

A COMPARATIVE ANALYSIS OF TWO FLEET DYNAMIC MODELS

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ABSTRACT

In fisheries management it is important to consider how fleet dynamics and individual harvester behaviour may change in response to substantial changes in management regulations. To date, numerous studies have investigated different techniques for modelling fleet behaviour; however, a comparative analysis examining the efficacy of different methods as predictors of future fishing behaviour is lacking. I compare two methods of modelling harvesters' choice of fishing location. The first method uses an ideal free distribution (IFD) based on profitability and the second method is an agent based (AB) approach using a random utility model (RUM). The RUM links harvesting decisions with economic data and a harvester's prior experience. Using behaviourally based simulation modelling, I compare the spatial distributions of effort and catch produced by each model. Various elements believed to influence location choice decisions were incorporated into either the IFD or AB model. My results illustrate that the distribution of effort is dependent on which factors are taken into account when deciding fishing location. These findings will equip fisheries scientists with alternative fleet dynamic models that can be used in the development of control systems to determine what regulatory changes are most effective at meeting the objectives of the fishery.

Keywords: fleet dynamics; fishing behaviour; location choice; ideal free distribution; random utility model; decision making.

DEDICATION

To my parents, for encouraging and supporting me in everything I do.

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GLOSSARY

AB	Agent based
BC	British Columbia
CPUE	Catch per unit effort
DFO	Fisheries and Oceans Canada
EEZ	Exclusive economic zone
IFD	Ideal free distribution
ITQ	Individual transferable quota
IVQ	Individual vessel quota
MPA	Marine protected area
MSE	Management strategy evaluation
RUM	Random utility model
TAC	Total allowable catch

CHAPTER 1

INTRODUCTION TO THE DYNAMICS OF FISHING FLEETS

Problem Statement

Within the last twenty odd years, fisheries management has undergone a paradigm shift wherein fish populations are no longer perceived to be homogeneously distributed resources, rather, they are seen to be patchy and heterogeneously distributed metapopulations (Sanchirico & Wilen 1999; Smith 2000). This gradual shift in thinking has spurred a transition to spatial methods of fisheries management, which include the use of marine protected areas (MPAs), rotating spatial closures, and area specific limitations on effort or total allowable catches (TACs) (Smith 2000; Hicks & Schnier 2006). With the advent of spatially explicit management tools, coupled with the transition to individual vessel based limits, it has become increasingly important to study fleet dynamics (i.e., the behaviour of fishermen) in order to understand how fishermen change their fishing location, timing, target species, and techniques in response to changes in management regulation (Babcock & Pikitch 2000; Wilen *et al.* 2002; Smith 2002).

The spatial behaviour of fishermen in terms of how they choose to allocate fishing effort is an intrinsic determinant to the outcome of fisheries policy (Hilborn & Walters 1992; Holland 2000; Walters & Martell 2004; Little *et al.* 2004), irrespective of whether or not the policy is spatially delineated (Smith & Wilen 2003; Smith & Wilen 2005). Furthermore, knowledge of the mechanisms driving location choice and subsequent

allocation of effort is essential to understanding how a fishery develops over time and the relationships between fishery dependent data (e.g., catch per unit effort (CPUE)) and stock abundance (Wilén 1979; Hilborn & Walters 1987; Dorn 2001).

Despite the importance of fleet dynamics, the majority of research continues to focus on fish population dynamics rather than the dynamics of the fishery (Little *et al.* 2004; Branch *et al.* 2006a). Descriptive information on fisherman behaviour through space and time does exist, particularly in relation to stock collapse (Walters & Martell 2004), and researchers have attempted to incorporate fleet dynamics into various management models. However, much of the work is either ad hoc in nature (Wilén *et al.* 2002) or treats fishing effort as an aggregate of uniform units (i.e., vessel days) potentially leaving out important properties (Dreyfus-Leon 1999; Dorn 2001). Aside from a handful of studies (e.g., Hilborn & Walters 1987; Gillis *et al.* 1993; Gillis & Peterman 1998; Walters & Bonfil 1999; Gillis 2003; Voges *et al.* 2005; Walters 2007), minimal attention has been paid to the development of predictive models of fleet dynamics with respect to location choice and fisherman response to fisheries management policies. Furthermore, only a few researchers (e.g., Bockstael & Opaluch 1983; Dupont 1993; Dreyfus-Leon 1999; Holland & Sutinen 1999; Babcock & Pikitch 2000; Dorn 2001; Hutton *et al.* 2004) have taken an agent based (AB) approach where individual actors are identified within a fishery and their responses and actions are explicitly considered rather than assuming some global principle such as optimal efficiency or equilibrium state (Allen & McGlade 1986).

Four main modelling approaches have been developed to predict short-term changes in the allocation of fishing effort among fishing locations (Walters & Martell

2004): 1) gravity models wherein total effort is distributed across n sites according to some index of attractiveness (e.g., Walters & Bonfil 1999; Walters *et al.* 1999); 2) ideal free distribution (IFD) models wherein fishermen allocate their effort in such a fashion that no location stands out as being more profitable than another (e.g., Gillis *et al.* 1993; Voges *et al.* 2005); 3) sequential effort-allocation models (a numerical approach to IFD models) (e.g., Hilborn & Walters 1987); and 4) AB decision models in which the variation amongst fishermen can be explicitly accounted for (e.g., Holland & Sutinen 1999; Babcock & Pikitch 2000). The four approaches differ with respect to complexity, assumptions, and data requirements; however, to the best of my knowledge there does not appear to be a comparative evaluation of the various approaches in the literature.

Therefore, the study of fleet dynamics, in particular predictive models that deal with location choice, would greatly benefit from a comparative evaluation of a complex agent based decision model and a less complex model such as an IFD or gravity based model to determine if there is a practical advantage to using one method over the other.

Project Goals

The primary goal of my research was to evaluate two alternative approaches to modelling fisherman location choice and effort allocation using simulation models of a fishery and targeted fish population. The two methods I evaluated are an IFD approach based on profit maximisation (hereafter referred to as “IFD model”) and an AB decision model based on a random utility model (RUM) and maximisation of perceived utility (hereafter referred to as “AB model”). I addressed three major objectives:

- 1) Develop an agent based fleet dynamic model using a RUM framework for decision making;

- 2) Determine whether the spatial distribution of fishing effort produced by the IFD model and the AB model differ under alternative scenarios; and
- 3) Evaluate the advantages and disadvantages of each method.

To address my first objective I performed a literature review of AB fleet dynamic models and fishery ethnographic surveys to develop a model that was comparable to what exists in the literature, as well as one that adequately reflected fisherman decision making processes. To address the second objective, I simulated the two fleet dynamic models under various scenarios of stock distribution and rates of fish movement. This allowed me to assess whether the two methods yielded similar or different results under alternative fish population scenarios and what fish population characteristics had the greatest influence, if any, on the difference between spatial distributions of effort. Finally, I explored some of the preliminary management implications of my results.

Results of my study provide a foundation for future work examining the circumstances under which AB fleet dynamic models would be advantageous relative to aggregate fleet dynamic models (e.g., IFD model). The ultimate goal of this line of research is to equip fisheries managers and researchers with better tools and methods for the development of fisheries control systems that are most effective for fisheries management.

CHAPTER 2

LITERATURE REVIEW

Fleet dynamics

Fishermen make decisions ranging from long-term entry/exit decisions to daily, or even hourly, decisions of when and where to fish. Fleet dynamics are the aggregate result of these individual vessel decisions and they ultimately govern the spatial and temporal pattern of fishing in an exploited fishery (Wilén *et al.* 2002). The study of fleet dynamics explores fisherman behaviour and fishing effort as a dynamic process analogous to that of a prey-predator system (Hilborn & Walters 1992). The primary motivation for studying fleet dynamics is to understand how fishermen respond to biological and/or economic changes, as well as how they react to regulatory action that alters the landscape in which they operate (Hilborn & Walters 1992; Holland & Sutinen 1999). This research subsequently helps improve the ability of decision makers to design policies for more effective management.

In order to provide a framework for asking questions and analysing data about how fisherman behave, Hilborn (1985) classified the elements of fleet dynamics into four discreet categories (Table 2.1):

- 1) determinants of fleet size as a consequence of investment and disinvestment from the fishery;
- 2) determinants of when, where, and what to fish (i.e., effort allocation);
- 3) catching power or harvesting efficiency as a function of the fishing process, competition, interference, facilitation, and learning; and

4) discarding decisions and by-catch.

I provide a brief description of each of the four elements as well as examples from the literature that illustrate the importance of taking each into account. Within the context of my research I looked exclusively at item (2), the allocation of fishing effort, because the development and implementation of successful spatial management is contingent on the integration of fisherman behaviour into the evaluation of alternative management actions.

Investment and fleet size

According to Hilborn and Walters (1992) a key step to understanding how a particular fishery works is to identify the number of vessels operating and to be knowledgeable about the processes by which vessels enter and leave (i.e., how the fishery develops over time). The dynamics of fleet investment and size is often a difficult task to determine for several reasons. First, some vessels are active in multiple fisheries at any given time, where their participation is a function of the fishery's profitability, and entry and exit decisions are not well understood (Branch *et al.* 2006a). Second, the growth of a fishery can be a function of investment or disinvestment in gear and licenses (Hilborn & Walters 1992). Third, dedicated access privileges, which include territorial rights, cooperatives, community development quotas, and individual transferable quotas (ITQs) or individual vessel quotas (IVQs), further obscure the picture of investment and fleet size by making it difficult to trace who is actively participating in a fishery (Squires *et al.* 1994; Hannesson 2000). Finally, the issue of domestic versus foreign fleet composition, wherein foreign investment and participation in a fishery is more difficult to quantify (Charles 1986).

Effort allocation

A critical element of fishing behaviour is a fisherman's decision of when and where to allocate their fishing effort (Branch *et al.* 2005). The decision over location choice and effort allocation can be influenced by any number of factors including, but not limited to: catch history, seasonal variation in resource abundance, fishing preferences, distance from port, tradition, skipper skill, degree of information sharing between vessels, and risk factors (e.g., weather conditions) (Hilborn & Walters 1992; Holland & Sutinen 2000). In other words, location choice is a variable driven by human behaviour and the perceived spatial distribution of fish (Dreyfus-Leon 1999).

Research on location choice and effort allocation does not conclusively highlight a single dominant factor that influences effort allocation decision under all circumstances. Rather, the majority of studies show that several variables collectively influence decisions on location choice where variable significance varies depending on context. For example, Oostenbrugge *et al.* (2001) found that fishermen in the Ambonese purse-seine fishery based their daily decisions of effort allocation on minimising operational costs and risks, rather than maximising CPUE, whereas, Pradhan and Leung (2004) identified stock level of major target species abundance, vessel age and size, risk aversion, and utility maximisation as variables that most significantly influenced fishermen's decisions. Alternatively, Millisher and Gascuel (2006) and Little *et al.* (2004) emphasise information sharing and the resulting gains in search efficiency as the key variable influencing location choice.

Determinants of catching power

The analysis of catching power of individual vessels or aggregate fleets is the most well documented and researched of the four fleet dynamic components (Hilborn 1985). A vessel's ability to catch fish is a function of three factors (Hilborn & Walters 1992): 1) how often it fishes; 2) the abundance of fish at the fishing location; and 3) the skill of the vessel's crew and gear employed relative to other vessels fishing the same location. Catching power is typically thought of in terms of the third factor; if the first two factors are held constant across all vessels what determines how many fish a vessel will catch?

A large body of literature exists relating vessel characteristics such as gear used, vessel length, vessel tonnage, and engine power to catch rates (e.g., Goni *et al.* 1999; O'Neill *et al.* 2003; Mahevas *et al.* 2004). Conversely, a growing body of research highlights the role of skipper/crew skill as the prime factor distinguishing vessel catch rates from one another (Hilborn & Ledbetter 1985; Squires & Kirkley 1999; Alvarez & Schmidt 2006; Ruttan & Tyedmers 2007).

Highlighting the value of catching power analysis is a study by Rahikainen and Kuikka (2002), in which the authors documented the increase in vessel catchability that occurred over time as a consequence of improvements in fishing technology (i.e., trawl size). Rahikainen and Kuikka (2002) conclude that the oversight of increasing fishing power led to considerably biased population models and historic mismanagement of the Finnish herring stocks.

Discarding

The term discarding is the act of throwing away a portion or all of the total fish that are caught while still at sea (Clucas 1997). Discarding can be problematic from a biological perspective for some species because the majority of fish discarded at sea die as a result of either barotrauma or other injuries incurred through the act of fishing (e.g., *Sebastes* species) (Rudershausen & Buckel 2007). Furthermore, unreported mortality of fish can have consequences for stock assessment abundance estimates. Other concerns that arise from discarding are ecosystem disruption (e.g., seabird mortality; Gonzalez-Zevallos & Yorio 2006) and the social consideration for the waste generated by the practice (Harrington *et al.* 2005).

Factors influencing the decision to discard include, but are not limited to, the following: fish caught are not the target species; fish caught are below the minimum size limit; fish are damaged; fish caught may spoil rapidly causing problems with the rest of the catch; lack of space on board the vessel; high grading; quotas have been reached; and management regulation (Hilborn & Walters 1992; Clucas 1997; Stratoudakis *et al.* 1998). In an attempt to categorise discards by the motivating behaviour responsible for the act of discarding, Crean and Symes (1994) identified three main classes: 1) incidental catch caught while targeting other species and discarded at sea; 2) fish caught that are subsequently discarded because quota for the species is not available and fishermen must comply with legal requirements relating to permitted quota entitlements; and 3) high-grading, the practice of discarding less valuable grades of fish in order to fill quotas with more valuable grades.

Implications of fleet dynamics in fisheries management

In the past, conventional fisheries management methods have been criticised for failing to recognise that fisheries are highly dynamic and stochastic populations, and that uncertainties around fisherman behaviour exist (Wilén *et al.* 2002). Fisheries management would benefit from the explicit consideration of fleet dynamics in the use of: 1) commercially obtained data, in particular CPUE data; 2) input controls; 3) output controls; and 4) spatial management.

Fishery dependent data: CPUE indices

Commercial CPUE data is widely used as an index of relative abundance in fisheries management (Harley *et al.* 2001), where catch is assumed to be linearly related to abundance. However, it has long been recognised that CPUE, coupled with the assumption of proportionality, may not accurately reflect changes in abundance (Hilborn & Walters 1992). Retrospective data analyses of the Peruvian anchoveta (Hilborn & Ledbetter 1985; Bertrand *et al.* 2004), Norwegian herring (Hilborn 1985), and Atlantic cod (Hutchings & Ferguson 2000; Bertrand *et al.* 2004) fisheries reveal that all three collapses were partly the result of misleading CPUE data that did not decline proportionally with abundance.

CPUE is the most likely of all data inputs to be influenced by fleet dynamics (Branch *et al.* 2006a). This is a consequence of the relationship between abundance and catch being the result of interactions between several processes, including: schooling behaviour of fish (Hilborn & Walters 1992), the proportion of the stock found in areas above the minimum economic density (Hilborn & Walters 1992), variable catchability (Winters & Wheeler 1985), vessel movement in response to catch rates (Gillis *et al.*

1993), increases in fishing power (Branch *et al.* 2006a), information sharing (Little *et al.* 2004), and interference competition among vessels (Gillis & Peterman 1998). For example, simulations of information exchange between vessels fishing in spatially heterogeneous environment show that information sharing between fishermen contributes to the increasingly non-linear relationship between CPUE and abundance (Gaertner & Dreyfus-Leon 2004).

Input controls

Input controls aim to directly regulate the exploitation rate of a fishery by using management strategies that aim to limit vessel catching power to a level that is considered sustainable over the long-term (Walters & Martell 2004). A variety of tactics including restrictions on season length, gear type, vessel entry, vessel size, and engine horsepower have been employed in the past with varying degrees of success.

Successful use of input controls is hindered by oversight of or changes in fleet dynamics that then change the relationship between input controls and catch. Modifications in this relationship can culminate in unpredictable annual catches that can eventually lead to overharvesting and variation in fisheries employment levels (Branch *et al.* 2006a). Furthermore, because individual vessels have an incentive to compete with other vessels to maximise catch, restrictions placed on some input controls can lead to over-investment in other fishing inputs thereby undermining the efficacy of the initial input control that was introduced with the objective to reduce fishing effort (Elliston & Cao 2006; Branch *et al.* 2006a).

Output controls

Output controls aim to restrict the number of fish caught by setting an annual quota or allowable catch based on absolute stock abundance and expected recruitment (Walters & Martell 2004). Using both fishery dependent and independent data (when available), the TAC is determined from stock assessment models that provide estimates of total abundance. Output controls are generally easier to implement than input controls and place the burden of conservation and sustainable fishing plans on stock assessments (Walters & Martell 2004).

The use of output controls is however more complicated than simply knowing how many fish there are and implementing an appropriate TAC. This is illustrated by the derby style fishing that arises from the implementation of TACs without additional management measures that regulate fishing effort. For example, initial limits on TAC for the British Columbia (BC) halibut fishery lead to overcapitalisation in vessel technology and a race for fish. This derby style fishing lead to restrictions in season length in order to maintain a certain level of catch (season length decreased from 60 days in 1982 to 6 days in 1990) (Deweese 1998). Likewise, fisherman behaviour is often unaccounted for in the design and development of quota programs thereby leading to unforeseen problems in the implementation and maintenance of IVQ programs. Evidence suggests that the majority of quota systems have been found to induce discarding behaviour among fishermen (Turner 1997), a circumstance that can be quite problematic for some stocks such as rockfish which have high discard mortality rates (McGovern *et al.* 2005).

In order to address the discard problem fishermen need to be provided with alternatives to manage their bycatch in addition to implementation of reliable

enforcement measures (Diamond 2004). Both requirements have been met in the BC groundfish fishery through the introduction of at sea observers and more recently the introduction of full catch monitoring and accountability. The latter has led to a 10 percent decline in the marketable discard fractions of the trawl fishery (Branch *et al.* 2006b).

Spatial management

The delineation of catch, effort, vessel and gear restrictions, and temporary and permanent closures by area has become an increasingly common practice over the past few decades (Branch *et al.* 2006a). However, very few analyses of spatial controls have included realistic representations of fisherman behaviour despite the explicit spatial nature of fishing effort allocation and the fact that area-based management will impact the spatial distribution of fishing effort (Wilén *et al.* 2002). In addition, spatial management is likely to affect fishermen differently depending on their fishing strategy (area generalist versus area specialist) making it important to take into account the behavioural variation within a fleet when testing and evaluating different regulations (Hilborn 1985).

Marine protected areas (MPA) are gaining popularity as a tool for marine conservation and fisheries management. Advocates of MPAs cite a number of potential benefits including: protection of habitat (Lubchenco *et al.* 2003; Allison *et al.* 2003); conservation of biodiversity (Hastings & Botsford 2003; Botsford *et al.* 2003); protection or enhancement of ecosystem service (Kritzer 2004); assistance in the recovery of depleted fish stocks (Wallace 1999; Lubchenco *et al.* 2003); insurance against environmental and/or management uncertainty (Allison *et al.* 2003); and export of individuals (larvae and adults) to fished areas (Man *et al.* 1995; Zeller *et al.* 2003;

Hastings & Botsford 2003). However, the potential of MPAs as tools for fisheries management has long been a subject of debate and controversy (Willis *et al.* 2003). The efficacy of a MPA in achieving any one of these benefits is a function of the (Lubchenco *et al.* 2003): 1) connectivity to other MPAs; 2) size and shape of the MPA; 3) number of MPAs in an area; and 4) location/placement of the MPAs.

The location and boundaries of most MPAs have largely been determined by political and social processes (e.g., public acceptance) rather than scientific study (Roberts 2000). The questions of how the creation of marine reserves will affect the biology, ecology, and fishing activity both in the immediate and surrounding areas is often overlooked (Lynch 2006). Furthermore, with respect to the point of fishing activity, the majority of MPA models investigating the effects on fishing are based on the assumptions that: fishing effort is a dynamic pool, homogeneously distributed over an area (Lynch 2006); effort displaced by area closures is proportional to the size of the area closure (Lynch 2006); and fishing effort is constant before and after reserve creation (Man *et al.* 1995). If MPA models are to become a reliable method for predicting reserve success or failure, as well as address the concerns of displaced fishermen, analysis and case study tests of commonly accepted assumptions need to occur (Lynch 2006) in addition to the incorporation of more realistic fisherman behaviour that is motivated by choice over space and time (Sanchirico & Wilen 2001).

Modelling approaches for location choice

To reiterate, there are four main modelling approaches to predict short-term changes in the allocation of fishing effort of which I focus on two, an IFD model and an

AB decision model. I describe these two approaches below, and evaluate them in a simulation framework.

Ideal free distribution (IFD) approach

The IFD (Fretwell & Lucas 1970) is a theory from behavioural ecology that was developed to predict the distribution of foragers relative to the distribution of the resource (e.g., Talbot & Kramer 1986; Abrahams & Dill 1989). IFD theory is the predominant method used to explain the relationship between resource and vessel distribution in fleet dynamic models; a circumstance that may be the result of IFD theory offering the simplest starting assumptions for studies of effort allocation (Hilborn 1985).

The IFD has several assumptions, the first of which is that overall location quality is not altered by fishing, meaning resources are renewed at a similar rate to that at which they are consumed in order to maintain constant relative quality between locations (Gillis 2003). A second assumption of the IFD is that all vessels have perfect knowledge of the fishing quality at each location and are free to move between locations without restrictions or cost. Perfect knowledge refers to knowledge of the distribution of both the resource and other vessels and competitors (Gillis *et al.* 1993). Third, all vessels are assumed to be equal in their ability to catch fish and all vessels have equal access to the fish; however, competition amongst vessels must exist (interference competition) in the sense that increases in fishing vessel density at a given location will eventually result in a decline in fishing success making the site less attractive (Gillis 2003) (Figure 2.1).

When the assumptions underlying IFD theory are adequately met, the IFD predicts that the proportion of vessels at a given location will equal the proportion of fish

located there and all vessels across all areas will receive equal benefits from fishing (i.e., the profit rate of individuals will be the same across all locations) (Gillis *et al.* 1993) (Figure 2.2). The IFD prediction is based on the notion that differences in profitability will cause individual fishermen to distribute themselves across all possible fishing locations such that, at equilibrium no individual fishermen would experience an increase in profitability by moving to another fishing location (Parkinson *et al.* 2004).

