Research*, 99(3), 216-225.

Pradhan, N. C. & Leung, P. (2004) Modeling trip choice behavior of the longline fishers in Hawaii. *Fisheries Research*, 68(1), 209-224.

Prellezo, R., Lazkano, I., Santurtún, M., & Iriondo, A. (2009) A qualitative and quantitative analysis of selection of fishing area by Basque trawlers. *Fisheries Research*, 97(1-2), 24-31.

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

Rijnsdorp, A. D., Dol, W., Hoyer, M., & Pastoors, M. A. (2000) Effects of fishing power and competitive interactions among vessels on the effort allocation on the trip level of the Dutch beam trawl fleet. *ICES Journal of Marine Science: Journal du Conseil*, 57(4), 927-937.

Rijnsdorp, A. D., Piet, G. J. & Poos, J. J. (2001) Effort allocation of the Dutch beam trawl fleet in response to a temporarily closed area in the North Sea. *In: ICES Theme Session on Case Studies in the System Analysis of Fisheries Management*. pp. 1-17.

Ringland, G. & Schwartz, P. P. (1998) *Scenario planning: Managing for the future*. John Wiley & Sons.

Roberts, C. M., Bohnsack, J. A., Gell, F., Hawkins, J. P., & Goodridge, R. (2001) Effects of marine reserves on adjacent fisheries. *Science*, 294(5548), 1920-1923.

Robinson, C. & Pascoe, S. (1997) *Fisher behaviour: exploring the validity of the profit maximising assumption*. Centre for the Economics and Management of Aquatic Resources, Portsmouth, UK.

Robinson, J., Guillotreau, P., Jiménez-Toribio, R., Lantz, F., Nadzon, L., Dorizo, J., Gerry, C., & Marsac, F. (2010) Impacts of climate variability on the tuna economy of Seychelles. *Climate Research*, 43(3), 149-162.

Romanov, E. V. (2002) Bycatch in the tuna purse-seine fisheries of the western Indian Ocean. *Fisheries Bulletin*, 100(1), 90-105.

Roy, N. (1998) Fishing behavior and the length of the fishing season. *Marine Resource Economics*, 13, 97-213..

Russ, G. R., Alcala, A. C., Maypa, A. P., Calumpong, H. P., & White, A. T. (2004) Marine reserve benefits local fisheries. *Ecological applications*, 14(2), 597-606.

Salas, S. & Gaertner, D. (2004a) The behavioural dynamics of fishers: management implications. *Fish and Fisheries*, 5(2), 153-167.

Salas, S., Sumaila, U. R., & Pitcher, T. (2004b) Short-term decisions of small-scale fishers selecting alternative target species: a choice model. *Canadian Journal of Fisheries and Aquatic Sciences*, 61(3), 374-383.

Sale, P. F., Cowen, R. K., Danilowicz, B. S., Jones, G. P., Kritzer, J. P., Lindeman, K. C., Planes, S., Polunin, N. V., Russ, G. R., & Sadovy, Y. J. (2005) Critical science gaps impede use of no-take fishery reserves. *Trends in ecology & evolution*, 20(2), 74-80.

Sempo, G., Dagorn, L., Robert, M., & Deneubourg, J. -L. (2013) Impact of increasing deployment of artificial floating objects on the spatial distribution of social fish species. *Journal of Applied Ecology*, 50(5), 1081-1092.

Sheppard, C. (2010) Marine protected areas and pelagic fishing: the case of the Chagos Archipelago. *Marine Pollution Bulletin*, 60(11), 1899-1901.

Sheppard, C. R. C., Ateweberhan, M., Bowen, B. W., Carr, P., Chen, C. A., Clubbe, C., Craig, M. T., Ebinghaus, R., Eble, J., & Fitzsimmons, N. (2012) Reefs and islands of the Chagos Archipelago, Indian Ocean: why it is the world's largest no-take marine protected area. Aquatic Conservation: marine and freshwater ecosystems, 22(2), 232-261,

Smith, C. L. & McKelvey, R. (1986) Specialist and generalist: roles for coping with variability. *North American Journal of Fisheries Management*, 6(1), 88-99.

Smith, M. D. (2005) State dependence and heterogeneity in fishing location choice. *Journal of Environmental Economics and Management*, 50(2), 319-340.

Smith, M. D. & Zhang, J. (2007) Sorting Models in Discrete Choice Fisheries Analysis. American Agricultural Economics Association Annual Meeting, July 29-August 1, 2007, Portland, Oregon, Smith, M. D., Zhang, J., & Coleman, F. C. (2006) Effectiveness of marine reserves for large-scale fisheries management. *Canadian Journal of Fisheries and Aquatic Sciences*, 63(1), 153-164.

Song, L. M., Zhang, Y., Xu, L. X., Jiang, W. X., & Wang, J. Q. (2008) Environmental preferences of longlining for yellowfin tuna (*Thunnus albacares*) in the tropical high seas of the Indian Ocean. *Fisheries Oceanography*, 17(4), 239-253.

Strand, I. E. (2004) Spatial variation in risk preferences among Atlantic and Gulf of Mexico pelagic longline fishermen. *Marine Resource Economics*, 19(1), 145-160.

Sumaila, U. R., Zeller, D., Watson, R., Alder, J., & Pauly, D. (2007) Potential costs and benefits of marine reserves in the high seas. *Marine Ecology Progress Series*, 345, 305-310.

