Development of an agent-based model to communicate implications of recruitment variability of finfish to recreational fishers

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OBJECTIVES

1. Provide a simulation tool to communicate to fishers the implications of recruitment variability for a fish stock and for the catches of individual recreational fishers.
2. Explore how individual recreational fishers are likely to respond to changes in fish abundance and to changes in commonly-used fisheries regulations.
3. Develop the computer simulation and modelling skills of an early-career fisheries scientist.

NON TECHNICAL SUMMARY

OUTCOMES ACHIEVED TO DATE

A simulation tool (computer model) has been developed that can be used to communicate to fishers and fisheries researchers and managers the implications of recruitment variability of finfish species for their stocks and associated recreational catches. This tool will enable recreational anglers to become aware of the importance of understanding how recruitment variability can influence the sustainability of fish stocks and their catches. The results of preliminary simulations undertaken using the new model predicted how individual fishers are likely to respond to changes in fish abundance and certain common fisheries regulations. A meeting was held with a group of experienced recreational fishers during which they actively participated in the project by filling out a detailed survey. That survey yielded valuable data on how recreational fishers target key demersal finfish species in south-western Australia. The project has greatly enhanced the computer simulation and modelling skills of A. Hesp (through mentoring by N. Hall), and introduced an Honours student, a PhD student and another early-career researcher to fisheries modelling techniques. The model will continue to be developed beyond this FRDC project, which will lead to the production of a sophisticated tool for researchers, managers and industry stakeholders, and enhance the training of early-career researchers. The project investigators have received very positive feedback from representatives of WAFIC, RecFishWest, DoF WA, and recreational fishers.

This study produced a visual computer-modeling tool (called an “agent-based model”) which simulates the behaviour of and interactions between recreational fishers and reef-dwelling demersal finfish, *i.e.*, fish such as West Australian Dhufish that live close to the bottom of the water column. The model simulates the effects of different levels of recruitment variability on finfish stocks and thereby facilitates the implications of this variability for the sustainability of fish stocks and the catches of recreational fishers to be assessed. It also enables the ways in which individual fishers are likely to respond to changes in fish abundance and commonly-used fisheries regulations to be explored.

Unlike more traditional modeling approaches, agent-based models (or individual-based models) focus on the lowest level entities in a system and thus constitute a "bottom up" rather than "top down" approach to modeling. In this study, the system represented by the model is a recreational fishery for demersal finfish species located in coastal waters of the Perth metropolitan region. The lowest level entities of this system (*i.e.* the agents) are individual, recreational fishers and the individual fish they target. An advantage of agent-based models over traditional models is that, by focusing on individual agents, they can often capture important details about interactions that take place between agents and these can have important impacts on the modeled system.

The information required to produce and run the computer model was obtained from available scientific literature on the biology of the fish species of interest (West Australian Dhufish and Snapper), and from the results of a detailed survey of experienced recreational fishers who regularly catch these fish species. The survey yielded valuable information on the ways in which recreational fishers target Dhufish and Snapper, and on the habitats in which these fish species are most likely to occur.

A series of preliminary simulations have been undertaken to explore the utility of the model for assessing the implications of recruitment variability in finfish, and to predict the likely responses of recreational fishers to changes in fish abundance and management measures. The simulations demonstrated that, by influencing, at any given time, the relative abundances of fish of different sizes and ages in a population, recruitment variability can affect catches and also the fish-targeting behaviours of recreational fishers. Similarly, reducing the overall abundance of a fish species led to reductions in catches and to fishers fishing longer and searching for new fishing locations more often. The simulations showed that reducing the boat limit or increasing the minimum legal length for retention (MLL) for a species is likely to reduce the numbers of that fish species caught and retained and to increase greatly the numbers of individuals caught and released.

The study revealed the excellent potential of the agent-based model developed in this study as an exploratory tool for understanding and communicating the implications of recruitment variability in finfish, fish abundance, and different management strategies for recreational line fisheries for demersal fish species. The study has demonstrated that the model can provide meaningful predictions as to how fishers in a multi-species fishery respond to certain management changes. Over the next two years, the model will continue to be developed and its data inputs improved to provide a useful simulation tool for communicating the implications of recruitment variability in fishfish to fishers. Such improvements will include the incorporation of additional factors, such weather and its influence on the fish targeting behaviours of fishers, and water depth and its effect on the abundance of different fish species. The agent-based model provides a platform for further research aimed at assessing the management implications of differences in behaviors among individual recreational fishers. Ongoing interactions between the project investigators and their students with fishers, fisheries researchers and industry stakeholders has proved essential for the success of the project, and have laid the foundation for continuing to increase awareness among the recreational fishing community of important fisheries-related issues. Training of early-career researchers will continue as the agent-based modeling research is progressed further.