Within the context of commercial fisheries, several assumptions of the IFD are unrealistic. In particular the assumptions of unrestricted movement at no cost, perfect knowledge of resource distribution and competitors, and equal competitive ability between vessels are infrequently, if ever, met (Poos & Rijnsdorp 2007). However, several studies with human foragers have yielded results that coincide with IFD predictions in spite of assumption violations (e.g., Hilborn & Ledbetter 1985; Gillis *et al.* 1993; Campbell *et al.* 1993; Swain & Wade 2003; Branch *et al.* 2005; Voges *et al.* 2005), suggesting that IFD theory may be a useful platform from which to test hypotheses on fisherman behaviour in homogeneous fisheries, despite its oversimplified assumptions.

Agent based (AB) model approach

AB models attempt to represent the properties of ecological systems by capturing the individual properties of the agents that constitute them (Werner *et al.* 2001). An AB approach implies that individual vessel characteristics such as home ports, risk aversion, and experience are explicitly considered; something that is not easily achieved when employing an aggregate fleet model approach (Little *et al.* 2004). Accounting for individual variation is particularly important when rare individuals, or rare circumstances affecting a few individuals, strongly contribute to determining processes or variance at

the population level (Werner *et al.* 2001). AB models therefore attempt to encapsulate the decisions and actions of individual vessels (Dreyfus-Leon 1999) as a function of both the system in which they exist and their individual vessel characteristics.

According to Grimm (1999) there are two main reasons for using AB models: 1) for pragmatic reasons, i.e., to study problems that cannot be addressed using state variables; or 2) for paradigmatic reasons when the study is driven by the belief that much of what has been learned using classical approaches to modelling theoretical issues would have to be revised if individual variation were accounted for. Within the context of fleet dynamic research on effort allocation, the latter generally appears to be the motivation for using an AB approach because it emphasises understanding the mechanisms of a particular system as oppose to recreating the aggregate properties of that system.

Figures

Fig 2.1 Under IFD theory vessels are free to move among sites and will distribute themselves such that expected fitness (profitability) of individuals is constant across the habitat spectrum and the average fitness of all sites is equal. For example, as the number of vessels in Site 1 increases, its average suitability decreases with the result that Site 2 will become colonised whenever the average suitability of Site 2 is equal to that of site 1. The rate at which site suitability decreases is dependent on site characteristics (e.g., total area, habitat type, carrying capacity, etc.); consequently, each site can host a different number of vessels at any given average suitability (e.g., solid grey line).

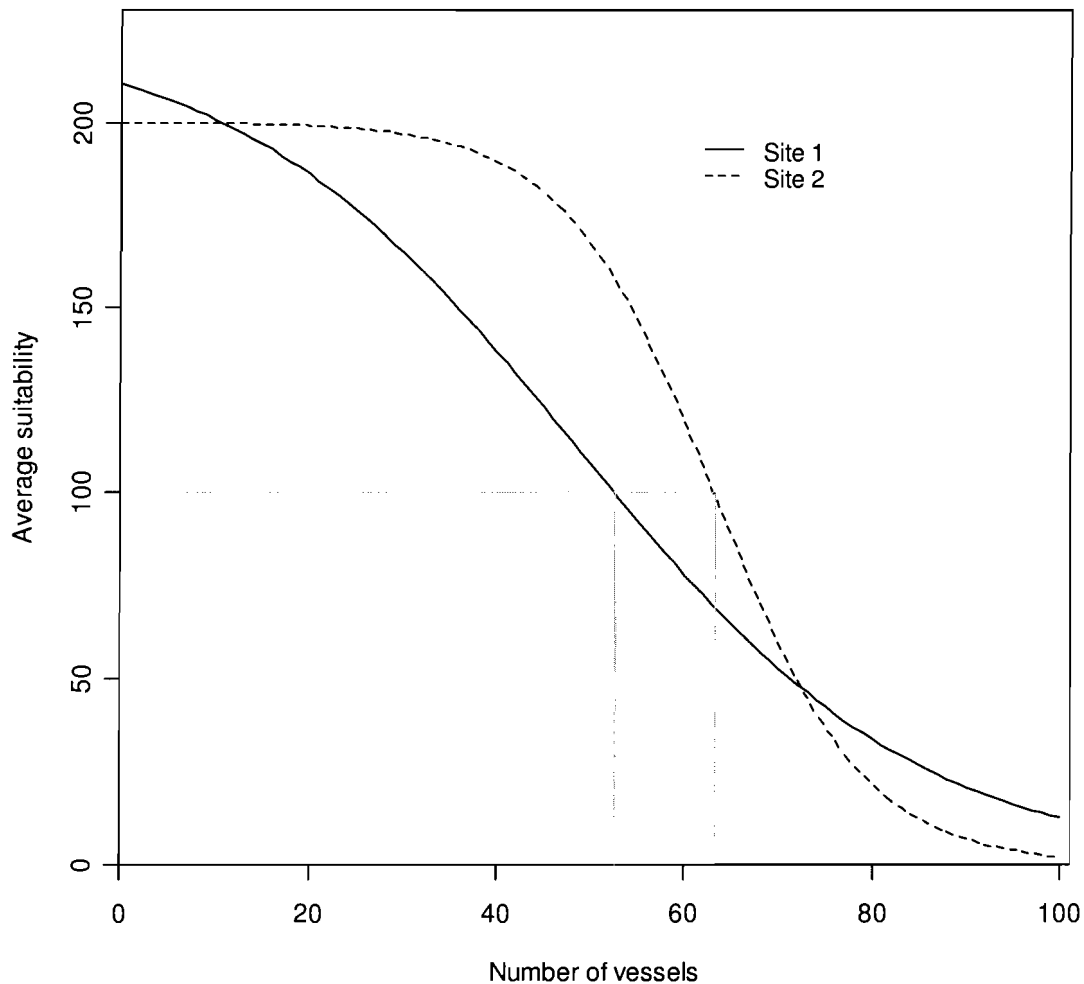
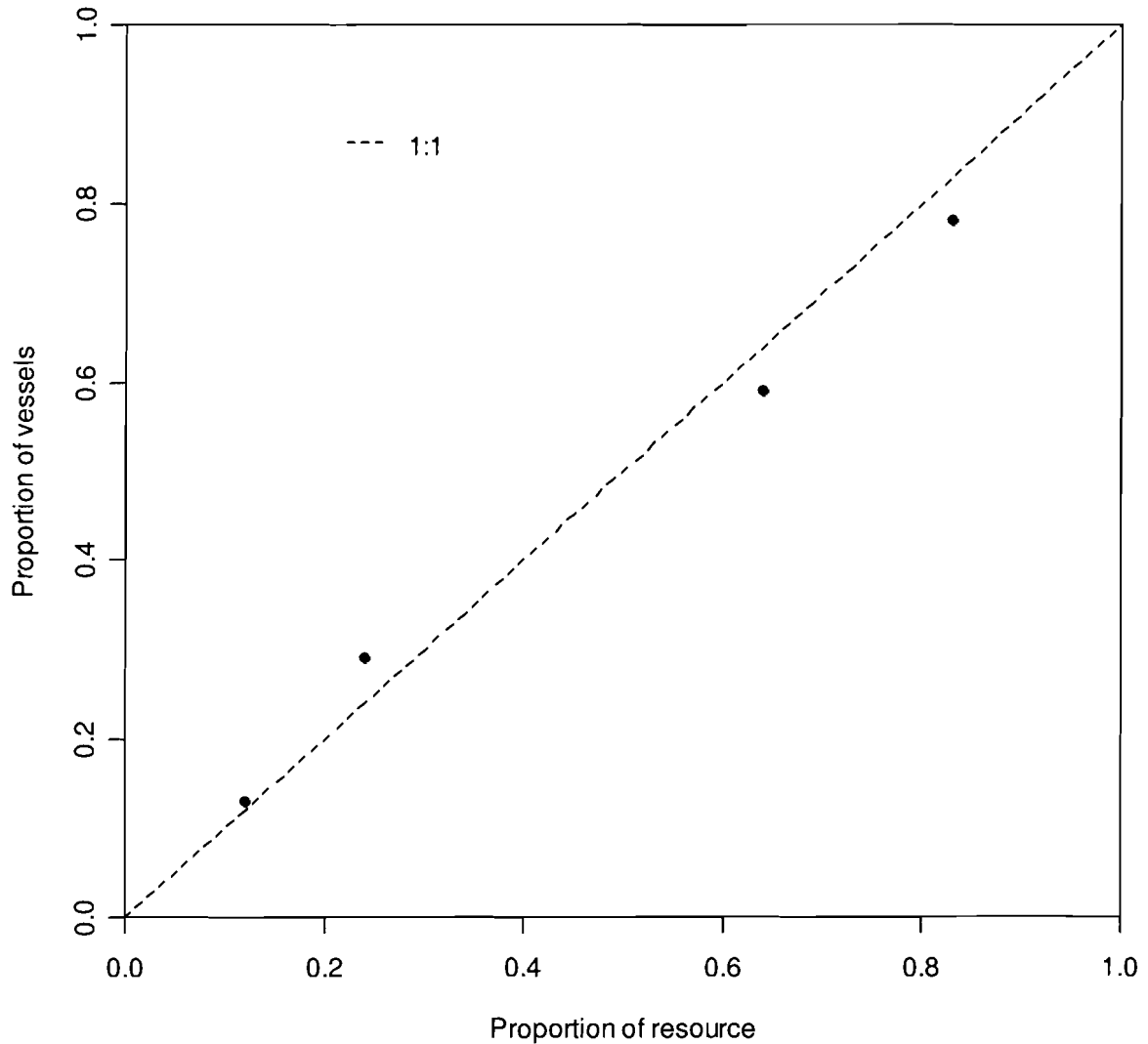


Fig 2.2 A graphical representation of IFD data. The dashed line follows a one to one relationship between the resource and foragers as predicted by the IFD (i.e., the proportion of vessels at a site equals the proportion of the resource located there). The points represent hypothetical sites, where a deviation between the line and point may be the result of interference competition and assumption violations mentioned in the text (e.g. imperfect information). Modified from Gillis (2003).



Tables

Table 2.1 Basic components of fleet dynamics. Modified from Hilborn (1985).

-
- I. Investment and fleet size**
 - a) Loss of vessels due to damage or transfer to other fisheries
 - b) Depreciating value of existing fleets
 - c) Entry of new vessels by construction or transfer from other fisheries
 - d) Maintenance and upgrading of existing vessels

 - II. Effort allocation**
 - a) When to fish
 - b) Where to fish
 - c) What to fish using which gear

 - III. Determinants of catching power**
 - a) Relationship between vessel attributes, crew, gear, and relative catching power
 - b) Time budget of catching process
 - c) Relationship between abundance, catch, and total effort

 - IV. Discarding decisions and by-catch**
 - a) Relationship between what is caught and what is kept
-

CHAPTER 3

AN EVALUATION OF TWO FLEET DYNAMIC MODELS FOR LOCATION CHOICE: THE IDEAL FREE DISTRIBUTION VERSUS AN AGENT BASED APPROACH

Introduction

Historically, fisheries science has focused on deriving indices of abundance from fishery catch and effort data; however, experience suggests that fishery dependent indices of abundance alone are insufficient for fisheries management purposes (Bannerot & Austin 1983; Walters & Maguire 1996). Research in the area of fleet dynamics aims to augment catch and effort data by helping to clarify some of the driving factors behind the data and their appropriate uses in traditional stock assessment methods. Fleet dynamics research also aims to provide deeper insight into how fishermen respond to changes in biological, economic, and regulatory conditions in order to facilitate and inform the design of management plans that best meet conservation and socio-economic objectives. In this study, I use simulation modelling to compare ideal free distribution (IFD) and agent based (AB) approaches for predicting the spatial distribution of fishing effort. The ability to model how fishermen allocate fishing effort is valuable for management because it allows testing of the potential regulatory effectiveness of old and new management strategies.

The relevance of fleet dynamics and the need for its consideration in fisheries management is becoming increasingly apparent, particularly as management strategies move towards the use of area closures, individual transferable quotas, and trip limits.

Hilborn (1985), concludes that it is the misunderstanding of fishing behaviour, as opposed to a lack of knowledge of the fish stock, that best explains the collapse of two major fisheries, the Peruvian anchoveta and the Norwegian herring fisheries. Fishermen behaviour is defined as the decisions made and actions taken by fishermen in the areas of fishery investment, location choice, gear, and discarding. Retrospective analyses of the Peruvian anchoveta (Bertrand *et al.* 2004), Norwegian herring (Rahikainen & Kuikka 2002), and Atlantic cod (Hutchings & Ferguson 2000) fisheries further illustrate the importance of accounting for fisherman behaviour in the design and implementation of management policies and regulations. Rahikainen and Kuikka (2002), Bertrand *et al.* (2004), and Hutchings and Ferguson (2000) all show that failure to account for changes in trawl gear and fishing strategies lead to misinterpretation of CPUE data. As illustrated by these three case studies, failure to account for fishermen behaviour can lead to missed economic and conservation objectives, and in the worse case scenario stock collapse.

Over the past decade, there has been a growing interest within the fisheries science literature to use models, particularly bioeconomic models, to analyse the dynamics of fishing effort as a consequence of fisherman behaviour. There are many different aspects of fisherman behaviour and a variety of methods have been used to specifically model fishermen's choice of fishing ground, target species, and/or response to regulation (e.g., Wilen 1979; Bockstael & Opaluch 1983; Hilborn & Ledbetter 1985; Wilson 1990; Gillis *et al.* 1993; Dreyfus-Leon 1999; Holland & Sutinen 1999; Walters & Bonfil 1999; Sanchirico & Wilen 2001; Smith 2002; Hutton *et al.* 2004).

The structure of fleet dynamic models in the literature often depends on the nature of the fishery and the questions being asked. A large proportion of models examine the

problem from an aggregated fleet perspective and often use the IFD from behavioural ecology (Fretwell & Lucas 1970) to explain the relationship between fish resource and vessel distribution. AB approaches on the other hand take into account the characteristics of individuals to explain how vessels distribute themselves and make decisions on how to allocate their effort. In this research, I focus on the element of location choice and the short-term decisions associated with choosing when and where to fish.

Economic theory predicts that the spatial distribution of fishing effort will be determined by expected economic returns to individual fisherman (Gordon 1991). Differences in profitability among locations cause individual fishermen to distribute themselves across all possible fishing locations such that no individual fishermen would experience an increase in profitability by moving to another fishing location (Parkinson *et al.* 2004), and thus an IFD equilibrium is reached. As described in Chapter 1, the IFD approach to fleet dynamics is based on several unrealistic assumptions, all of which can undermine its ability to accurately predict fishing effort that is driven by factors extending beyond the IFD principle of profit-dependent fishing location selection. In comparison, the greater complexity and individual-based nature of AB models may make them better able to represent the systems they are intended to mimic, particularly in multispecies fisheries where costs likely differ among locations, fisheries, and individuals (Holland & Sutinen 1999).

Aggregate fleet dynamic models based in part or entirely on IFD principles continue to be the predominant method used for modelling fisherman behaviour in both homogeneous and heterogeneous fisheries (e.g., Gillis *et al.* 1993; Walters & Bonfil 1999; Walters *et al.* 1999). A homogenous fishery is defined as a single species fishery

where vessels and fishing areas are identical. A heterogeneous fishery is defined as either a single or multi- species fishery where vessels and fishing areas differ from each other. Previous studies have examined alternative methods to modelling location choice for a particular fishery; however, there have been relatively few comparative studies that examine the outcomes from alternative methods of modelling spatial patterns of exploitation for the same fishery. I am aware of only one study; Smith (2002) analyses the spatial distribution of effort in the California sea urchin fishery using two different econometric approaches. My research focuses on modelling behaviour at both individual (AB) and aggregate (IFD) levels of fishermen behaviour. My research addresses the identified gap by comparing these two different methods of modelling fisherman location choice to determine whether the same outcome is attained (i.e., the spatial distribution of fishing effort) and what underlying factors make them different.

Methods

Model framework

The hypothetical fishery that I examine is composed of a fleet of mobile vessels targeting a single fish species. The fish population is distributed over a spatial grid of total area A , and the fishing fleet operates over the entire area. Area A is divided into J cells, where each spatial cell is represented as an element in a matrix. Cells are assigned a unique set of characteristics that include, among other things, local fish abundance, fish habitat suitability, and relative cost of fishing. The spatial grid is a set of x and y locations measured between cell midpoints, meaning that distances in the model are scale invariant. The model therefore has the capability to be spatially explicit making it possible to represent actual physical locations for future applications. For the purposes of my study, I

used a 10 cell by 10 cell spatial grid (100 cells in total) to represent area A , where each cell is a 20 nautical mile (nmi) by 20 nmi square, or 400 nmi^2 . The rationale for choosing these cell dimensions is that the sum of all cells lengthwise or widthwise equals 200 nmi, where a distance of 0 nmi in either direction would be adjacent to the shoreline and 200 nmi would be the EEZ boundary. In this paper, the term “fishing location” is used interchangeably with “grid cell”.

With respect to the research questions addressed by my study, I deemed it sufficient to simulate a single fish stock distributed across the spatial grid, although a multispecies fishery would be a more realistic representation of a groundfish fishery. The rationale behind this decision is to compare and contrast the two fleet dynamic submodels under the simplest possible conditions. Simulations were run using R statistical computing software, version 2.2 (Ihaka & Gentleman 1996) .

The primary goal of my study is to examine whether the spatial distribution of fishing effort resulting from an IFD fleet model and an AB fleet model are similar. I combine both the AB and IFD fleet dynamic models with separate, but identical, biological fish models to determine the spatial distribution of fishing effort through time. Trajectories of local fish abundance, fishing effort, and in the case of the AB model, individual vessel movement are simulated over a daily time step (t) that is subsequently simulated over a yearly time step (Y). Figure 3.1 illustrates the sequence of operations performed and the flow of information through the model (i.e., the fleet dynamic component integrated with the biological fishery component). Detailed methods are broken down into four sections:

- i) fish population model;

- ii) IFD fleet dynamic model;
- iii) AB fleet dynamic model;
- iv) simulation, experimental, and statistical design.

In the following sections I index individual vessels by i , fishing location by j , and time in days by t . In addition, elements of matrices are denoted by the subscript j , where j refers to a cell (i.e., fishing location) within a matrix.

Stock dynamics model

Stock abundance

The fish population is initially distributed across the spatial grid in proportion to the relative suitability of each cell. The intrinsic growth rate of each cell is dependent on the carrying capacity and fish density of that cell, where maximum fish density for a given cell is determined by the cell's carrying capacity. Habitat suitability is heterogeneous across cells in order to capture the patchiness of real systems and the heterogeneity of productivity across space (Wilen *et al.* 2002). Consequently, the fish population is spatially variable with high suitability cells having higher fish abundance than low suitability cells. Local fish abundance is calculated using a biomass dynamic model of the form:

$$(1) \quad N_{t,j} = (N_{t-1,j} - C_{t-1,j}) \cdot S,$$

where $N_{t,j}$ is the number of fish in the current time step t in the j th cell, $N_{t-1,j}$ is the number of fish in the j th cell the previous day ($t-1$), $C_{t-1,j}$ is the catch taken in the j th cell the previous day, and S is the daily survival rate,

$$(2) \quad S = e^{\frac{-M}{365}} .$$

Fish move among cells in response to fitness gradients, i.e., cells where the local intrinsic growth rate and carrying capacity are both high. Habitat selection among animal populations is often density dependent, meaning that individuals will move to less suitable habitat only when the average fitness of individuals at more suitable sites is equal to that of less suitable sites (MacCall 1990). Over time, the spatial distribution of fish that results from density dependent habitat selection approximates an IFD.

Fish movement

Daily fish movement occurs via two mechanisms: i) diffusive or non-directed movement defined by an array of diffusion probabilities based on a bivariate normal distribution, and ii) directed movement defined by movement rules and cell suitability. The diffusive movement component determines the initial probability that fish will leave a given cell and directed movement updates the daily movement of the fish. The suitability for each cell ($s_{t,j}$) is calculated daily and is a function of the local fish population productivity ($\rho_{t,j}$) and carrying capacity (K_j),

$$(3) \quad s_{t,j} = \rho_{t,j} \left(1 - \frac{N_{t,j}}{K_j} \right).$$

Cell suitability determines whether fish stay in certain cells or leave to explore neighbouring cells. The probability of fish staying in a given cell is calculated daily and is a function of cell suitability and diffusion probability (see Barton 2006, page 25). The

combination of diffusive and directed movement allow fish to actively or passively explore the grid and settle into new cells or return to their previous cell. Barton (2006) provides a more detailed description of both movement mechanisms. Once movement is complete, the population is updated for natural mortality $M(\text{year}^{-1})$.

The stock dynamic model has been developed to allow for fish migration to occur. During a simulation, alternative fish migration patterns are achieved by gradually increasing or decreasing cell carrying capacity during a simulation (i.e., K is modified daily in equation 3), and consequently changing cell suitability in a way that will entice fish to move in certain directions.

Recruitment

Recruitment is characterised by logistic growth. The annual number of recruits produced follows a logistic production function of the form:

$$(4) \quad R_Y = N_{Y-1} \left(1 - e^{-M} \right) \left(1 + \overline{\rho_{Y-1}} \left(1 - \frac{N_{Y-1}}{K_o} \right) \right),$$

where R_Y is the total number of recruits added to the total fish population at year end, N_{Y-1} is the total number of fish the previous year, e^{-M} is the survival rate, $\overline{\rho_{Y-1}}$ is the weighted mean productivity of the fish population the previous year, and K_o is the initial number of fish at $t = 0$ summed over j cells. Recruitment is calculated at the end of each year. Recruits are subsequently dispersed across the grid from the common pool of larvae produced by all adults,

$$(5) \quad R_j = R_y \phi_j,$$

where R_j is the recruitment to cell j . The proportion of fish that recruit to each cell (ϕ_j) at the end of each year is assumed to be proportional to the initial carrying capacity of the population in cell j ,

$$(6) \quad \phi_j = \frac{K_{o,j}}{\sum_j K_{o,j}}.$$

Recruits diffuse across the spatial grid in the same manner and at the same movement rate as adult fish in this study (see Barton 2006, page 20 - 24). The rate of diffusion can be adjusted to reflect species specific rates of movement.