Swain, D. P. & Wade, E. J. (2003) Spatial distribution of catch and effort in a fishery for snow crab (*Chionoecetes opilio*): tests of predictions of the ideal free distribution. *Canadian Journal of Fisheries and Aquatic Sciences*, 60(8), 897-909.

Tidd, A. N., Hutton, T., Kell, L. T., & Blanchard, J. L. (2012) Dynamic prediction of effort reallocation in mixed fisheries. *Fisheries Research*, 125–126(0), 243-253.

Tidd, A. N., Hutton, T., Kell, L. T., & Padda, G. (2011) Exit and entry of fishing vessels: an evaluation of factors affecting investment decisions in the North Sea English beam trawl fleet. *ICES Journal of Marine Science*, 68(5), 961-971.

Torres-Irineo, E., Gaertner, D., de Molina, A. D., & Ariz, J. (2011) Effects of time-area closure on tropical tuna purse-seine fleet dynamics through some fishery indicators. *Aquatic Living Resources*, 24(4), 337-350.

Tversky, A. & Kahneman, D. (1974) Judgment under uncertainty: Heuristics and biases. *Science*, 185(4157), 1124-1131.

Valcic, B. (2009) Spatial policy and the behavior of fishermen. *Marine Policy*, 33(2), 215-222.

Valsecchi, A. (2007) European Markets for Canned Tuna. *In: Proceedings of the Tuna 2006 Bangkok 9th World Tuna Trade conference*. (eds.) Anthonysamy S, Pawiro S, Subasinghe S. INFOFISH, Kuala Lumpur.

Van der Heijden, K. (1996) *Scenarios: the art of strategic conversation*. John Wiley & Sons, Inc.

van Oostenbrugge, J., Densen, W. V., & Machiels, M. A. M. (2001) Risk aversion in allocating fishing effort in a highly uncertain coastal fishery for pelagic fish, Moluccas, Indonesia. *Canadian Journal of Fisheries and Aquatic Sciences*, 58(8), 1683-1691.

van Putten, I. E., Kulmala, S., Thébaud, O., Dowling, N., Hamon, K. G., Hutton, T., & Pascoe, S. (2011) Theories and behavioural drivers underlying fleet dynamics models. *Fish and Fisheries*, 13(2), 216-235.

Venables, W. N., Ellis, N., Punt, A. E., Dichmont, C. M., & Deng, R. A. (2009) A simulation strategy for fleet dynamics in Australia's northern prawn fishery: effort allocation at two scales. *ICES Journal of Marine Science*, 66(4), 631-645.

Vermard, Y., Marchal, P., Mahévas, S., & Thébaud, O. (2008) A dynamic model of the Bay of Biscay pelagic fleet simulating fishing trip choice: the response to the closure of the European anchovy (Engraulis encrasicolus) fishery in 2005. *Canadian journal of fisheries and aquatic sciences*, 65(11), 2444-2453.

Vignaux, M. (1996) Analysis of vessel movements and strategies using commercial catch and effort data from the New Zealand hoki fishery. *Canadian Journal of Fisheries and Aquatic Sciences*, 53(9), 2126-2136.

Voges, E., Gordoa, A., & Field, J. G. (2005) Dynamics of the Namibian hake fleet and management connotations: application of the ideal free distribution. *Scientia Marina*, 69(2), 285-293.

Wack, P. (1985) Scenarios: shooting the rapids. *Harvard business review*, 63(6), 139-150.

WCPFC (2013) *Report of the 9th Regular Session of the Scientific Committee*. Pohnpei, Federated States of Micronesia.

Wilcox, C. & Pomeroy, C. (2011) Do Commercial Fishers Aggregate around Marine Reserves? Evidence from Big Creek Marine Ecological Reserve, Central California. *North American Journal of Fisheries Management*, 23(1), 241-250.

Wilen, J. E. (1979) Fisherman behavior and the design of efficient fisheries regulation programs. *Journal of the Fisheries Board of Canada*, 36(7), 855-858.

Wilen, J. E., Smith, M. D., Lockwood, D., & Botsford, L. W. (2002) Avoiding surprises: incorporating fisherman behavior into management models. *Bulletin of Marine Science*, 70(2), 553-575.

Wise, L., Murta, A. G., Carvalho, J. P., & Mesquita, M. (2012) Qualitative modelling of fishermen's behaviour in a pelagic fishery. *Ecological Modelling*, 228, 112-122.

Wollenberg, E., Edmunds, D., & Buck, L. (2000) Using scenarios to make decisions about the future: anticipatory learning for the adaptive co-management of community forests. *Landscape and Urban Planning*, 47(1), 65-77.

Wood, S. (2006) *Generalized additive models: an introduction with R*. CRC press, Florida, USA.

Worm, B., Hilborn, R., Baum, J. K., Branch, T. A., Collie, J. S., Costello, C., Fogarty, M. J., Fulton, E. A., Hutchings, J. A., & Jennings, S. (2009) Rebuilding global fisheries. *Science*, 325(5940), 578.

Wright, B. G. (2007) Environmental NGOs and the dolphin-tuna case. *Environmental Politics*, 9(4), 82-103.

Zainuddin, M. & Saitoh, K. (2008) Albacore (*Thunnus alalunga*) fishing ground in relation to oceanographic conditions in the western North Pacific Ocean using remotely sensed satellite data. *Fisheries Oceanography*, 17(2), 61-73.