KEYWORDS: Recreational fishers, agent-based model, recruitment variability, demersal finfish

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We wish to express our gratitude to the recreational fishers who gave up their time to attend our recreational fisher survey evening at RecFishWest and share their valuable knowledge, which was crucial for the success for the project. We thank RecFishWest, and particularly Kane Moyle, for his assistance in helping to organise the survey, and Kane, Richard Stevens and Felicity Horn (WAFIC), and Brent Wise and Brett Molony (DoF) for their feedback during the study. We thank Corey Wakefield (DoF) for providing unpublished data to estimate the size-selectivity of Snapper. We are also very appreciative of the excellent advice provided by Steve Sutton (JCU) and Eric von Dietze (Murdoch University) on survey design and process.

BACKGROUND

Agent-based models (ABMs), sometimes referred to as individual-based models (IBMs) (Grimm and Railsback, 2005), have proliferated in the literature in the last thirty years. These models have been used in a variety of disciplines including economics, social sciences, ecology and fisheries science, providing an alternative to traditional modelling approaches such as those based on differential equations (Van Dyke Parunak *et al.*, 1998). They enable investigations of the emergence of system-level properties as a result of behaviours and interactions of “agents” (or individuals) with each other and their environment (Lomnicki, 1992; Grimm, 1999; Breckling *et al.*, 2006).

Before discussing the relevance of ABMs to fisheries science and then more specifically their potential use in communicating implications of recruitment variability of finfish to recreational fishers, it is necessary first to define the terms “agent” and “agent-based model” and describe some of the key characteristics of agent-based models.

WHAT ARE AGENTS AND AGENT-BASED MODELS?

Definition of an agent

Several definitions of agents are available in the literature. Jennings *et al*. (1998) define agents as computer systems situated in an environment, capable of flexible and autonomous actions to meet their design objective. O’Sullivan (2008) emphasised that agents are computer code representations of “real-world” actors, whether the actors are individuals or collective social actors. Grimm *et al*. (2005) described agents as autonomous and adaptive entities whose interactions make up complex systems. In ecology, where agents are usually representative of individuals in a particular population, definitions of agents emphasise variability between all individuals as a key characteristic (Grimm *et al.*, 1999; DeAngelis and Mooij, 2005; Breckling *et al.*, 2006). From the above, agents are considered to be *computer simulations of unique actors, which are capable of autonomous and adaptive actions*. Examples of agents that have been modelled range widely, from drug users and police in a suburban environment (Dray *et al.*, 2008), to firms offering vacancies to potential employees (Neugart, 2008; Martin and Neugart, 2009), to recruitment of spiny lobsters in the Florida Keys (Butler *et al.*, 2005).

Definition of an agent-based model

As is the case with agents, several definitions are available in the literature for agent-based models. O'Sullivan (2008) defined an ABM as a simulation of real-world scenarios involving the agents of interest. Similarly, Grimm (1999) describes the models as simulations that treat individuals as unique and discrete entities. In ecology, where agent-based models are referred to as individual-based models (IBMs), they have been defined as models of populations made up of unique individuals that take into consideration the complexity of an individual's life cycle and resource use (Uchmański and Grimm, 1996). Central to the above definitions is the notion of simulation. The purposes of simulation include prediction, performing tasks, education and training, entertainment, proof and discovery (Axelrod, 1997). It thus follows that agent-based models may potentially be used for a variety of purposes. In fisheries science, these could include, for example, an investigation by researchers of the emergence of certain dynamics within a simulated fishery as a result of the behaviours of fishers and fish in the environment and under a particular set of management arrangements. Alternatively, agent-based models could be used as a visual communication tool for managers and fishing industry stakeholders, perhaps to illustrate the need for certain management changes. Additionally, they could potentially be adopted as an educational tool for fisheries science students, for example, to demonstrate the importance of certain socio-economic factors.

CHARACTERISTICS OF AGENT-BASED MODELS

Differences between agent-based and traditional modelling approaches

ABMs are fundamentally different from traditional modelling approaches. Traditional modelling refers to state-variable models (Huston *et al.*, 1988), differential and difference equations (Van Dyke Parunak *et al.*, 1998; DeAngelis and Mooij, 2005; Breckling *et al.*, 2006), and classical mathematical models such as the logistic model of population growth (Uchmański and Grimm, 1996). Traditional modelling is typically “top-down” in that it starts from an upper level in a system, and describes the (mean) dynamics of a pool of individuals, such as a population (Grimm, 1999). In contrast, agent-based modelling involves computer simulation to generate multiple agents that interact with each other and the environment (Railsback, 2001). Thus, agent-based modelling represents a “bottom-up” approach to modelling because its focuses on the properties of the lowest level entities in the system (Grimm, 1999).