Ideal free distribution fleet dynamics model

Similar to the fish population, the fishing fleet in the IFD model behaves as an aggregate unit and moves using the same directed and diffusive movement mechanisms as described for the stock dynamic model. The daily directed movement of the fleet follows the sequence presented in Figure 3.2. The two movement mechanisms, coupled with the IFD assumption of perfect, universally shared information on fish densities, allow the fleet to closely mirror fish abundance and concentrate effort in fishing hotspots. Consequently, fishing tends to be located in areas where the catch rate and profit are highest. As a profitable area becomes depleted to a level equivalent to that of the next most profitable area, the fishing fleet partitions equally between the two areas until the profitability of the two areas drops to the level of the third most profitable area causing the fleet to partition again, and so on (Gillis & Peterman 1998). The distribution of the

fleet will approximate an IFD, where all areas are equally profitable, and become stable as the model approaches equilibrium.

Fishing effort is initially distributed uniformly across the grid. Total nominal fishing effort is assumed to be constant, however, the distribution of fishing effort ($E_{t,j}$) is stochastic and is updated daily. The proportion of fishing effort applied in cell j is dependent on the cell's profitability during the previous day. Profitability ($P_{t,j}$) is the product of the daily catch rate in each cell ($r_{t,j}$) and the selling price of fish (p_t) minus the cost of fishing (c),

$$(7) \quad P_{t,j} = p_t r_{t,j} - c .$$

In the results presented here the cost of fishing (c) is constant across all cells, however, p_t , $p_t \sim N(\mu, \sigma^2)$, varies daily to emulate market fluctuations. Per-kilogram daily mean price (μ) is equal to the mean landed price of groundfish from 1997 to 1999 (\$0.68 per kilogram; BC Stats 2001) and variance of 0.1. A variance of 0.1 was selected in order to constrain p_t between the maximum and minimum prices paid from 1997 to 1999. For the purpose of the research presented here, a simple determination of price is deemed sufficient. A more realistic approach would involve demand-supply relationship modelling for price determination (see Herrmann & Criddle 2007).

The profitability ($P_{t,j}$) of a cell affects the cell's desirability ($D_{t,j}$) to the fleet according to the relationship

$$(8) \quad D_{t,j} = P_{t,j} \left(1 - \frac{E_{t,j}}{E \max_{t,j}} \right),$$

where $E_{\max_{t,j}}$ is the maximum carrying capacity for the effort in each cell (j). IFD theory assumes that competition among foragers occurs in proportion to their local density (Gillis *et al.* 1993). Therefore, to account for interference competition, the total fishing effort expended in a cell on any given day is limited by setting $E_{\max_{t,j}}$ equal to the proportion of fish in cell j multiplied by 100. Exploitation competition also occurs through the daily reduction of fish abundance in each cell as a consequence of catch; however, exploitation competition is not necessary for the classic IFD distribution to form (Gillis 2003).

The catch equation used to calculate the total catch taken from each cell (j) fished is:

$$(9) \quad C_{t,j} = r_{t,j} E_{t,j} e_t,$$

where $C_{t,j}$ is the catch in tons on the t th day in the j th cell, $r_{t,j}$ is the daily catch rate, $E_{t,j}$ is the fishing effort in the j th cell, and e_t is an effort modulator allowing effort in each cell to decrease or increase by a small increment each day (t). The effort modulator allows effort to increase in each cell when fishing is profitable and decrease when fishing is not. Cell-specific daily catch rates are calculated as

$$(10) \quad r_{t,j} = qN_{t,j},$$

where q is a constant catchability coefficient, and $N_{t,j}$ is the population size in the cell. Catch is subtracted from the local population in each cell at the end of each day prior to fish movement (Figure 3.1). All parameter values are listed in Table 3.1.

Agent based fleet dynamics model

The hypothetical trawl fishery mimicked by the AB model operates out of a single port at the most southwestern point of area A, i.e., the origin (0,0). Each vessel has a unique vessel length ranging from 13 to 52m, hold capacity ranging from 30 to 120 metric tons, and vessel efficiency. The average vessel speed and efficiency are 12.82 knots and 0.85, respectively. Vessel speed is calculated from the equation:

$$(11) \quad \text{Speed} = 2.43\sqrt{\text{Length}},$$

where *length* is the vessel waterline length in meters. Vessel efficiency refers to a crew's efficiency at setting gear and handling fish.

Daily fishing effort is distributed across the spatial grid using a random utility model (RUM). I employed a RUM to study discrete daily participation and fishing location decisions because a RUM allows individuals to be treated as heterogeneous (Wilén *et al.* 2002). A RUM assumes that utility is the primary metric that motivates individual choice (Hicks & Schnier 2006). The utility function of an individual decision maker in a RUM is assumed to be made up of two parts: a deterministic component of utility that is common to all individuals being modeled and a random component that is unique to individuals. The random component is unobservable and is therefore treated as a random variable within the RUM (Bockstael & Opaluch 1983; Pradhan & Leung 2004).

The unobservable components can be characteristics of the individual (e.g., level of risk aversion) or attributes of the choices themselves (e.g., probability of gear damage) (Hutton *et al.* 2004). The observable components include, but are not limited to, explanatory variables that are assumed to have an affect on expected profit.

Variables included in RUM

Information sharing of catch rates and recent revenue rates for different areas is a fundamental element informing the decision making process for location choice (Holland & Sutinen 1999; Little *et al.* 2004). Ethnographic interviews suggest that vessels network in groups of various sizes and that group dynamics change rapidly (Holland & Sutinen 1999; Holland & Sutinen 2000) depending on the abundance and patch size of fish aggregations (Wilson 1990). I do not explicitly model information sharing between individual vessels; however, I use a proxy for information sharing that is the average revenue for the fleet for a given area during a 10 day window prior to the day a skipper sets out from port (Holland & Sutinen 1999). A cut off period of ten days is used because older information is not perceived to be of great value to fishermen (Holland & Sutinen 1999). I use revenue in the AB model for fleet metrics as opposed to profit rates because individual vessels have a unique cost of fishing, consequently, profit is not comparable across vessels.

Location and vessel specific profit and catch information are also included in the list of explanatory variables. Similar timeframe constraints surrounding the day of departure from port as described in the preceding paragraph are applied to profit and catch information entering the RUM. In addition, catch and profit data are discounted at a

rate of 0.5 to 0.7 (discount rates are vessel dependent) to account for information decay (Smith 2000) and memory distortion over time.

Travel time is included in the RUM to account for the opportunity cost of time spent travelling to a fishing location versus time spent fishing. Opportunity cost enters the model by dividing the number of hours spent travelling from port to the centre of a given fishing location by the expected trip length. I used this metric because it is the proportion of time spent travelling versus fishing that is relevant to assessing a trip's potential profitability (Holland & Sutinen 1999). The average expected trip duration for the fleet is five days; individual trips vary depending on vessel and fishing location.

Knowledge of time- and location-specific fish abundance is assumed to increase a fisherman's expected revenue by decreasing the amount of time spent looking for fish (Holland & Sutinen 1999). However, Bockstael and Opaluch (1983) hypothesise the propensity of fishermen to follow historical patterns for non-monetary reasons such as family tradition and force of habit. In order to account for fisherman specific habits, traditions, and knowledge, recent and historic habit variables are included in the RUM. This information enters the model in dummy variables, where a value of 1 is assigned to an area that has been fished by a given vessel during the past 10 days (recent habit) or during a 20 day period surrounding the departure day in prior years.

Vessel utility function

Vessels are assumed to have unique utility functions that vary across the population. Vessels choose between several discrete alternatives, where the alternative chosen is assumed to be the one that generates the greatest expected utility. The utility

function evaluates the relative attractiveness of different fishing locations based on the locations characteristics, all of which are tracked by the simulation. Within the context of this research, utility (U_i) is a vector and is defined as a deterministic linear combination of explanatory variables and a stochastic error term. The i th vessel is viewed as deriving utility U_i from the j th cell, where each element of U_i refers to a cell (j). The form of the utility function is,

$$(12) \quad U_i = \beta \cdot X_{.i} + \varepsilon_i .$$

$X_{.i}$ is a vector of characteristics facing vessel i , where each element of $X_{.i}$ refers to a cell (j). $X_{.i}$ is multiplied by a vector of coefficients β . The error term (ε_i) is also a vector of length J , where each element of ε_i pertains to a specific cell. ε_i represents unobservable factors such as weather and/or random individual behaviour.

This RUM hypothesises that given J possible fishing locations and the possibility of not fishing, the i th vessel on day t will probably choose location j if the utility (U_i) derived from location j is higher than the alternatives, including the choice of not fishing. Error terms (ε_i) are assumed to be independent across choices and are normally distributed with mean zero and standard deviation of 0.01, which is approximately a CV of 0.1 on the random utility equation. Explanatory variables and coefficient values are based on empirical evidence from published studies investigating fisherman location choice (Table 3.2, see Holland & Sutinen 1999; Holland 2000; Holland & Sutinen 2000; Wilen *et al.* 2002; Smith & Wilen 2003; Pradhan & Leung 2004).

A vessel specific utility score is calculated for each alternative, where the probability of a vessel choosing a alternative j is

$$(13) \quad \Pr(i \text{ choose } j) = \frac{e^{U_i}}{\sum_{k \in C} e^{U_{ik}}}$$

A vessel's target fishing location is chosen by drawing from a multinomial distribution of location choice probabilities ($\Pr(i \text{ choose } j)$) that are specific to the vessel.

AB model structure

The structure and information flow of the AB model for location choice and fishing activity are based on sequential decision making, where each decision leads to a set of actions (Figure 3.3). A more detailed description of the AB model is found in Appendix A. Time is incremented daily, however an hourly record of all vessel activities is kept allowing decisions and fishing activities to occur hourly. On any given day, vessels choose to go or not go fishing. In the event that a vessel chooses not to go fishing, the decision to fish or not to fish is made again the following day. Total daily nominal effort is stochastic in the simulation, as is the distribution of fishing effort. Vessels deciding to go fishing choose a fishing location and proceed to head towards their respective target destinations. Upon arrival vessels engage in search behaviour and begin to fish once searching is complete. Time spent searching is location and vessel dependent with some locations invariably necessitating longer search periods than others and some vessels being better at finding fish than others (i.e., skipper skill (see Squires & Kirkley 1999)). Set and handling times per fishing event are also tracked for each vessel, where both are a function of vessel efficiency and catch.

Daily catch ($C_{t,i}$) is calculated using the catch equation

$$(14) \quad C_{t,i} = q_i N_{t,j} E_{t,i},$$

where $N_{t,j}$ is the number of fish in the j th cell on day t , $E_{t,i}$ is the amount of effort expended by vessel i (swept area (km²)) and varies with each trawl event, and q_i is the catchability coefficient for vessel i and is assumed to vary at random across vessels and locations (Cooke & Beddington 1984). $E_{t,i}$ is equal to the area swept by the i th trawl and is calculated using the equation:

$$(15) \quad E_{t,i} = d_t \cdot net_i,$$

where d_t is the distance trawled and net_i is the width of the trawl net opening (vessel specific). Trawl events are spatially explicit with start and end coordinates, thereby allowing fishing effort from trawls that cross the boundary between two cells to be accounted for in both locations. Using trawl coordinates will allow future analyses to categorise individual trawls as either fishing opportunities (trawls that are consistently placed over the same geographic area) or exploratory fishing (a few random trawls over a geographic area) (Branch *et al.* 2005).

If the utility of fishing at the target location is less than expected (i.e., catch more variable than anticipated), vessels can decide to either stay and continue fishing in the same location or proceed to the adjacent cell with the highest perceived utility. The probability of doing the latter is set at 0.3 in order to account for the role of tradition and habit in the decision making process (Bockstael & Opaluch 1983; Holland & Sutinen

2000). In addition, this attempts to emulate the reality that a vessel does not necessarily leave a fishing location because of single bad haul.

Vessels return to port when their holds become full of fish or the time spent at sea thus far plus the time required to travel home is equal to the expected trip length. Upon returning to port, the i th vessel's cumulative profits (P_i) are calculated for the trip which started on day t_1 and ended on day t_2 ,

$$(16) \quad P_i = \sum_{t_1 \leq t \leq t_2} (p_{t_2} \cdot C_{t,i} - c_{t,i}).$$

Trip revenue is the product of the selling price of fish on the day the catch is landed in port (p_{t_2}) and the i th vessel's catch ($C_{t,i}$) for the trip. The selling price of fish varies daily as describe in the IFD model section. The cost of fishing ($c_{t,i}$) per time step is the sum of daily and variable costs accrued. Variable costs include the length of time spent doing different activities, where different activities have different costs (α). Possible activities include: fishing (T_f), searching (T_s), setting and retrieving the net (T_{set}), and handling fish (T_h) (see Table 3.1). Variable costs also take into account distance from port (i.e., cost of traveling (T_T)) and the cost of fishing in a given location (c_L) (i.e., physical attributes of a cell such as habitat type and weather which may make fishing more or less expensive relative to other locations). Fixed costs (c_F) are constant across all vessels (\$25,000 per year, \$68.50 per day).

$$(17) \quad c_{t,i} = \alpha_1 T_T + \alpha_2 T_s + \alpha_3 T_{set} + \alpha_4 T_f + \alpha_5 T_h + c_L + c_F$$

Experimental design

The distribution of fishing effort is sensitive to several characteristics of the target fish population. Consequently, I compare the performance of the alternative fleet behavioural models under various assumptions of fish movement rates and fish migration. The rationale in doing so is to determine if the spatial distributions of effort resulting from each fleet dynamic model approximates the other under different resource scenarios. For example, under the scenario of no fish migration it is possible that hot spots of fish abundance will be easier to find because fish are not moving and vessels in the AB model will consequently target only a few selected cells. Because relative fish distribution is constant in space and time, vessels in the AB model may develop histories (i.e., memories) that are functionally analogous to the assumption of perfect resource information in the IFD model. As a result, the final distribution of fishing may be more likely to approximate that produced by the IFD model in non-migratory scenarios.

Two spatial scenarios of fish stock distribution were tested. In the first scenario, the stock undergoes an annual east to west followed by a west to east migration. In the second scenario the stock does not undergo any migration, i.e., its relative distribution across cells remains constant. The diffusion rate of fish is a key element within the model governing fish movement. In order to test whether rates of fish movement affect the resulting distributions of fishing effort (either making the IFD and AB distributions of fishing effort more or less similar), alternative assumptions of stock diffusion rate were tested (diffusion rates used are 1.0 and 0.1). In total, four scenarios were tested: 1) no migration, diffusion rate 0.1 (**nomig0.1**); 2) no migration, diffusion rate 1.0 (**nomig1.0**); 3) migration, diffusion rate 0.1 (**mig0.1**); 4) migration, diffusion rate 1.0 (**mig1.0**).

The fish population is initially set to carrying capacity and is distributed across the spatial grid. The IFD fleet dynamic model is subsequently initialised by running the simulation at a given level of effort for a period of 200 years. For the IFD model, 200 years is sufficient time to allow the fleet to converge on an ideal free distribution of fishing effort, given that the fleet is initially distributed uniformly across the grid. With respect to the AB model, the model is initialised using the base fish population from the IFD model at equilibrium (i.e., after the IFD model has been run for 200 years). The AB model is subsequently run for 5 years to provide sufficient time for vessels to explore the fishing ground and develop histories of fish abundance and habitat characteristics of specific fishing locations. Exploratory fishing within the context of the AB model means that vessels randomly choose their initial target location at the outset of each trip. The intention behind the period of exploratory fishing is to allow for a period of learning in which vessels can learn which fishing locations have greater fish abundances and are consequently of greatest utility. Both AB and IFD models are then run for an additional 10 and 15 years, respectively, so that the fish population used in both models is subject to a total of 215 years of fishing effort.

Upon completion of each model's respective initialisation period, cell specific harvest, revenue, stock abundance, and fishing effort information is tracked for the last 10 years. Because the distribution of fishing effort is stochastic in the case of the AB model, each version of the simulation is run five times and the average results are presented here. I chose to limit the number of runs to five because of the computationally intense nature of the AB model, where each run takes four hours. The IFD model is deterministic, therefore a single run is sufficient.

Statistical Design

I test for statistically significant differences between spatial distribution of fishery effort from the two fleet dynamic models using a method described by Syrjala (1996). To conduct this test, each variable is first normalised in order to make the test independent of the total amount of effort in each model. Variables in this case are the observed fishing efforts at each location. For each location j , a cumulative distribution function for each variable (v) can be defined as,

$$(18) \quad \Gamma(x_j, y_j) = \sum_{\forall x \leq x_j, \forall y \leq y_j} \gamma_v(x, y),$$

where γ_v is the normalised variable v , and x and y are the coordinates for location j . The test statistic is the square of the difference between the cumulative distribution functions for the two variables being compared, summed over all J locations,

$$(19) \quad \Psi = \sum_j [\Gamma_1(x_j, y_j) - \Gamma_2(x_j, y_j)]^2.$$

The statistic Ψ is not spatially invariant with respect to the corner of the grid used as the origin, consequently, it was calculated four times, once with each corner of area A defined as the origin, where the average of the four values is used as the test statistic,

$$(20) \quad \Psi = \frac{1}{4} \sum_{c=1}^4 \Psi_c.$$

Each value of c identifies a different corner of A .

The level of significance of Ψ is determined using a randomisation test. Under the null hypothesis that the distributions of the two variables are the same, either fishing effort observation $\Gamma_i(x_j, y_j)$ for a specific location is equally likely for each fleet dynamic model. Therefore, a random permutation of the data is conducted by randomly assigning one of the two values for each location to one of the variables and the remaining value to the other variable. This is repeated 999 times, and the significance of the test statistic Ψ is determined from its position in the ordered set of test statistic values from all the permutations. The P -value is the proportion of the 1000 test statistic values (999 pseudo-random permutations and the predicted permutation) that are greater than or equal to the observed test statistic.

Results

Comparisons of aggregate effort and CPUE

Lorenz curves are used to compare how evenly effort and CPUE are distributed across locations. If, for example, effort were distributed evenly among grid cells, the Lorenz curve would be a straight line through the origin. As the distribution becomes more unequal, the Lorenz curve becomes more convex. It is important to note that a Lorenz curve does not take into account the spatial distribution of the CPUE and effort data, it plots the cumulative proportion of effort (or CPUE) starting with the cell that has the largest proportion of effort and ending with the cell that has the smallest proportion of effort.

In general, CPUE from the IFD model is the most evenly distributed across fishing locations for all scenarios, in all years, and for both fleet dynamic models (Figures

3.4 and 3.5. Graphs for scenarios with a diffusive movement rate 1.0 are not shown as they exhibit a similar pattern to those with a diffusive movement rate of 0.1). Comparing only CPUE Lorenz curves, CPUE from the IFD model is more evenly distributed in all scenarios than CPUE from the AB model (Figures 3.6 and 3.7). This is consistent with the IFD prediction that CPUE should tend to equalise among areas (Swain & Wade 2003), and is particularly true for scenarios with fish migration. The IFD CPUE Lorenz curve from scenarios with fish migration clearly show the tendency for CPUE to equalise among areas as the Lorenz curve closely approximates an identity function, i.e., $x = y$ (Figure 3.6). Interestingly, the cumulative IFD and AB distributions of CPUE (i.e., cumulative across all ten years) are very similar for all four scenarios (Figures 3.6 and 3.7). Differing rates of fish diffusive movement do not appear to greatly affect the distribution of CPUE in both migrating and non-migrating scenarios.

Under the scenarios with a non-migratory fish population, the distributions of fishing effort across cells are virtually identical for both the AB and IFD fleet dynamic models under both rates of diffusive movement (Figure 3.8). For the scenarios with fish migration, fishing effort from the IFD model is slightly more evenly distributed than that from the AB model (Figure 3.9). The difference between model specific Lorenz curves of effort with different rates of fish diffusive movement are minimal.

The spatial distributions of effort

The spatial distribution of effort from the AB model under the scenario **mig1.0** shows the highest concentration of effort occurred in cells to the left of grid center, with the level of effort decreasing abruptly in cells farthest from port (Figure 3.10). This general pattern is consistent for all years in scenario **mig1.0**; however, fishing effort does

appear to become slightly more equally dispersed across fished cells over time. The distribution of effort from the IFD model under the scenario **mig1.0** is identical for all years (Figure 3.11). This is an artefact of the assumption that fishermen have perfect information of a resource's distribution, as the pattern and timing of fish migration does not change from year to year. Higher levels of fishing effort appear to occur along the eastern and western edges of the grid, in particular the four corners. Fishing effort becomes more uniformly distributed between cells towards the center of the grid. The spatial distribution of fishing effort from the AB model (Figure 3.10) and IFD model (Figure 3.11) for scenario **mig1.0** appear to be quite different based on visual comparisons.

The spatial distribution of fishing effort from the AB model for scenario **nomig1.0** (Figure 3.12) is different to that of **mig1.0** (Figure 3.10) in that fishing effort in any given year appears to be distributed among a greater number of cells and farther from port in scenario **mig1.0** compared to **nomig1.0**. In addition, the cell with the highest level of effort in **nomig1.0** is the one closest to port, whereas in **mig1.0** the cell with the highest level of fishing effort is generally close to the center of the grid. Both scenarios do however exhibit a similar overall pattern of effort fanning out from port, with cells in the farthest corner receiving the least effort.

The spatial distribution of effort from the IFD model for scenario **nomig1.0** is distributed across the grid such that locations with high fish abundance received high levels of effort (Figure 3.13). Furthermore, the distribution of effort is largely unchanging from year to year, which is an artefact of the assumption that fishermen have perfect information and is consistent with the fact that 1) the fish population is non-migrating and

2) relative cell carrying capacity is constant from year to year. IFD and AB distributions of effort in scenario **nomig1.0** are more akin to each other than in scenario **mig1.0**. However, locations that are farther from port receive less fishing effort in the AB model than in the IFD model for both scenarios demonstrating the effect that distance from port, among other things, has on distribution of fishing effort. Figures of the spatial distributions of effort for scenario **mig0.1** and **nomig0.1** are not shown as they are very similar to **mig1.0** and **nomig1.0**, respectively.

Scenario specific spatial distributions of fishing effort were not significantly different between AB and IFD models for migratory scenarios, but were significantly different for non-migratory scenarios (Table 3.3). Differences between cumulative distributions of effort were also significant in scenarios with no migration, but insignificant in scenarios with migration (Scenarios: **mig0.1**: $P=0.453$; **mig1.0**: $P=0.388$; **nomig0.1**: $P=0.002$; and **nomig1.0**: $P=0.001$). Comparing levels of significance between rates of fish diffusive movement in the non-migratory scenarios were equally significant.

In an attempt to characterise the difference between IFD and AB models' distributions of fishing effort, I plotted the residual of the proportion of total effort by the AB and IFD models for each scenario (Figures 3.14 to 3.17). For scenarios with fish migration (Figures 3.14 and 3.15), there is an obvious edge effect on sides opposite port location, where the proportion of effort in cells along the edges of the grid is greater for the IFD model than the AB model. This is likely a result of the mechanics behind each model as well as the migratory pattern of the fish population. For example, in the AB model distance from port will affect the distribution of effort as there is an opportunity cost for time spent travelling. Consequently, vessels in the AB model may be less likely

to fish in cells farther from port (i.e., northern and western edges of the grid) for a given abundance of fish that would attract fishing effort in the IFD model. Fish follow an east-west migration pattern moving to the east for six months and moving to the west for the remainder of the year. The migration pattern likely contributes to the observed edge effect because at the six month turn around point the fish population tends to concentrate in fewer cells along the eastern and western edges of the grid. Because of the assumption of perfect information in the IFD model, fishing effort is targeted at these cells at a much higher rate relative to the AB. Consequently, fishing effort over the course of the year in the IFD model is much higher along the edges opposite port. Cells that receive equal proportions of fishing effort from both models, or where the AB model proportion of effort is greater than that of the IFD, are those close to port or in the central region of the grid.

Scenarios with no fish migration are characterised by a different set of qualities than those with a migratory fish population. Fishing effort from the AB model in scenarios with no fish migration is visibly more concentrated in cells closer to port resulting in the proportion of effort observed being greater in these cells for the AB model than the IFD model (Figures 3.16 and 3.17). Conversely, cells along the northern and eastern edges of the grid receive a greater proportion of fishing effort from the IFD model. This is likely a consequence of the opportunity cost of travel time in the AB model. Cells in the central region of the grid tend to receive equal proportions of effort from both models

Residual plots for the cumulative proportion of effort exhibit the same patterns as those described for individual years within a given scenario (Figure 3.18). The migration

of fish (i.e., migratory or territorial) appears to have a greater effect on the distribution of fishing effort than rate of fish diffusive movement. Comparing **nomig1.0** and **nomig0.1** the pattern of residuals does not change much in either the plots of individual years or cumulative years. The same can be said when comparing **mig1.0** and **mig0.1**, however, in **mig1.0** cumulative effort is slightly greater in cells farther from port than in **mig0.1**. This difference is most likely a consequence of fish movement, where increased rates of fish movement will draw vessels farther from port with increasing frequency.

AB model sensitivity to utility

The sensitivity of the distribution of effort from the AB model to different coefficient values in the utility function (Table B1) was found to be minimal suggesting that the way vessel movement and location choice while at sea is programmed (i.e., vessels are programmed to stay on a relatively straight trajectory between initial location and port) carry greater weight than the coefficient values in the utility function (see Appendix B). In general, the AB model was found to be more sensitive to changes in utility function coefficient values in scenarios with fish migration. This result may be a consequence of it being more difficult to find fish during the exploratory period, which leaves individual vessels with poorer logbook histories of where optimal fishing locations occur. In addition, fish migration will draw vessels away from port to the extent that the opportunity cost of travelling does not outweigh the benefits of fishing farther from port making the AB model more sensitive to the coefficient value of opportunity cost in migratory scenarios.

Discussion

The purpose of this study was to test under what conditions a fleet dynamic model based on IFD theory has the same spatial distribution of fishing effort as that produced by an AB model using a RUM. The results of this analysis show that the two models were significantly different in non-migratory scenarios indicating that when fisherman heterogeneity, travel time, and fishermen's experiences are accounted for (as in the AB model) location choice differs from that when only profitability is considered. The differences between the spatial patterns of exploitation for scenarios with fish migration, although not significant, were visually quite different (Figures 3.10 and 3.11). The lack of significance in migratory scenarios may be a consequence of the fish migration mechanisms within the model.

In the model, fish migration is simulated as a school of fish moving eastwards and then westwards across the grid, where fish density is distributed (east to west) across the expanse of the school. Throughout the simulation, the school of fish spans several cells in width and is vertically uniform across cells. However, when fish reach the eastern and western edges of the grid the width of the school condenses to one cell as fish moving in opposite directions overlap. The pattern and timing of fish migration is also identical from year to year meaning that the average annual abundance of fish in any given cell is identical. This pattern may result in a more uniform distribution of effort over the course of a year (effort shifts from cell to cell following migrating fish), which would explain why from the perspective of statistical difference the AB model more closely approximates the IFD spatial distribution of fishing effort in migratory scenarios than in non-migratory scenarios. These results also suggest that the IFD assumption of perfect

knowledge plays a more substantial role in differentiating the model results from each other in non-migratory scenarios where the average annual abundance in cells is heterogeneous across cells.

This study differed from previous studies evaluating models of fisherman behaviour and location choice by focusing on the comparison of alternative model predictions of fishing effort that were obtained under the same resource distribution conditions. Previous studies have tended to focus on comparing the predictions of aggregate effort generated from a complex AB fleet dynamic model against that which actually occurred in a fishery (e.g., Dreyfus-Leon 1999; Holland & Sutinen 1999; Dorn 2001; Hutton *et al.* 2004; Pradhan & Leung 2004).

My research attempts to provide the means to answer a basic question that has not to my knowledge been clearly answered in the literature on fisherman location choice and that is, is it necessary to develop data intensive and computationally expensive models that include the microbehaviour of individuals (i.e., AB models) to predict the spatial distribution of effort with sufficient accuracy for management purposes? If, for example, the final outcomes from alternative models are the same, it may not be as important to create a complicated AB model of fisherman behaviour; a simple IFD model may be good enough for explaining the distribution of fishing effort across space. Given the current level of government funding for fisheries management in Canada, it is important for managers to prioritise where funding resources for data collection should be directed within a given fishery in order to best understand the economic and social circumstances of that fishery. In order for them to do this, fisheries managers need to determine what

type of fleet dynamic model is a reasonable representation of the fishery they are managing.

Comparison of alternative fleet dynamic models

In order to better understand the results derived by each modelling approach, it is important to discuss their respective characteristics and assumptions which make them different. The AB and IFD models were designed to produce different results by virtue of their taking into account different factors to make decisions on location choice. There are several elements in each model that could be changed to minimise the differences between them without changing the structure of either.

Beginning with the IFD model, there are two assumptions that could be relaxed to make it more similar to the AB model. First, the IFD model assumes a uniform cost of fishing across all cells, whereas the AB model does not. Changing this within the IFD model so that the cost of fishing includes distance from port would change the profitability of cells and would consequently influence location choice and the spatial distribution of effort. Second, the assumption of perfect information of the resource distribution could be modified to include a small random error term on cell desirability so that fishermen would not know exactly where the most profitable fishing spots are on any given day. Applying a small error term to expected profitability would have a similar effect on location choice as using perceived utility for the selection of fishing location in the AB model. Bernstein *et al.* (1988) showed that relaxing some of the IFD assumptions and applying them to individuals can help explain some of the discrepancies between theory and reality.

With respect to the AB model, the utility function could be parameterised so that individuals place higher consideration on revenue generation relative to other factors like weather, safety, habit, and tradition. The intention would be for a vessel to choose fishing locations based primarily on profit, and thus approximate more of an IFD spatial distribution of effort (vessels would target locations that have the highest abundance of fish and are the most profitable). The AB model does not have constant daily nominal effort as in the IFD model. This could be altered so that the AB model has the same nominal effort as the IFD model and hence the same degree of interference competition which would cause vessels to distribute effort differently.

The simulation results from the models presented here suggest that the use of an aggregate fleet perspective (as used in the IFD model) that assumes effort flows freely between areas until catch and revenue rates are equalised, may not be an accurate representation of fisheries where individual vessel characteristics and preferences differ and where they heavily influence location choice. These results do not suggest that one method is better than the other, only that they are different and that their relevance to a particular fishery will vary depending on the characteristics of that fishery. It is therefore of paramount importance to determine which model is more representative of a given fishery so that the correct one can be used to test regulatory effectiveness prior to implementation.

IFD theory has been used extensively to investigate how fishing fleets distribute their effort between areas, and in several studies of single species fisheries that are homogeneous across both fishermen and fishing areas, IFD theory has been shown to be an adequate predictor of aggregate effort (e.g., Hilborn & Ledbetter 1985; Gillis *et al.*

1993; Campbell *et al.* 1993; Swain & Wade 2003; Voges *et al.* 2005). However, research on multispecies fisheries where expected profits differ across fishermen, demonstrates that IFD theory is too coarse for modelling fisherman behaviour in these fisheries, because it is not able to capture the heterogeneity of a fishery, nor how expected profits for a given area vary across fishermen (e.g., Holland & Sutinen 1999; Babcock & Pikitch 2000; Holland 2000; Wilen *et al.* 2002; Smith & Wilen 2005). A RUM framework for testing explanatory variables, and then applying those that are significant in a simulation model, provides a pragmatic methodological approach for spatial analyses of location choice in heterogeneous fisheries (Hutton *et al.* 2004). Modeling location choice as a function of fish abundance is not always representative of reality as shown by the analysis of an Indonesian coastal fishery, where the aggregated distribution of effort is thought to be the result of factors such as the small scale of operations, not fish abundance (Pet-Soede *et al.* 2001).

The importance of spatial and temporal dimensions

The interest in spatial fisheries issues stems from a shift in perspective, where fisheries were once ubiquitously perceived to be homogeneously distributed resources, but are now known to be patchy and heterogeneously distributed metapopulations in some fisheries (Sanchirico & Wilen 1999; Smith 2000). The delineation of catch, effort, vessel and gear restrictions, and temporary and permanent closures by area has as a result become standard practice in many of the world's fisheries (Branch *et al.* 2006a). The effect of spatial management on fisherman behaviour is likely to differ across fishermen and fisheries, therefore making it important to take into account the behavioural responses when evaluating fishery specific regulations (Hilborn 1985).

The importance of spatially analysing effort and CPUE data, as well as examining these data on an appropriate temporal scale is highlighted by the comparison of the simulation results presented here. In scenarios with no fish migration, comparison of the proportion of effort across cells from both models, without taking into account the spatial orientation of cells (i.e., using only Lorenz curves), might result in the incorrect conclusion that the AB and IFD models produced similar distributions of fishing effort (see Figure 3.8). However, statistical analysis of the spatial distribution of effort across cells shows that the patterns of exploitation from the two models are significantly different from each other in all years (see Figures 3.16 and 3.17; Table 3.3).

Comparison of annual Lorenz plots in any scenario to the cumulative Lorenz plot for that same scenario (Figures 3.6 to 3.9) illustrates why it is important to identify the proper temporal scale for data analysis. In the case of this research, data analysis on a decadal time scale (i.e., plots labelled as cumulative) may yield the incorrect conclusion that both IFD and AB models distributed fishing across cells in similar manners. Annual analysis on the other hand shows that a high degree of variability between models does in fact exist in any given year. Aggregation of data to a decadal time scale in this case results in a substantial loss of detail that is vital to drawing proper inferences on model performance.

Limitations

The models I presented here are an attempt to use relatively simple mathematics to capture the complexity of fishermen's location choice decisions. It was possible to incorporate realistic parameters for some aspects of the models (e.g., individual vessel characteristics in the AB model), as well as a few well documented behavioural

preferences for fishing locations; however, it was necessary to make a few assumptions where data and information were not available. Because of the uncertainty in the parameter values used as well as the hypothetical nature of the fishery modelled, the conclusions drawn from this research should be used to provide direction and act as a foundation for future research on fisherman location choice in relation to an actual fishery. For example, the relative importance and weighting of each element in the utility function for the AB model, will depend on the characteristics of the fishery under question and may include variables not identified in the utility function used in the AB model presented here. Model comparison to fishery derived data will permit investigators to determine which model is more consistent with the reality of that fishery, and which should therefore be used in the development and evaluation of policies and regulations. For example, analyses of the Californian sea urchin fishery by Smith (2002), show that aggregating a RUM model of microbehaviour to achieve a macroresult (i.e., using an AB model) does not necessarily outperform directly modelling the relevant macroresult (i.e., modelling the fleet as unit). Smith's (2002) analysis provides fisheries managers with valuable information for the evaluation of trade-offs between models which will help them decided which model is the best one for their purposes.

A second limitation of this study is the assumption of uniform environmental conditions through time, meaning that cell habitat condition and relative attractiveness to fish does not change in response to varying ocean condition or habitat degradation as a consequence of fishing. The relative carrying capacity of each cell stays constant throughout the simulation and areas of high fish concentration do not shift with time. In order to improve the degree of realism in the models, environmental variation should be

incorporated into the models to reflect habitat degradation as a consequence of fishing and/or changing climatic conditions.

Research extensions

The models presented here were originally developed to predict effort distributions for a single species fishery. Application of the AB and IFD models to a multispecies fishery would be an important avenue to explore. Modelling predictions of effort at the individual level and subsequently rolling up to an aggregate level has been purported by a number of researchers as the most sensible method for modelling fleet dynamics in a heterogeneous multispecies fishery (e.g., Dreyfus-Leon 1999; Hutton *et al.* 2004; Smith & Wilen 2005). It would be interesting to test this statement by comparing the patterns of exploitation produced by the IFD and AB models with multiple fish populations to effort data from an actual multispecies fishery to see if rolling up to an aggregate level from the individual data is better for multispecies fisheries. Both AB and IFD models are spatially explicit and therefore have the capacity to incorporate location data.

The effects of different policy and regulatory actions on location choice, and consequently the spatial distribution of effort are areas that I recommend exploring. Policy implications for fisheries management have the potential to be drastically different depending on what motivations exist within a fishery for making decisions on fishing locations (Hilborn 1985). For example, simulations of the economic impacts of marine reserves have been shown to dramatically change the conclusions about reserves depending on the type of behavioural model used (see Smith & Wilen 2003).

Last, it may be insightful to apply a relaxed set of IFD assumptions both to the aggregate IFD model and to an AB approach where location choice is a function of profitability only. A handful of possible aspects and assumptions that could be modified in the IFD model are discussed in the section on model comparison. The modified IFD model would then be compared the AB RUM model developed here. The exercise of relaxing IFD assumptions one by one could help to identify which elements of IFD theory are most responsible for the disparity between the results of the IFD model and the AB.

Fisheries management and fleet dynamics

Fisheries management objectives can be summarised in three parts (de la Mare 1998): 1) maximise economic, social, ecological benefits; 2) avoid deleterious changes to the stock and the environment; and 3) maintain stability in the fishing industry. Trade-offs between objectives will inevitably occur as it is not possible to maximise all three simultaneously. A critical element to any evaluation of a management procedure's efficacy in meeting social and economic objectives will require modelling how fishermen participation and investment in a fishery responds to regulatory variation. Testing harvest strategy robustness and effectiveness a priori to a myriad of possible fishermen responses can prevent irreversible mistakes from being made.

A useful framework for evaluating fisherman response to regulatory change is in a management strategy evaluation (MSE). MSE evaluates the consequences of different management actions or strategies and presents the results in a way that clearly shows the trade-offs of each alternative relative to a range of management objectives (Smith *et al.* 1999). The advantage of using MSE is that it provides a flexible and transparent means of

comparing alternative management actions (e.g., rules for spatial closures) for a set of (usually conflicting) management objectives, thus providing decision makers with the requisite information they need to make management choices (Smith *et al.* 1999; Punt *et al.* 2001). Smith *et al.* (1999), Punt *et al.* (2001), and de la Mare (1998) provide detailed descriptions of the steps required in a MSE.

One interest for MSE from a fisheries management perspective is to know the effect that fishing has on spatially distinct sub-populations of fish. MSE can be used to test alternative harvest strategies (e.g., spatial rules for when and where vessels can fish) that could be implemented to minimise the observed or hypothesised effect of fishing on the sub-populations. This will require the use of a spatially representative fleet dynamic model that captures the relevant behavioural elements of the fishing fleet involved in the fishery.

Conclusions

For use as a policy tool, each method of modelling location choice has its advantages and disadvantages. One straightforward advantage of the IFD approach is that it is easier to develop, parameterise, and use as a simulation tool compared to the AB approach. Moreover, the IFD approach does not require any data on individual decision makers, rather it relies on long time-series data that are disaggregated only at the spatial scale. In contrast, the AB approach explicitly incorporates decision making of individuals as an internal process, making it more consistent with reality, and requires fewer assumptions in simulation. The increased availability of georeferenced data via new tools like vessel monitoring systems (Bertrand *et al.* 2007) opens new opportunities for using AB models to understand spatial mechanisms of fleet dynamics as it makes accurate

spatial data on individuals more available. Methods for collecting data on learning and information sharing between vessels are still in need of development as there is not currently a straightforward method that is utilised by fisheries managers or scientists for that manner (Little *et al.* 2004).

Modelling fleet dynamics is clearly a complex matter that requires the characteristics of a fishery to be identified and subsequently taken into account when selecting an appropriate modelling framework to predict fishing effort distribution. The results for the hypothetical fishery simulated here emphasise this point where under scenarios of no migration and a single species fishery, the AB model and IFD model produced spatial distributions of fishing effort that were significantly different from each other. Although not an easy task, failure to identify key factors motivating fisherman behaviour within a fishery and testing how these drivers influence fishermen's choices and actions in the face of regulatory change can result in inaccurate predictions of regulatory effectiveness that could be quite costly, both economically and biologically, if implemented.

Figures

Fig 3.1 Flow chart illustrating the general path of data flow through the model in a simulation: t is daily time step; y is annual time step; C , E , and N are catch, fishing effort and fish abundance, respectively. *Figures 2.2 and 2.3 illustrate the flow of data in the IFD and AB fleet dynamic models, respectively. Modified from Barton (2006).

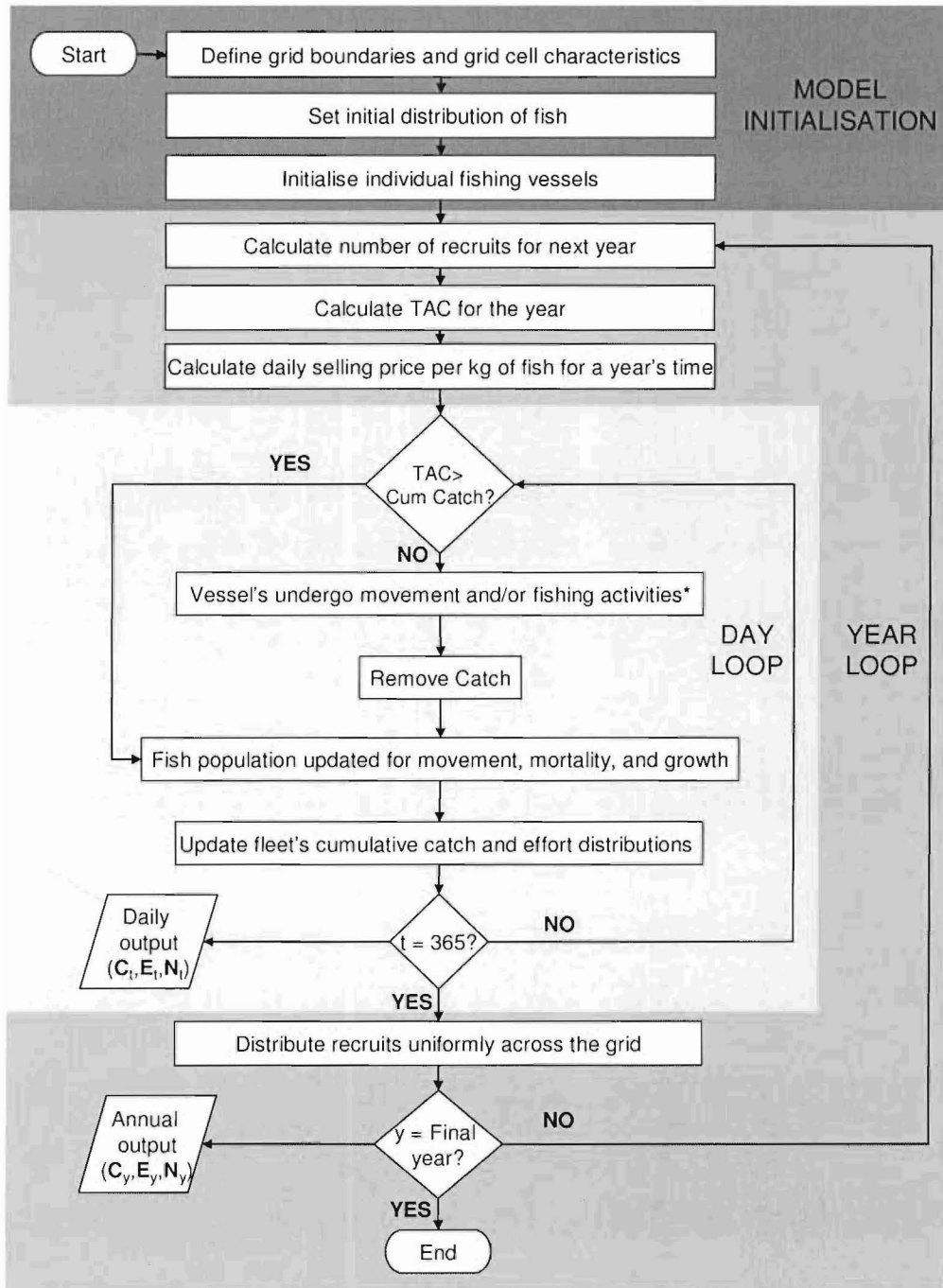


Fig 3.2 Flow chart illustrating vessel movement from one time step (t) in the IFD model. Modified from Barton 2006.

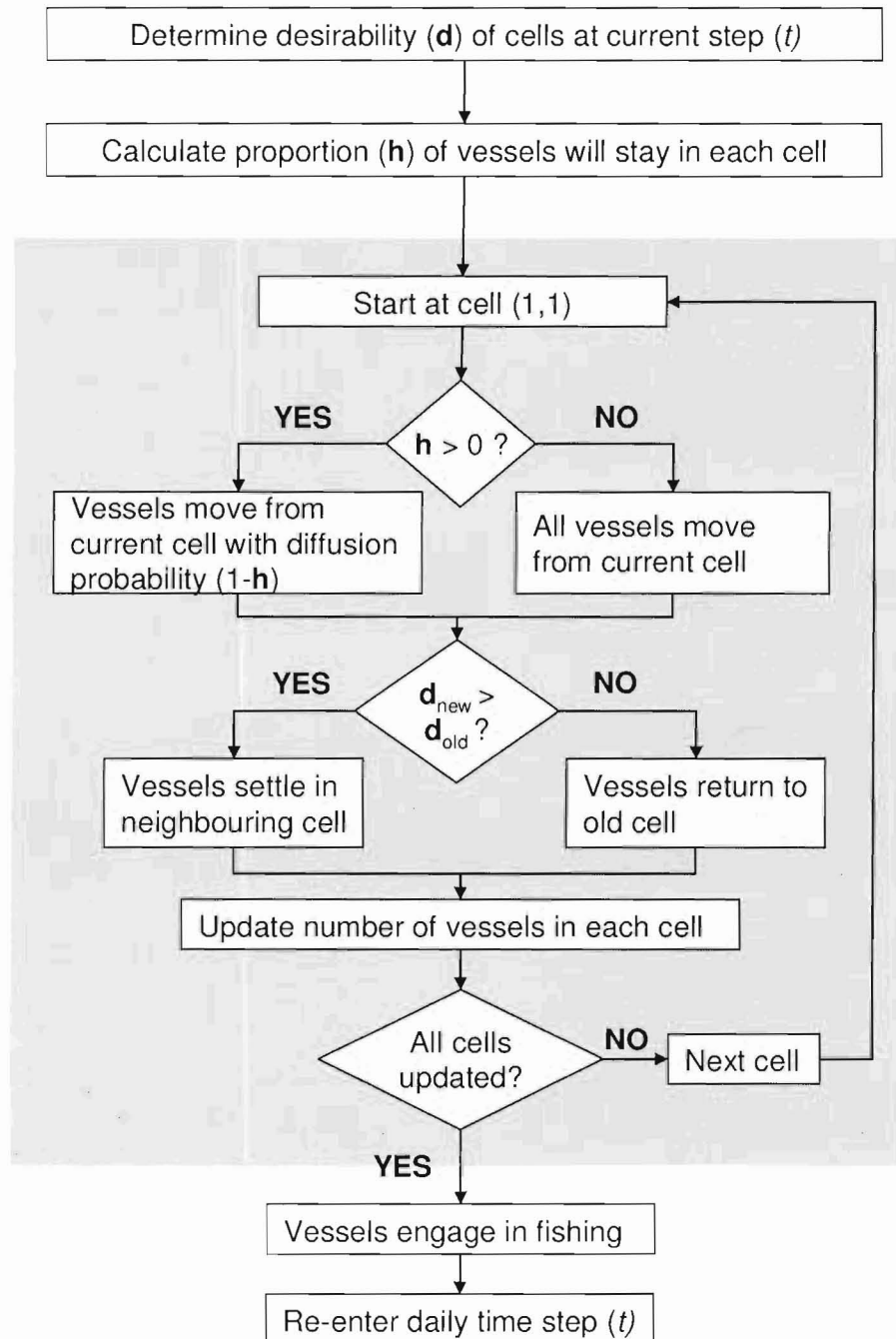


Fig 3.3 Flow chart illustrating calculations and information flow for individual vessel movement and fishing; an expansion of the daily vessel activity step shown in Figure 2.1.

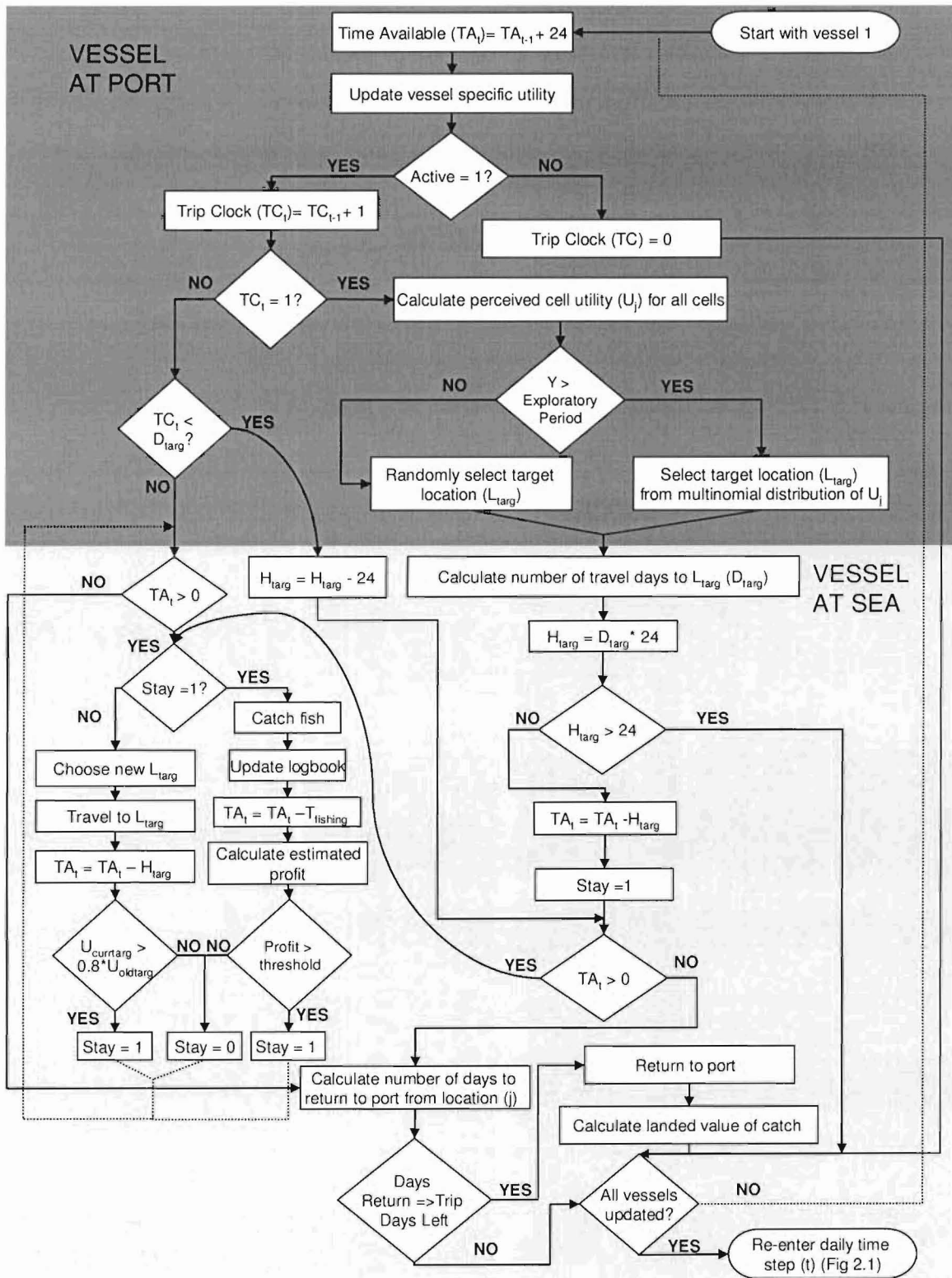


Fig 3.4 Lorenz curves for annual and cumulative effort (dashed lines) and CPUE (solid lines). Results for both fleet dynamic models are shown (IFD – grey lines; AB – black lines). The fish population is migratory and the rate of diffusive movement is 0.1.

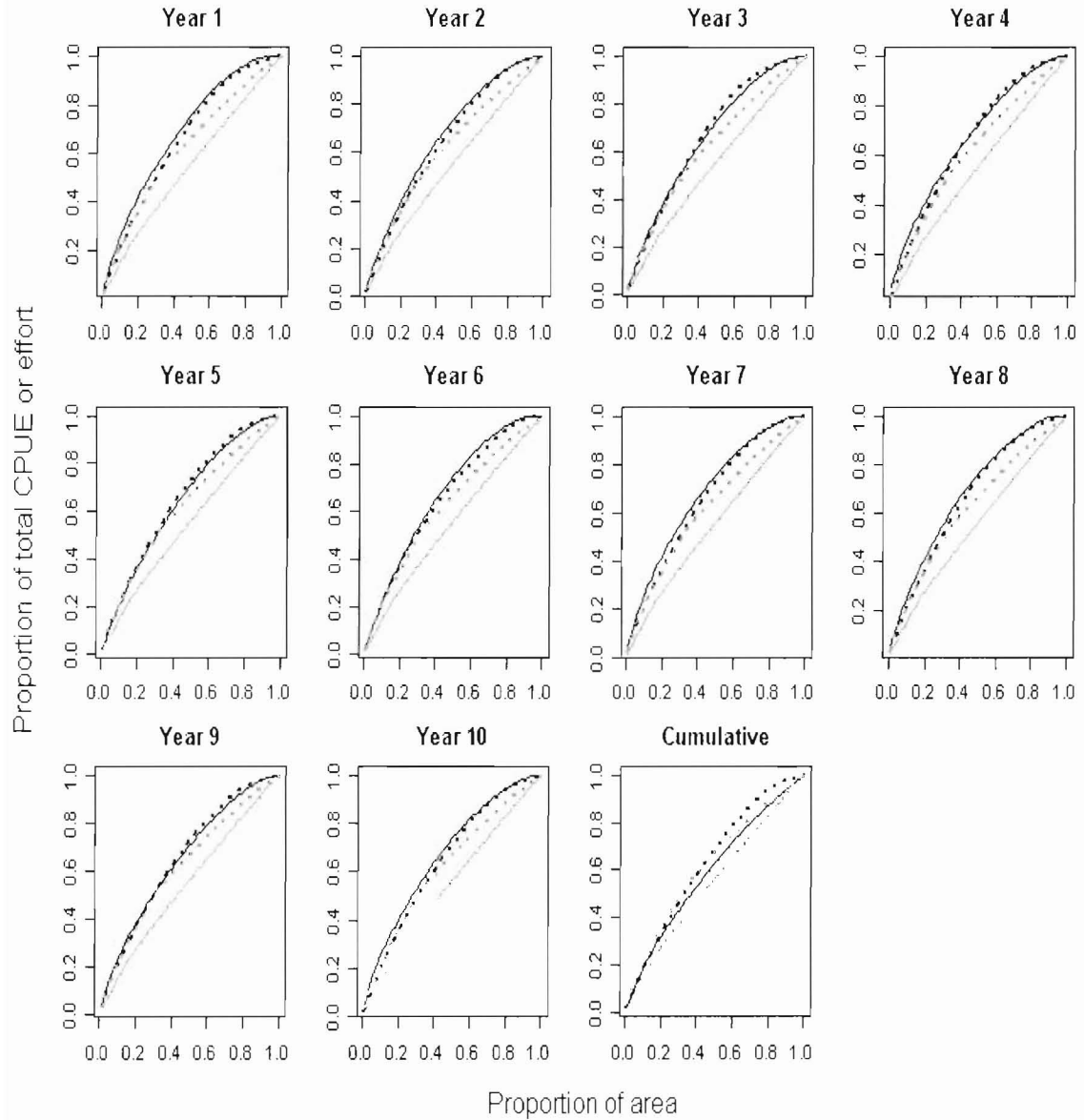


Fig 3.5 Lorenz curves for annual and cumulative effort (dashed lines) and CPUE (solid lines). Results for both fleet dynamic models are shown (IFD – grey lines; AB – black lines). The fish population is non-migratory and the rate of diffusive movement is 0.1.

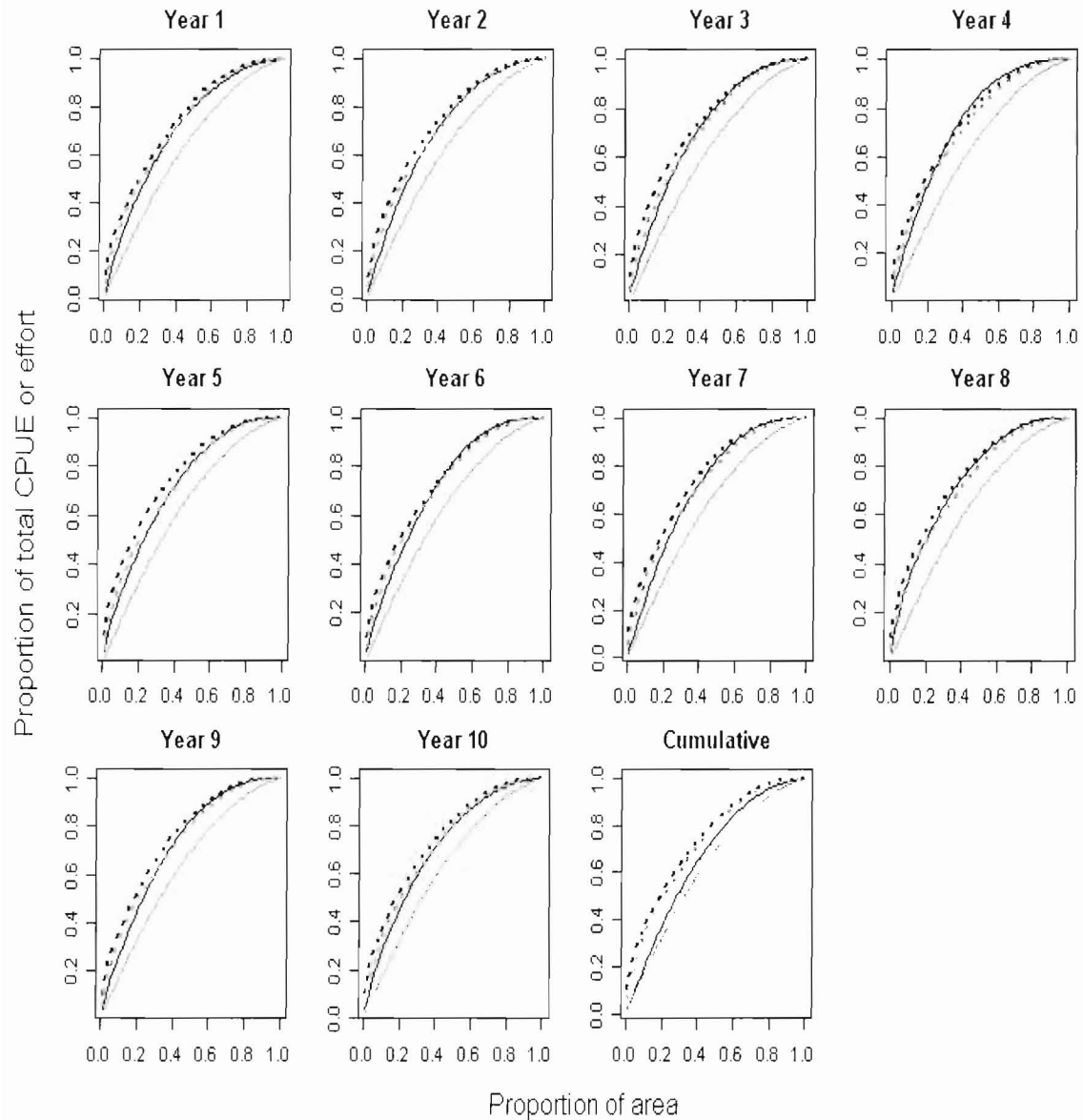


Fig 3.6 Lorenz curves for annual and 10 year cumulative CPUE from IFD (grey lines) and AB (black lines) models. The fish population is migratory for all scenarios; however rate of diffusive movement varies, 0.1 (dashed lines) or 1.0 (solid lines).

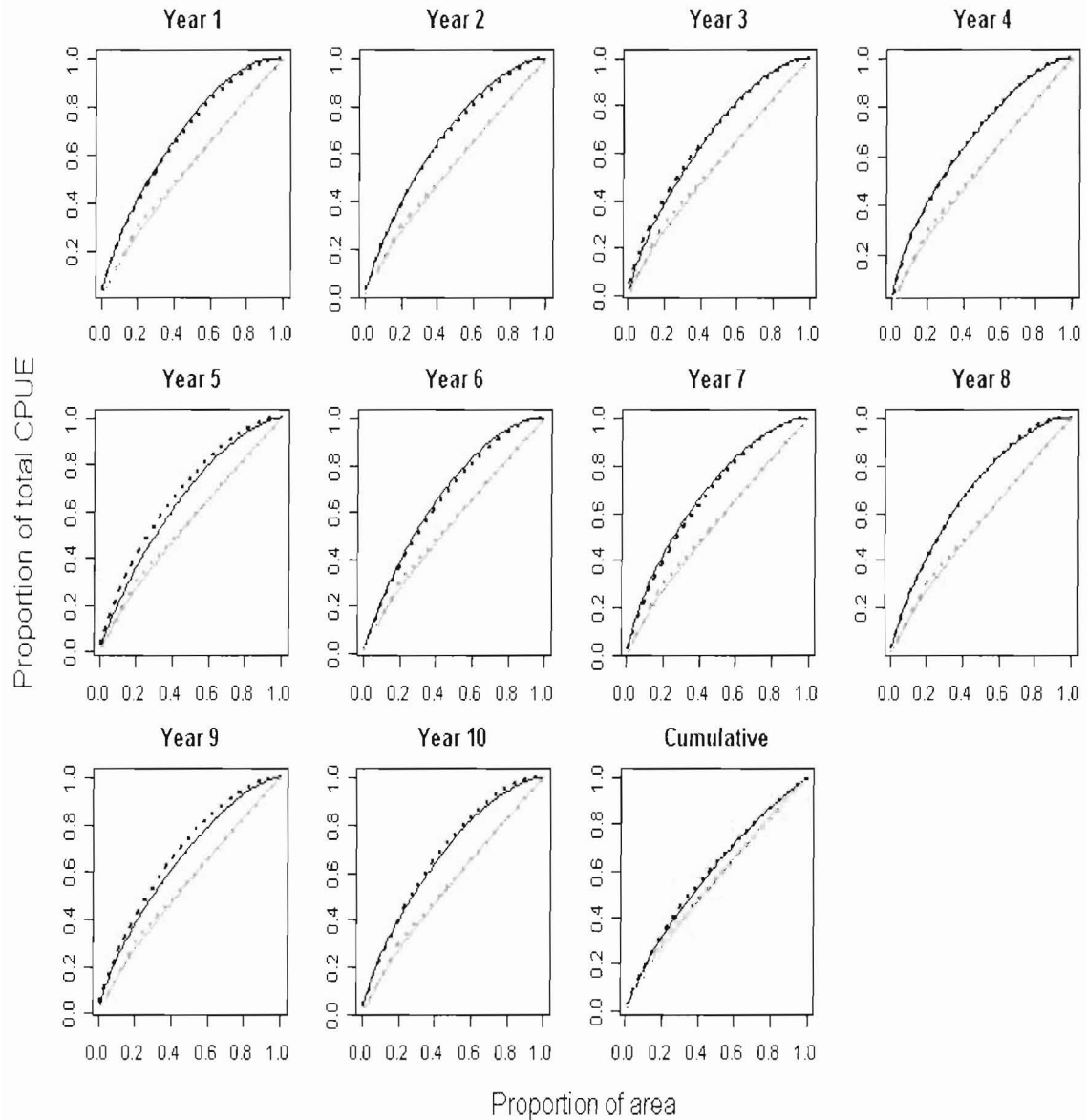


Fig 3.7 Lorenz curves for annual and 10 year cumulative CPUE from IFD (grey lines) and AB (black lines) models. The fish population is non-migratory for all scenarios; however rate of diffusive movement varies, 0.1 (dashed lines) or 1.0 (solid lines).

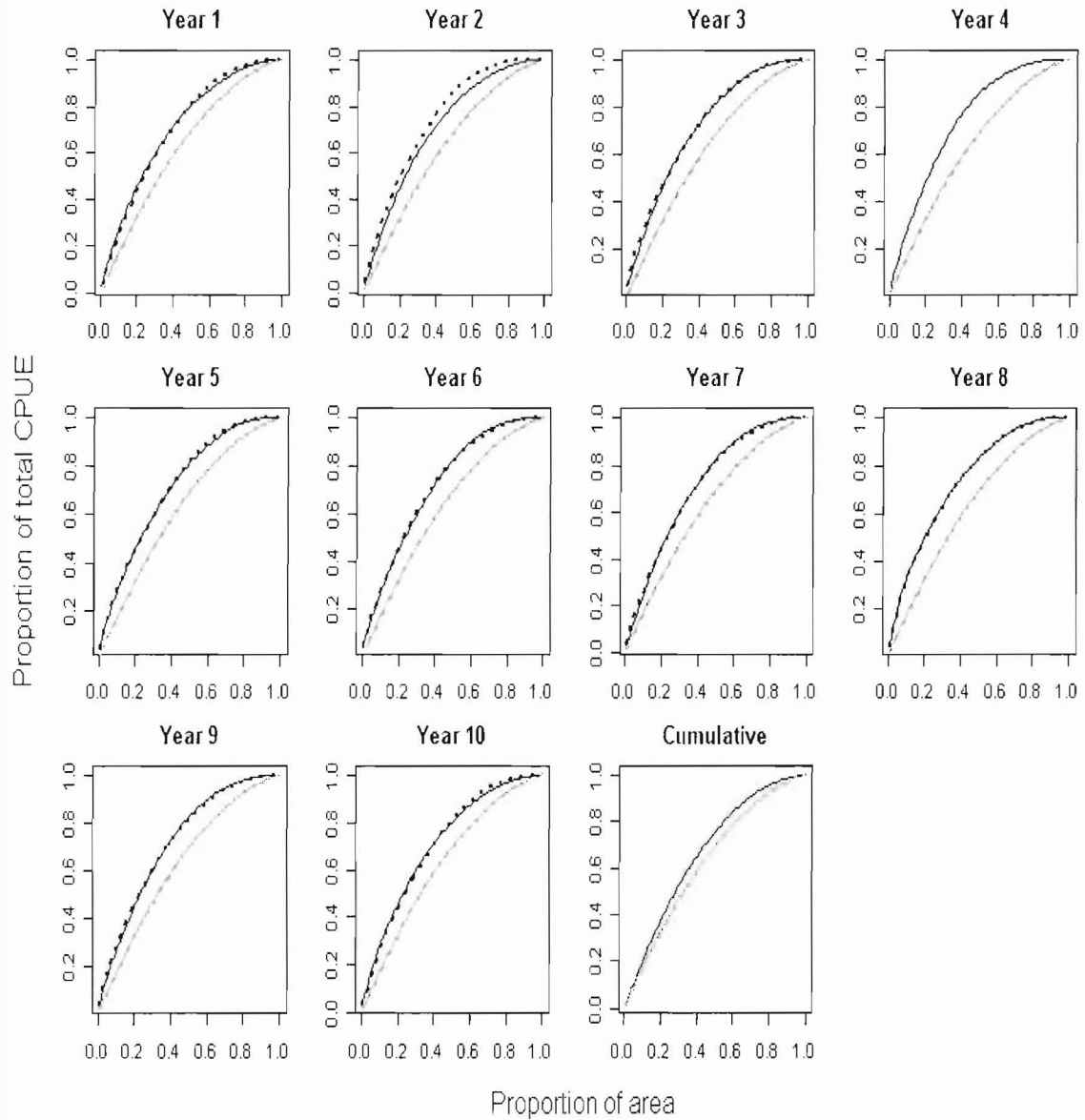


Fig 3.8 Lorenz curves for annual and 10 year cumulative effort from IFD (grey lines) and AB (black lines) models. The fish population is non-migratory for all scenarios; however rate of diffusive movement varies, 0.1 (dashed lines) or 1.0 (solid lines).

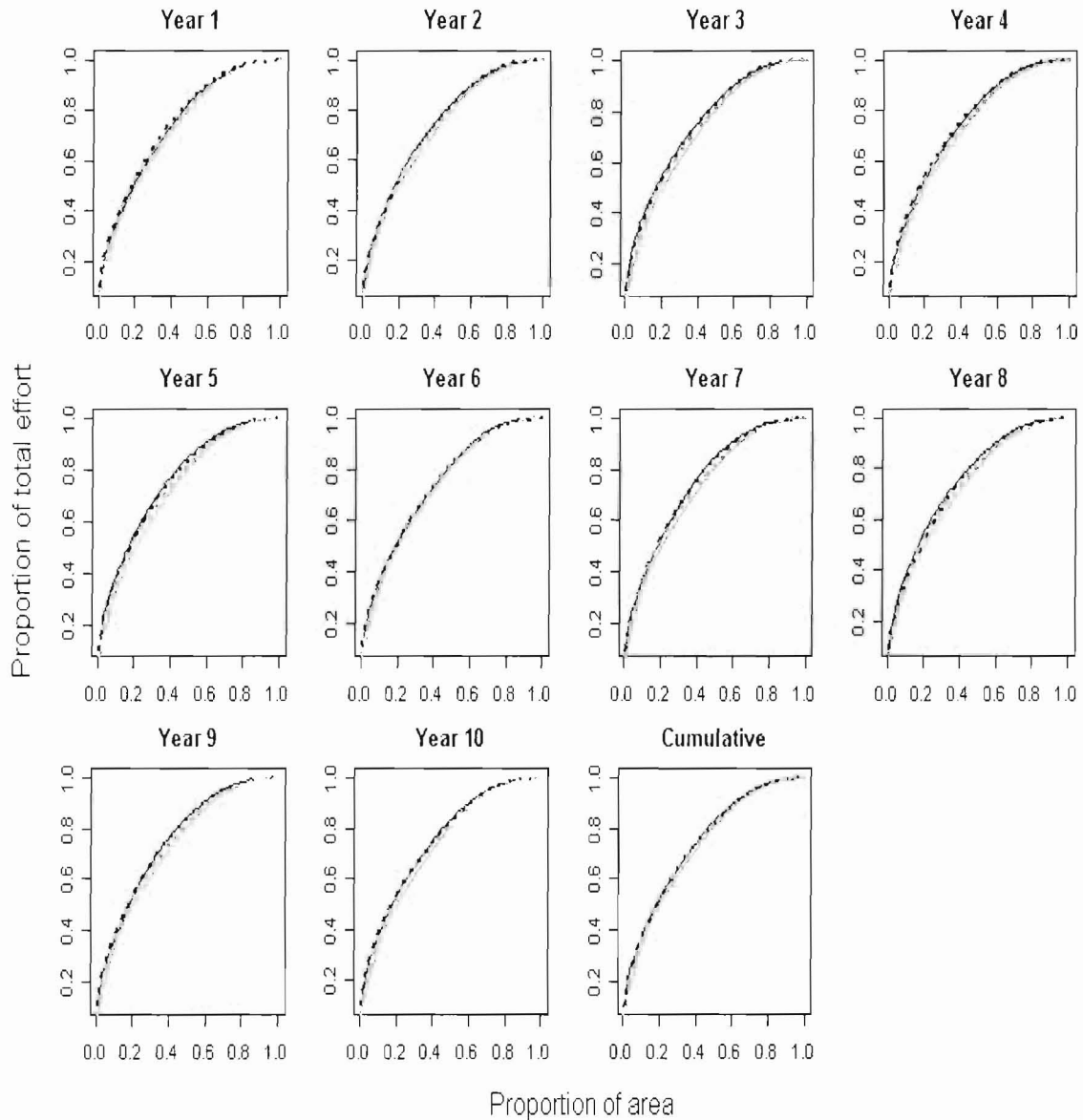


Fig 3.9 Lorenz curves for annual and 10 year cumulative effort from IFD (grey lines) and AB (black lines) models. The fish population is migratory for all scenarios; however rate of diffusive movement varies, 0.1 (dashed lines) or 1.0 (solid lines).

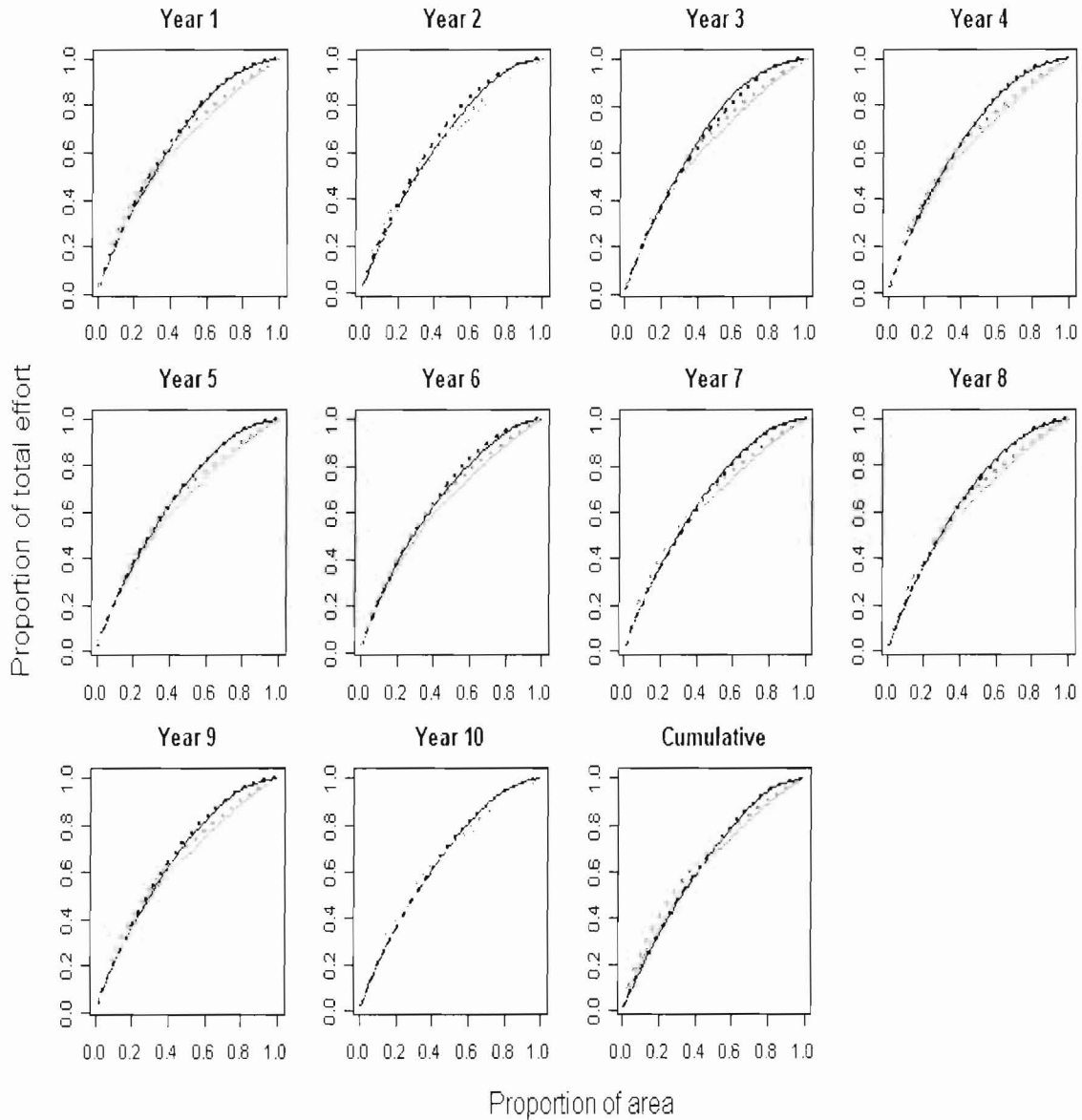


Fig 3.10 The spatial distribution of fishing effort from the AB model. Grey shading in cells is representative of the level of effort exerted in the cell, with white being the highest level of effort. The fish population is migratory and has a diffusion rate of 1.0.

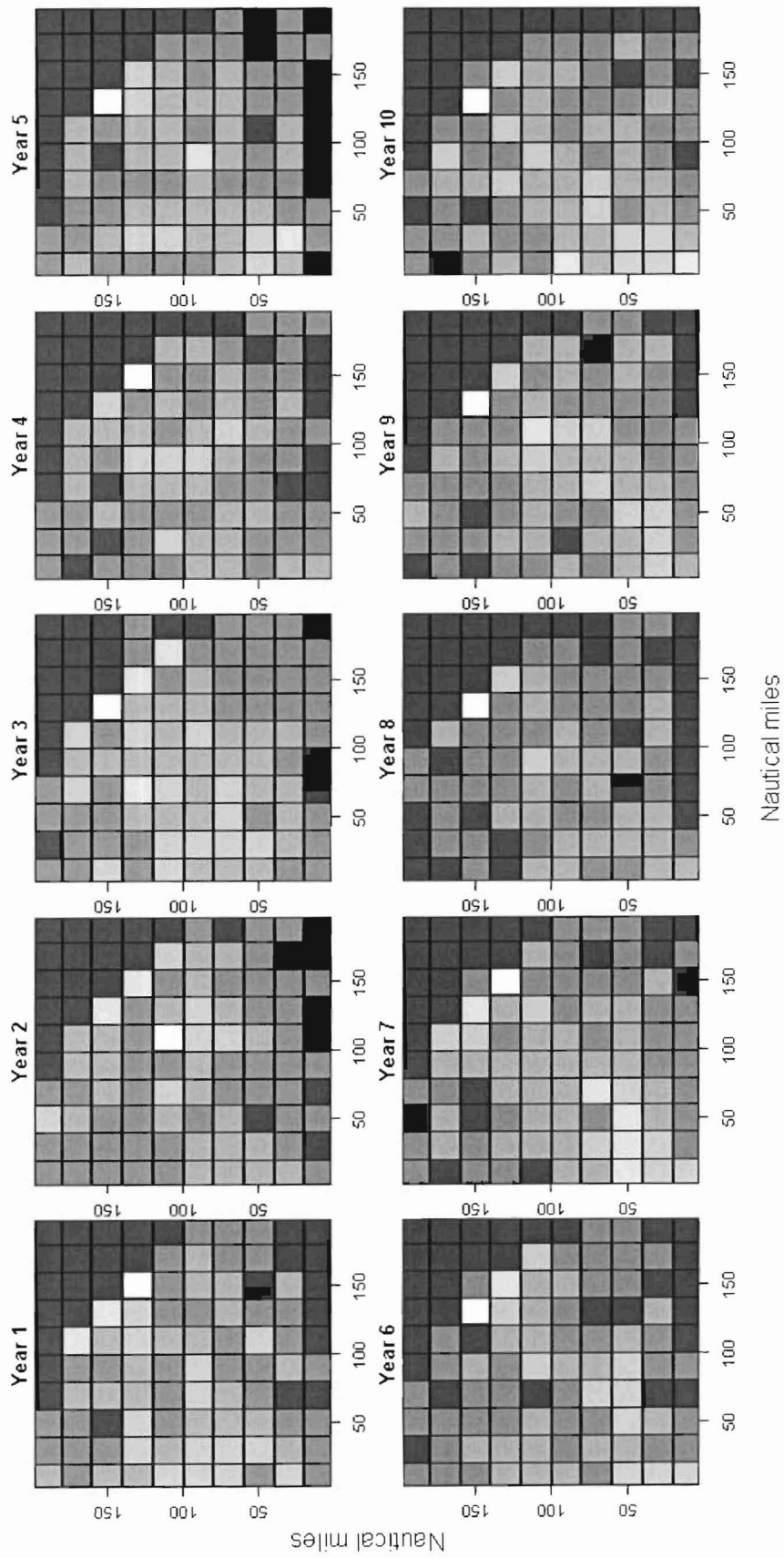


Fig 3.11 The spatial distribution of fishing effort from the IFD model. Grey shading in cells is representative of the level of effort exerted in the cell, with white being the highest level of effort. The fish population is migratory and has a diffusion rate of 1.0.

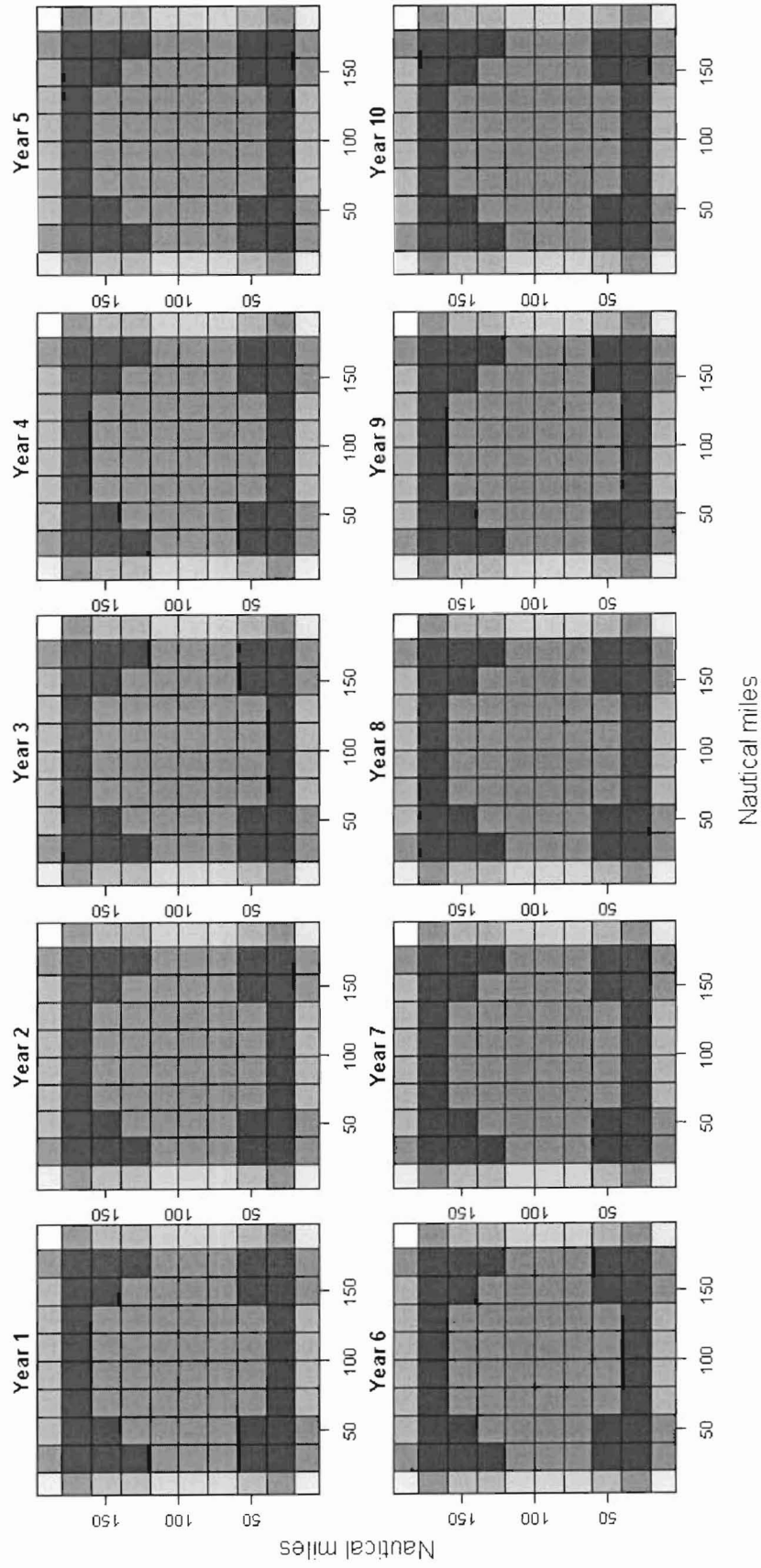


Fig 3.12 The spatial distribution of fishing effort from the AB model. Grey shading in cells is representative of the level of effort exerted in the cell, with white being the highest level of effort. The fish population is non-migratory and has a diffusion rate of 1.0.

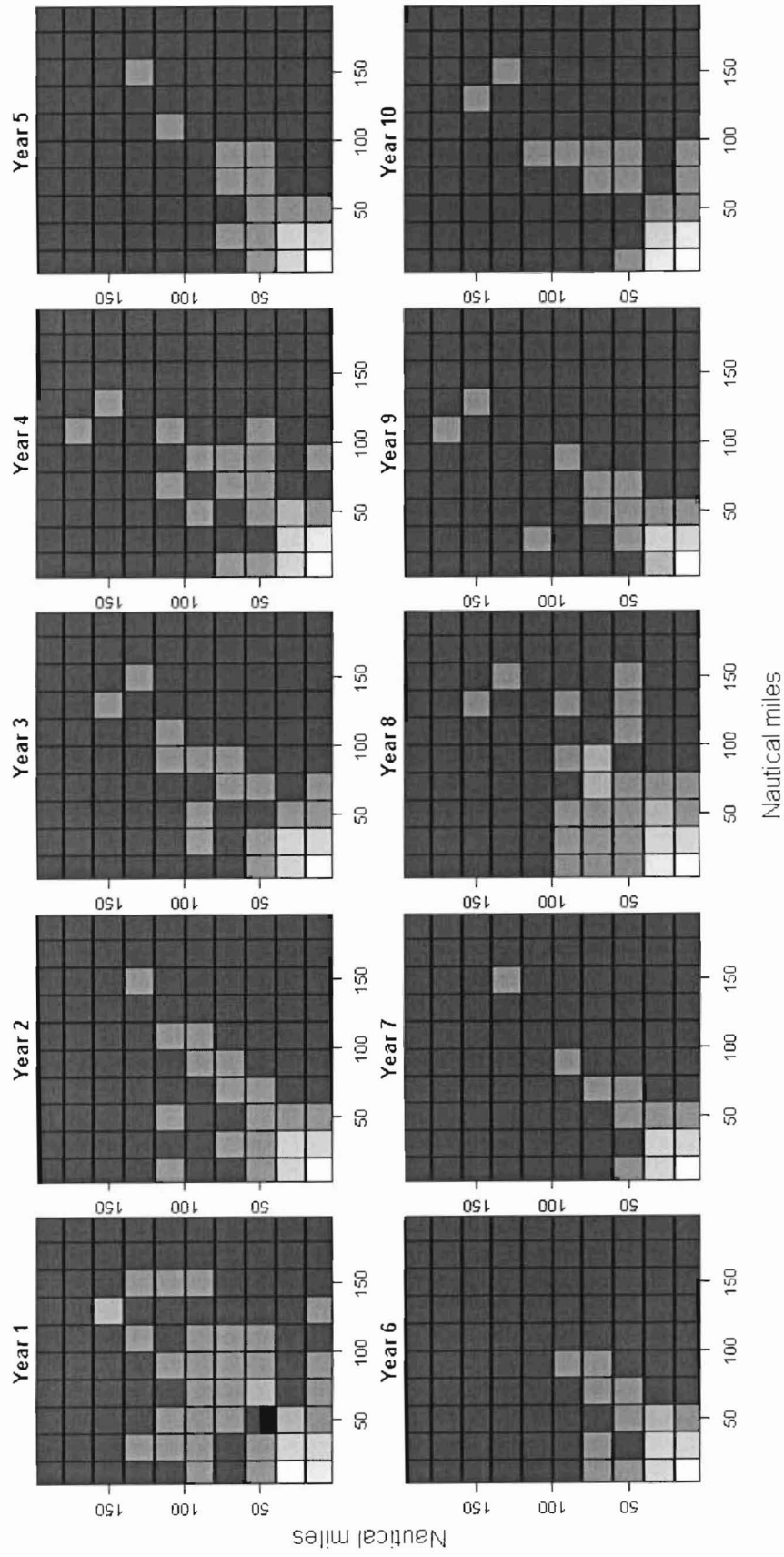


Fig 3.13 The spatial distribution of fishing effort from the IFD model. Grey shading in cells is representative of the level of effort exerted in the cell, with white being the highest level of effort. The fish population is non-migratory and has a diffusion rate of 1.0.

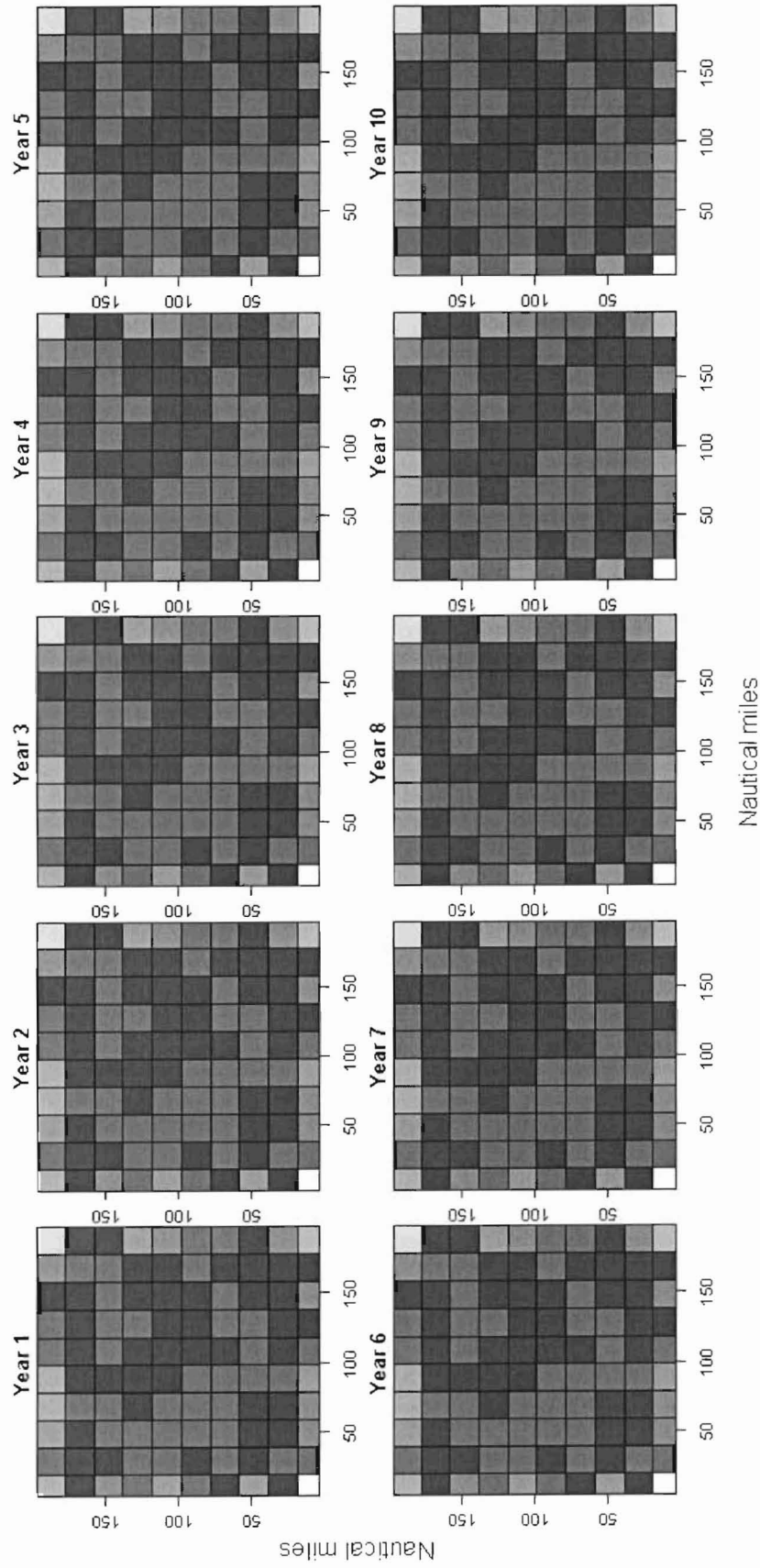


Fig 3.14 Residuals of the proportion of total effort predicted by IFD and AB models. Circle size indicates the magnitude of difference in the proportion of effort between IFD and AB fleets for a given fishing locations. Circle colour indicates which fleet model exerted more effort in a given cell; black indicate cells where the proportion of effort was greater for the AB model and grey indicate cells where the proportion of effort was greater in the IFD model. The fish population is migratory and has a diffusion rate of 0.1. The maximum value in each panel is scaled to the same symbol size in all panels.

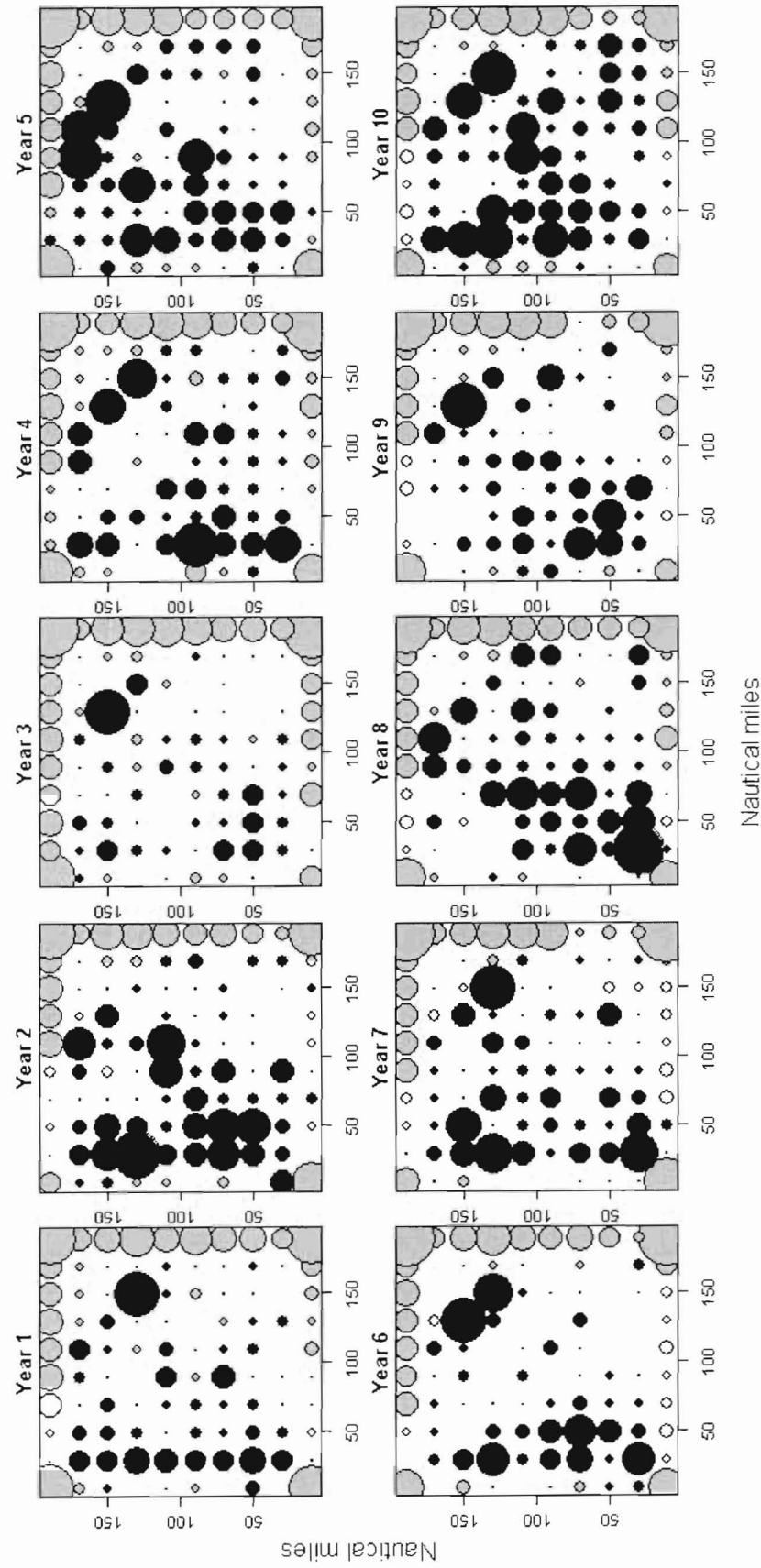


Fig 3.15 Residuals of the proportion of total effort predicted by IFD and AB models. Circle size indicates the magnitude of difference in the proportion of effort between IFD and AB fleets for a given fishing locations. Circle colour indicates which fleet model exerted more effort in a given cell; black indicate cells where the proportion of effort was greater for the AB model and grey indicate cells where the proportion of effort was greater in the IFD model. The fish population is migratory and has a diffusion rate of 1.0. The maximum value in each panel is scaled to the same symbol size in all panels.

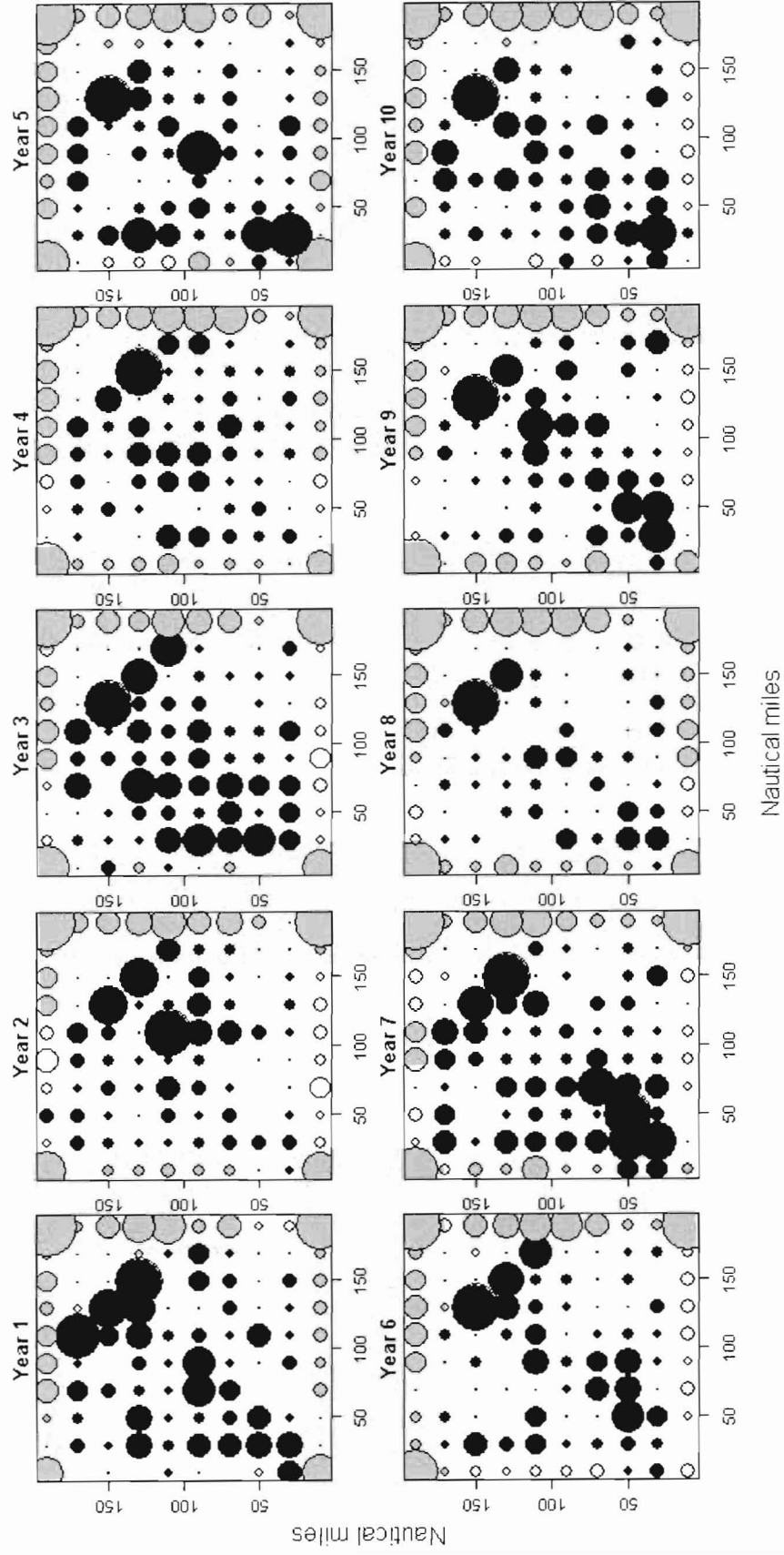


Fig 3.16 Residuals of the proportion of total effort predicted by IFD and AB models. Circle size indicates the magnitude of difference in the proportion of effort between IFD and AB fleets for a given fishing locations. Circle colour indicates which fleet model exerted more effort in a given cell; black indicate cells where the proportion of effort was greater for the AB model and grey indicate cells where the proportion of effort was greater in the IFD model. The fish population is non-migratory and has a diffusion rate of 1.0. The maximum value in each panel is scaled to the same symbol size in all panels.

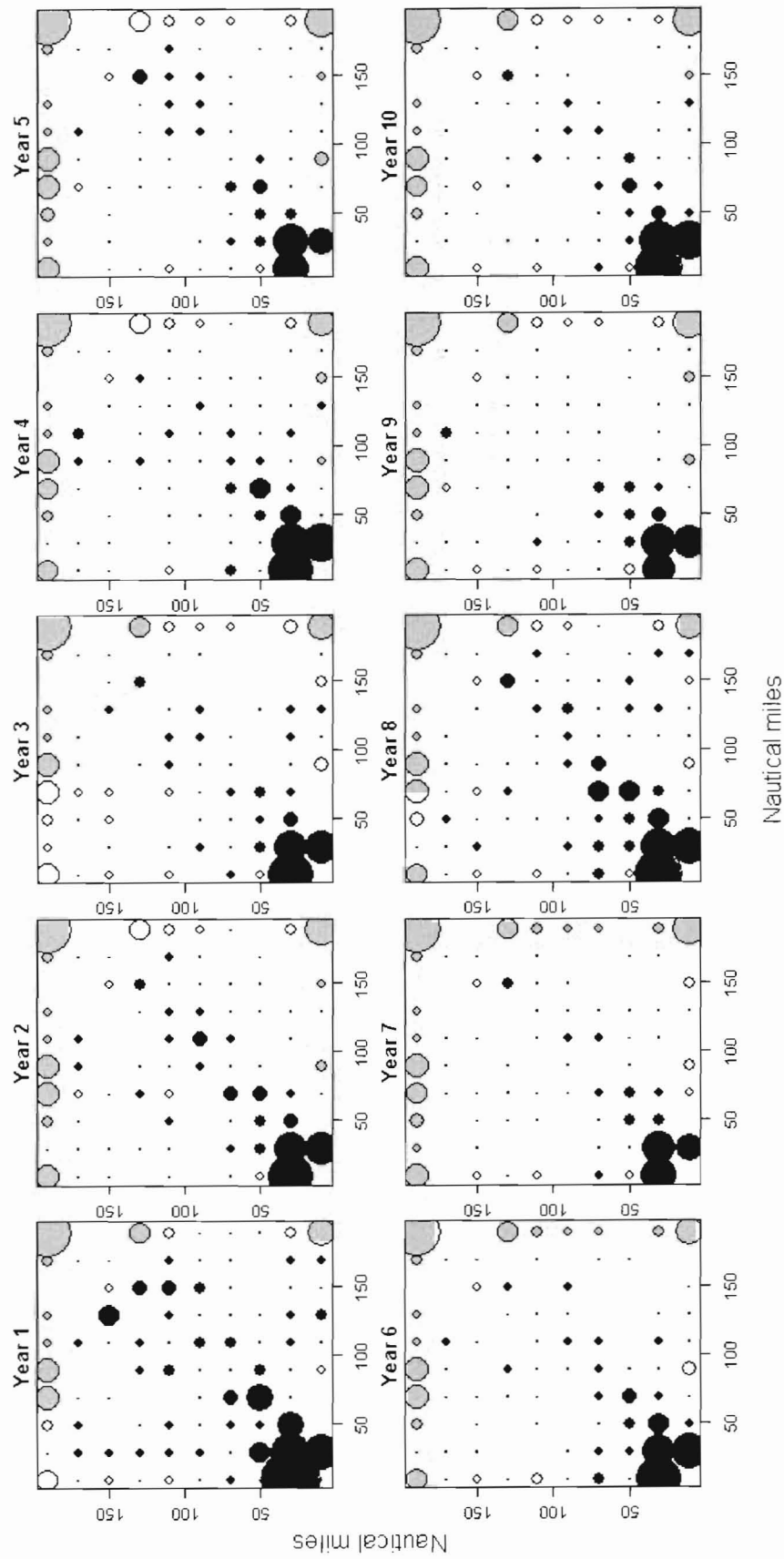


Fig 3.17 Residuals of the proportion of total effort predicted by IFD and AB models. Circle size indicates the magnitude of difference in the proportion of effort between IFD and AB fleets for a given fishing locations. Circle colour indicates which fleet model exerted more effort in a given cell; black indicate cells where the proportion of effort was greater for the AB model and grey indicate cells where the proportion of effort was greater in the IFD model. The fish population is non-migratory and has a diffusion rate of 0.1. The maximum value in each panel is scaled to the same symbol size in all panels.

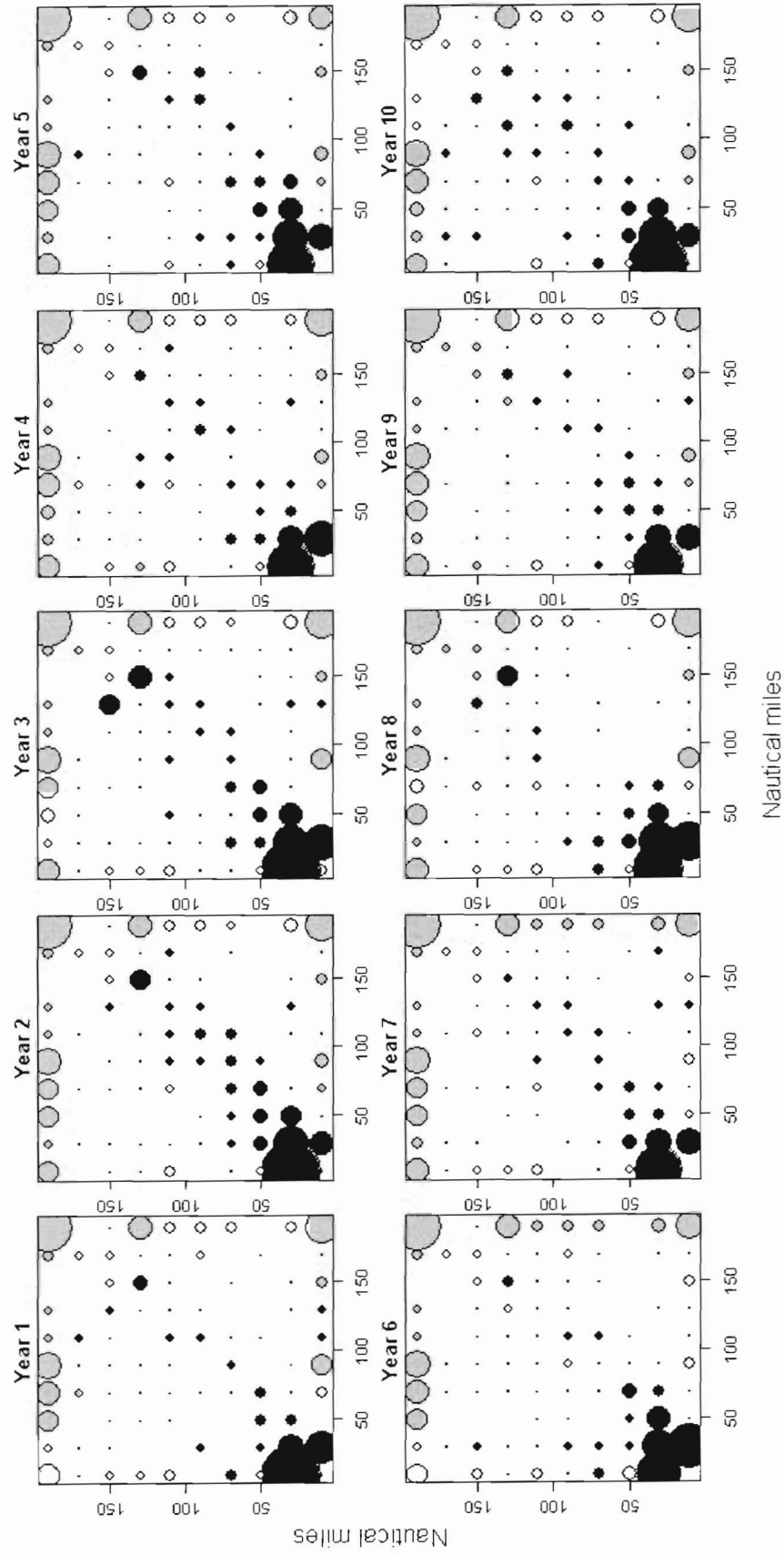
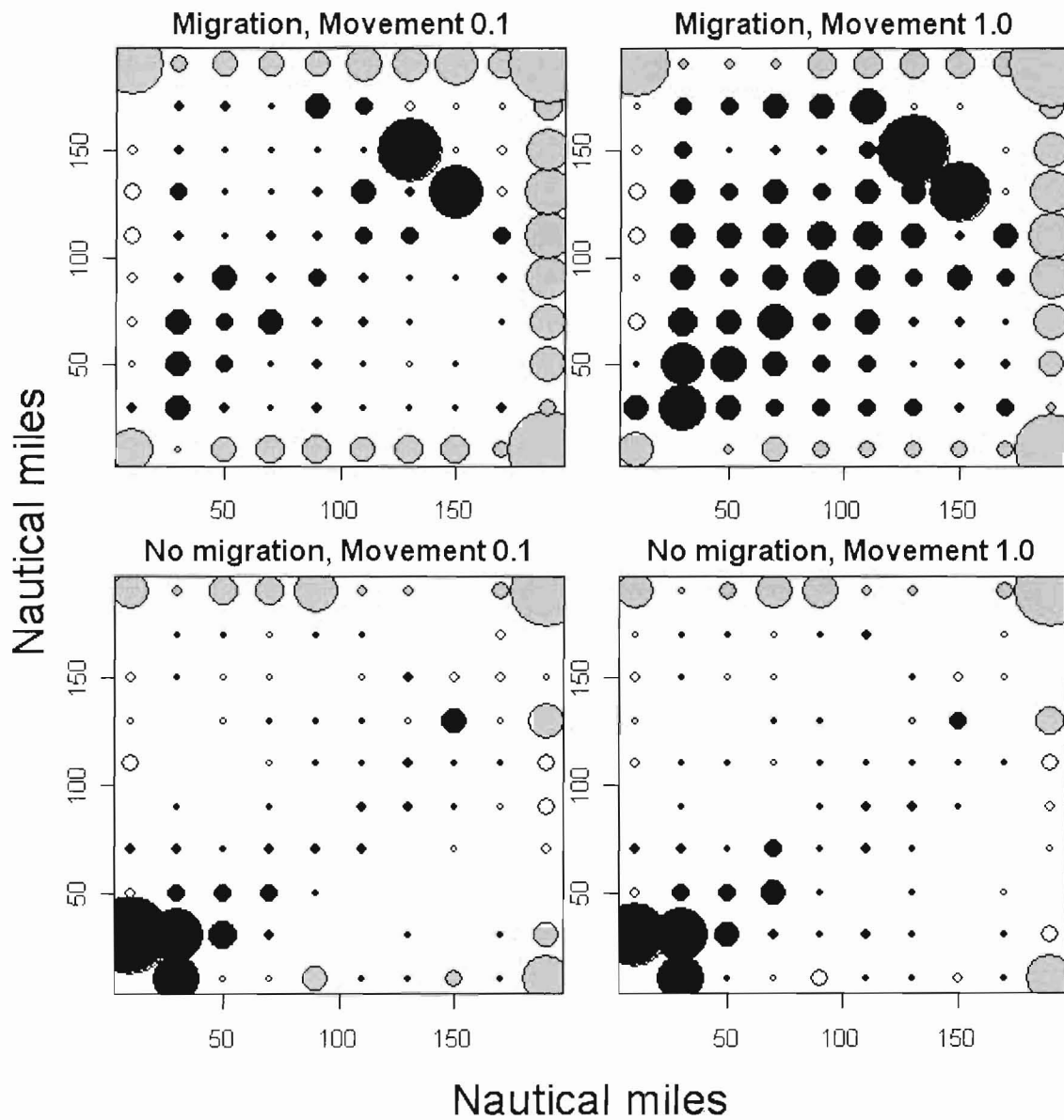


Fig 3.18 Residuals of the proportion of total cumulative effort predicted by IFD and AB models. Circle size indicates the magnitude of difference in the proportion of effort between IFD and AB fleets for a given fishing location. Circle colour indicates which fleet model exerted more effort in a given cell; black indicate cells where the proportion of effort was greater for the AB model and grey indicate cell where the proportion of effort was greater in the IFD model. The maximum value in each panel is scaled to the same symbol size in all panels.



Tables

Table 3.1 Parameter values used in hypothetical trawl fishery simulation

Parameter	Parameter value	Source
<i>A. Fish density dynamics</i>		
Time increment	1 day	-
Virgin biomass	10 ⁶ t	-
Baseline mean fish density	2500 kg km ⁻²	Mean density by 20 km blocks
Natural mortality rate	0.2	-
Diffusive movement rate	0.1, 1.0	Barton 2006; Holland 2000
Intrinsic rate of increase	0.6	Barton 2006
<i>B. IFD vessel state dynamics</i>		
Catchability coefficient	0.001	Barton 2006
Effort growth or decay (e_i)	± 0.01	Barton 2006
Nominal effort	1000 units	-
Level of effort that triggers interference competition	$\frac{N_j}{N_{total}} \cdot 100$ units	Gillis <i>et al.</i> 1993
<i>C. AB vessel state dynamics</i>		
Number of vessels	20	-
Net capacity	50t	Inoue and Matsuoka 2003
Bin capacity	30 to 120t	Transport Canada vessel registry
Per nautical mile cost of travelling	\$35	-
Per hour cost of searching	\$25	-
Per hour cost of setting and retrieving net	\$38	Ratio of travel cost to set cost as in Dorn 2001
Per hour cost of handling / processing	\$42	-
Annual fixed cost (e.g., labour, licences, insurance)	\$25,000	Hilborn and Walters 1992
Catch Threshold	10t	“Rule of thumb”
Number of time steps to transit to new area	1 (1.5h)	Based on average running speed of 13.3 knots

Table 3.2 Explanatory variables and coefficients for a fishery and location choice utility function.

Explanatory variable	Coefficient	Source*
Individual and choice specific variables		
Same area past 15 days	1.75	Based on Holland and Sutinen 1999
Same area past years	1.21	Based on Holland and Sutinen 1999
Steam Time / Expected Trip Length	-7.96	Based on Holland 2000
Coefficient of variation catch per day past 15 days	-0.45	Based on Holland and Sutinen 1999
Coefficient of variation catch per day past years	-0.34	Based on Holland and Sutinen 1999
Coefficient of variation profit per day past 15 days	-0.99	Based on Holland and Sutinen 1999
Coefficient of variation profit per day past years	-0.82	Based on Holland and Sutinen 1999
Total effort past 15 days	0.29	Based on Holland and Sutinen 1999
Total effort last year	0.06	Based on Holland and Sutinen 1999
Fleet average revenues per day past 10 days (\$1000's)	0.15	Based on Holland 2000

* Source refers to the study from which the coefficient value was adopted.

Table 3.3 Radomisation tests for a difference in the spatial distribution of fishing effort between the IFD model and the AB model under the various assumptions of fish movement rates (i.e., 1.0 or 0.1) and fish migration (i.e., migration or no migration) tested.

Year	Scenario							
	IFD _{mig0.1} vs. AB _{mig0.1}		IFD _{mig1.0} vs. AB _{mig1.0}		IFD _{nomig0.1} vs. AB _{nomig0.1}		IFD _{nomig1.0} vs. AB _{nomig1.0}	
	ψ	<i>P-value</i>	ψ	<i>P-value</i>	ψ	<i>P-value</i>	ψ	<i>P-value</i>
1	0.618	0.426	0.706	0.417	3.152	0.002	3.492	0.003
2	0.563	0.447	0.795	0.330	3.462	0.001	3.626	0.003
3	0.674	0.365	0.781	0.379	3.931	0.001	3.684	0.002
4	0.601	0.428	0.810	0.367	3.699	0.001	3.991	0.001
5	0.514	0.553	0.717	0.425	3.838	0.002	3.635	0.002
6	0.555	0.496	0.667	0.466	3.188	0.002	2.957	0.003
7	0.558	0.466	0.607	0.516	3.823	0.001	3.602	0.001
8	0.640	0.416	0.791	0.359	4.019	0.001	3.479	0.004
9	0.583	0.476	0.784	0.356	3.491	0.001	3.623	0.001
10	0.516	0.508	0.648	0.474	3.827	0.003	3.895	0.001
Cum.	0.569	0.453	0.717	0.388	3.634	0.002	3.584	0.001

Note: ψ is the test statistic and *P* is its significance based on 999 random permutations of the data under the null hypothesis of no difference in distribution.

APPENDICES

APPENDIX A: DETAILED DESCRIPTION OF AGENT BASED MODEL

Using Figure 3.3 as a guide the following paragraphs walks through the decisions and actions taken by a single vessel for one fishing trip. Notation in italics corresponds to elements in Figure 3.3. The same sequence of steps is followed for every trip and vessel.

The AB model operates on a daily time step (t), where decisions and subsequent actions are tracked hourly within the daily time step. At the start of each trip, a vessel is given an initial time budget of 24 hours for each day of the fishing trip. When the time available to a vessel on day t (TA_t) has been used through the performance of various actions, the AB model advances to the next time step $t+1$.

While in port, a vessel decides whether or not to leave on a fishing trip. There is a 0.8 probability that a vessel will choose to leave on a fishing trip. If they do not decide to leave port the model advances to the next time step. When a vessel decides to go fishing it becomes ($Active=1$) and its trip clock (TC_t) is set to 1 (i.e., first day of the fishing trip). Every time the model advances to the next time step the trip clock is advanced by one (e.g., $TC_{t+1}=TC_t+1$). When $TC_t = 1$, a vessel chooses a fishing location (L_{targ}) based on *vessel specific utility* scores for each cell (during the exploratory period vessels choose L_{targ} randomly). Before leaving port a vessel is also given a total trip length, which ranges between 5 and 7 days. Once L_{targ} is chosen, we know the number of days required to travel there (D_{targ}). To determine the number of hours needed to travel to L_{targ} , D_{targ} is multiplied by 24 hours (H_{targ}). If H_{targ} is greater than 24 hours the model advances to the

next time step. If H_{targ} is less than 24 hours (i.e., TA_t), a vessel arrives at its fishing location (L_{targ}) that same day.

Once at L_{targ} , a vessel drops its nets and fishes. A vessel's log book is then updated (log books used to calculate *vessel specific utility* scores), and the time passed fishing is subtracted from TA_t . If the *profit* made by fishing at L_{targ} is greater or equal to a vessel's *cost recovery threshold* it remains at L_{targ} and continues fishing. If the *profit* is less than the *cost recovery threshold* then it chooses a new L_{targ} based on utility scores and travels to its new location (travel time is subtracted from TA_t). On route to L_{targ} , a vessel passes through various cells and evaluates their utility to determine whether it would like to stop and fish. A vessel decides to stop in the current if the utility (U_{curr}) is at least equal to 80 percent of the previous target cell ($U_{curr} > 0.8 * U_{oldtarg}$), if not it continues to travel towards its new L_{targ} . As a vessel engages in decision making and fishing activities time is being tracked, such that when $TA_t \leq 0$ the model advances to the next time step.

A vessel continues to fish and/or search for new fishing locations until the number of days required to travel back to port (*Days Return*) is equal to the number of trip days remaining (*Trip Days Left*). When $Days Return = Trip Days Left$, a vessel returns to port and the model advances to the next time. A vessel cannot leave on a subsequent fishing trip until the day after he returns to port.

APPENDIX B: SENSITIVITY ANALYSIS OF AGENT BASED MODEL

Sensitivity analyses were performed on the coefficient values for opportunity cost (OC), historical habitat (HH) and recent habitat (RH). Distance from port, and consequently the trade off between time spent fishing and time spent travelling was examined because it was identified in previous studies as an important factor in determining location choice (Holland & Sutinen 2000; Hutton *et al.* 2004). Likewise, historical habit and recent habit were chosen because a fisherman's past personal experiences was identified as being of primary importance when choosing a fishing location (Holland & Sutinen 1999; Babcock & Pikitch 2000; Holland & Sutinen 2000; Hutton *et al.* 2004).

For the sensitivity analysis, simulations were run using alternative coefficient values that were found in the literature. In order to test the sensitivity to coefficient values that were both larger and smaller than the original values used, I tested values on either side of the original value whose differences from the original value were equal (e.g., $\beta_{original} \pm x$, where $x = \beta_{original} - \beta_{alternative}$) (Table A1). Across all years, the AB model was not found to be particularly sensitive to changes in the coefficient value for opportunity cost, historical habit, and recent habit (Tables A2 to A7). The model was most sensitive to RUM parameter changes in HH in scenario **nomig1.0**.

Tables

Table B1 Coefficient values used in sensitivity analysis of the utility function coefficient. Alternative coefficient values are tested in conjunction with the original set of coefficients defined in Table 2.2.

Explanatory variable	Original coefficient values	Alternative coefficient values in sensitivity analysis	
	$\beta_{original}$	$\beta_{alternative}$	
<i>Individual and choice specific variables</i>			
Same area past 15 days (RH)	1.75	1.11	2.39
Same area past years (HH)	1.21	0.91	1.51
Steam time/expected trip length (OC)	-7.96	-3.17	-12.75

Table B2 Sensitivity test for a difference in the spatial distribution of fishing effort between scenarios of the AB model under different assumptions of opportunity cost (OC = -7.96 vs. OC = -3.17 or OC = -7.96 vs. OC = -12.75) and fish migration. The lower the OC value the greater the opportunity cost. Rates of fish diffusive movement are held constant at 0.1.

		Scenario							
		mig0.1				nomig0.1			
		AB _{OC-7.96} vs. AB _{OC-3.17}		AB _{OC-7.96} vs. AB _{OC-12.75}		AB _{OC-7.96} vs. AB _{OC-3.17}		AB _{OC-7.96} vs. AB _{OC-12.75}	
Year		ψ	<i>P-value</i>	ψ	<i>P-value</i>	ψ	<i>P-value</i>	ψ	<i>P-value</i>
1		0.026	0.238	0.016	0.566	0.014	0.691	0.039	0.115
2		0.075	0.053	0.099	0.014	0.044	0.128	0.028	0.293
3		0.013	0.339	0.030	0.123	0.052	0.018	0.012	0.505
4		0.032	0.151	0.025	0.151	0.120	0.003	0.012	0.463
5		0.024	0.291	0.058	0.009	0.025	0.185	0.062	0.059
6		0.023	0.175	0.010	0.725	0.020	0.321	0.019	0.382
7		0.010	0.873	0.040	0.130	0.010	0.937	0.007	0.914
8		0.033	0.037	0.025	0.190	0.072	0.028	0.011	0.718
9		0.012	0.724	0.013	0.518	0.045	0.063	0.013	0.805
10		0.100	0.007	0.087	0.007	0.120	0.002	0.059	0.058

Note: ψ is the test statistic and *P* is its significance based on 999 random permutations of the data under the null hypothesis of no difference in distribution.

Table B3 Sensitivity test for a difference in the spatial distribution of fishing effort between scenarios of the AB model under different assumptions of opportunity cost (OC = -7.96 vs. OC = -3.17 or OC = -7.96 vs. OC = -12.75) and fish migration. The lower the OC value the greater the opportunity cost. Rates of fish diffusive movement are held constant at 1.0.

		Scenario							
		mig1.0				nomig1.0			
		AB _{OC-7.96} vs. AB _{OC-3.17}		AB _{OC-7.96} vs. AB _{OC-12.75}		AB _{OC-7.96} vs. AB _{OC-3.17}		AB _{OC-7.96} vs. AB _{OC-12.75}	
Year		ψ	<i>P-value</i>	ψ	<i>P-value</i>	ψ	<i>P-value</i>	ψ	<i>P-value</i>
1		0.067	0.115	0.005	0.969	0.045	0.057	0.046	0.023
2		0.022	0.183	0.057	0.018	0.012	0.693	0.032	0.266
3		0.031	0.339	0.015	0.576	0.117	0.001	0.073	0.045
4		0.021	0.423	0.003	0.991	0.016	0.330	0.009	0.774
5		0.011	0.806	0.034	0.164	0.009	0.905	0.023	0.544
6		0.057	0.044	0.013	0.604	0.014	0.518	0.018	0.495
7		0.020	0.505	0.043	0.094	0.024	0.511	0.012	0.423
8		0.014	0.582	0.031	0.183	0.074	0.010	0.053	0.011
9		0.023	0.149	0.013	0.647	0.042	0.102	0.089	0.009
10		0.066	0.042	0.022	0.361	0.062	0.036	0.080	0.047

Note: ψ is the test statistic and *P* is its significance based on 999 random permutations of the data under the null hypothesis of no difference in distribution.

Table B4 Sensitivity test for a difference in the spatial distribution of fishing effort between scenarios of the AB model under different assumptions of historical habitat (HH = 1.21 vs. HH = 0.91 or HH =1.21 vs. HH = 1.51) and fish migration. Rates of fish diffusive movement are held constant at 0.1.

		Scenario							
		mig0.1				nomig0.1			
		AB _{HH1.21} vs. AB _{HH0.91}		AB _{HH1.21} vs. AB _{HH0.51}		AB _{HH1.21} vs. AB _{HH0.91}		AB _{HH1.21} vs. AB _{HH0.51}	
Year		ψ	<i>P-value</i>	ψ	<i>P-value</i>	ψ	<i>P-value</i>	ψ	<i>P-value</i>
1		0.013	0.699	0.034	0.119	0.018	0.698	0.022	0.374
2		0.049	0.080	0.022	0.172	0.022	0.149	0.016	0.468
3		0.021	0.380	0.028	0.087	0.021	0.210	0.024	0.254
4		0.019	0.415	0.018	0.299	0.038	0.053	0.050	0.031
5		0.107	0.005	0.056	0.068	0.139	0.002	0.021	0.227
6		0.016	0.330	0.016	0.614	0.051	0.075	0.013	0.554
7		0.036	0.152	0.020	0.532	0.015	0.805	0.031	0.432
8		0.094	0.004	0.036	0.095	0.086	0.012	0.158	0.647
9		0.017	0.388	0.022	0.410	0.018	0.311	0.030	0.185
10		0.031	0.129	0.086	0.007	0.167	0.006	0.094	0.004

Note: ψ is the test statistic and *P* is its significance based on 999 random permutations of the data under the null hypothesis of no difference in distribution.

Table B5 Sensitivity test for a difference in the spatial distribution of fishing effort between scenarios of the AB model under different assumptions of historical habitat (HH = 1.21 vs. HH = 0.91 or HH = 1.21 vs. HH = 1.51) and fish migration. Rates of fish diffusive movement are held constant at 1.0.

		Scenario							
		mig1.0				nomig1.0			
		AB _{HH1.21} vs. AB _{HH0.91}		AB _{HH1.21} vs. AB _{HH0.51}		AB _{HH1.21} vs. AB _{HH0.91}		AB _{HH1.21} vs. AB _{HH0.51}	
Year		ψ	<i>P-value</i>	ψ	<i>P-value</i>	ψ	<i>P-value</i>	ψ	<i>P-value</i>
1		0.083	0.449	0.006	0.918	0.082	0.014	0.014	0.508
2		0.024	0.009	0.068	0.014	0.051	0.038	0.010	0.913
3		0.039	0.067	0.026	0.061	0.125	0.002	0.054	0.069
4		0.013	0.578	0.014	0.514	0.016	0.512	0.016	0.514
5		0.076	0.054	0.075	0.049	0.037	0.002	0.061	0.047
6		0.015	0.511	0.043	0.051	0.038	0.023	0.032	0.224
7		0.012	0.597	0.050	0.069	0.069	0.008	0.022	0.328
8		0.012	0.526	0.026	0.069	0.006	0.944	0.015	0.580
9		0.016	0.206	0.009	0.709	0.033	0.303	0.099	0.013
10		0.017	0.242	0.058	0.205	0.026	0.477	0.010	0.905

Note: ψ is the test statistic and *P* is its significance based on 999 random permutations of the data under the null hypothesis of no difference in distribution.

Table B6 Sensitivity test for a difference in the spatial distribution of fishing effort between scenarios of the AB model under different assumptions of historical habitat (RH = 1.75 vs. RH = 2.39 or RH =1.75 vs. RH = 1.11) and fish migration. Rates of fish diffusive movement are held constant at 0.1.

		Scenario							
		mig0.1				nomig0.1			
		AB _{RH1.75} vs. AB _{RH1.11}		AB _{RH1.75} vs. AB _{RH2.39}		AB _{RH1.75} vs. AB _{RH1.11}		AB _{RH1.75} vs. AB _{RH2.39}	
Year		ψ	<i>P-value</i>	ψ	<i>P-value</i>	ψ	<i>P-value</i>	ψ	<i>P-value</i>
1		0.015	0.557	0.024	0.255	0.041	0.135	0.053	0.066
2		0.051	0.123	0.068	0.107	0.019	0.690	0.027	0.250
3		0.019	0.311	0.008	0.795	0.026	0.173	0.046	0.042
4		0.009	0.854	0.008	0.860	0.047	0.073	0.034	0.268
5		0.034	0.157	0.040	0.162	0.023	0.251	0.069	0.014
6		0.026	0.245	0.018	0.683	0.022	0.545	0.055	0.151
7		0.010	0.690	0.006	0.983	0.010	0.811	0.037	0.496
8		0.016	0.353	0.117	0.001	0.053	0.029	0.097	0.004
9		0.033	0.352	0.013	0.420	0.037	0.054	0.012	0.784
10		0.065	0.119	0.013	0.510	0.219	0.668	0.104	0.009

Note: ψ is the test statistic and *P* is its significance based on 999 random permutations of the data under the null hypothesis of no difference in distribution.

Table B7 Sensitivity test for a difference in the spatial distribution of fishing effort between scenarios of the AB model under different assumptions of historical habitat (RH = 1.75 vs. RH = 2.39 or RH =1.75 vs. RH = 1.11) and fish migration. Rates of fish diffusive movement are held constant at 1.0.

		Scenario							
		mig1.0				nomig1.0			
		AB _{RH1.75} vs. AB _{RH1.11}		AB _{RH1.75} vs. AB _{RH2.39}		AB _{RH1.75} vs. AB _{RH1.11}		AB _{RH1.75} vs. AB _{RH2.39}	
Year		ψ	<i>P-value</i>	ψ	<i>P-value</i>	ψ	<i>P-value</i>	ψ	<i>P-value</i>
1		0.021	0.463	0.045	0.361	0.057	0.033	0.033	0.133
2		0.008	0.837	0.016	0.541	0.040	0.172	0.013	0.659
3		0.033	0.215	0.058	0.051	0.050	0.106	0.051	0.119
4		0.019	0.284	0.012	0.527	0.009	0.839	0.019	0.338
5		0.042	0.176	0.026	0.321	0.013	0.747	0.016	0.726
6		0.026	0.231	0.012	0.545	0.024	0.385	0.013	0.863
7		0.059	0.144	0.103	0.063	0.017	0.379	0.014	0.713
8		0.042	0.052	0.039	0.172	0.081	0.005	0.018	0.337
9		0.012	0.462	0.026	0.367	0.106	0.017	0.068	0.023
10		0.010	0.436	0.020	0.233	0.009	0.934	0.017	0.451

Note: ψ is the test statistic and *P* is its significance based on 999 random permutations of the data under the null hypothesis of no difference in distribution.

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