One of the main advantages of traditional models is that they offer generality in that one model can often be applied to numerous systems with little or no modification (Murdoch *et al.*, 1992; Grimm, 1999). However, by aggregating and averaging critical system variables over space and time, traditional models ignore variation among entities at the base of the system (Van Dyke Parunak *et al.*, 1998), and they therefore often miss details that can have important effects on the modelled system (Uchmański and Grimm, 1996). This, in turn, can affect the testability of traditional models as they do not refer to the individual agents comprising a system (Grimm, 1999). In contrast, ABMs are usually highly testable because they refer directly to the agents that comprise the system (Grimm, 1999). However, this testability comes at the cost of generality (Murdoch *et al.*, 1992) and, unlike traditional models, it is often difficult to adapt an ABM to systems and scenarios other than those for which the model was originally designed (Grimm, 1999).

Characteristics of agent-based modelling

There are several characteristics that distinguish ABMs from other modelling approaches. In this regard, Grimm and Railsback (2005) provide a set of characteristics for what they refer to as “individual-based ecology” – the field of ecology concerned with the use of IBMs (or ABMs). Although specific to ecological applications, these characteristics can be used to illustrate the key attributes of ABMs in general.

(i). Systems are understood and modelled as collections of unique agents

The purpose of an ABM is to understand system properties and the impacts of agent behaviour on the emergence of such properties (Lomnicki, 1992; O'Sullivan, 2008). Agents do not exist in isolation, but interact with other agents of the same and different types and their environment (Bosquet and Le Page, 2004). Hence, to properly model a system using agent representations of the system’s actors, it is crucial that the system is modelled as a collection of unique agents (Breckling *et al.*, 2006).

(ii). ABMs are framed by complexity concepts rather than differential calculus

Unlike traditional modelling approaches, ABMs are not formed from differential equations, but from concepts derived from complexity science, *i.e.* the science of complex, adaptive systems (Railsback, 2001). These concepts include emergence and adaptability (Railsback, 2001; Grimm and Railsback, 2005). Emergence refers to the way in which system level properties arise from the characteristics of the system's component parts, namely the agents and the environment (Railsback, 2001). Adaptability refers to the way in which agents in a model increase their own "fitness", through "making decisions" by means of procedural rules in the model (Grimm and Railsback, 2005).

(iii). Models are implemented and solved using computer simulation

As described above, a key element of agent-based models is that they involve simulation. Important properties of simulation are that the agents in the system must be separately accessible and have at least one property that distinguishes them from each other. For this reason, agent-based modelling lends itself well to object-based programming.

(iv). Field and laboratory studies are crucial to developing an ABM

As the purpose of an ABM is to explore some aspect of a real world scenario, it is crucial that the researchers have some knowledge of the agents and system they are modelling. In this regard, field or laboratory studies can be useful in constructing models of agent behaviour, and organising and testing the model (DeAngelis *et al*., 1980; Grimm and Railsback, 2005; Benenson *et al*., 2008).

APPLICATIONS OF AGENT-BASED MODELS IN FISHERIES SCIENCE AND MANAGEMENT

Two key areas in which ABMs have been applied in fisheries science include studies of factors influencing recruitment and of the dynamics of commercial fishing fleets.

Understanding the factors that influence annual recruitment to a fishery has long been a concern of fisheries scientists and managers (Rothschild, 2000). The use of agent-based modelling to investigate recruitment includes, for example, the ABM of Rose and Cowan (1993) and Cowan *et al*. (1993) to investigate factors affecting recruitment in young-of-the-year striped bass in the Potomac River, Maryland, that of Butler *et al*. (2005) to explore how nursery habitat degradation influences recruitment of Caribbean spiny lobster (*Panulirus argus*) in the Florida Keys, and that of Griffin *et al*. (2001) which simulated the transport and movement of western rock lobster (*Panulirus cygnus)* larvae.

The behaviour of fishers is another key area of fisheries science where ABMs have found favour (Dreyfus-León, 1999). As ABMs rely on the interactions between autonomous agents within their environment, the models lend themselves to analysing how fishers behave. Dreyfus-León (1999) and Dreyfus-León and Kleiber (2001), for example, used neural networks to model the decision-making processes and search behaviours of fishers. Little *et al.* (2004) simulated fisher behaviour using Bayesian networks. To our knowledge, agent-based models have thus far been used to model the behaviours of fishers, only in commercial fisheries, with the exception of an ABM for a recreational fishery in Ontario, as briefly described by Hunt *et al.* (2006).

With fisheries managers becoming increasingly aware of the growing impacts of recreational fishing (*e.g.* McPhee *et al.*, 2002; Cooke and Cowx, 2004; Granek *et al.*, 2008), the modelling of the behaviours of recreational fishers represents an area where future research is needed. As shown above, agent-based modelling approaches are ideally suited to exploring the implications of recruitment processes for fisheries and of the behaviours of recreational fishers for the sustainability of recreational fish stocks.

IMPLICATIONS OF RECRUITMENT VARIABILITY FOR FISHERS AND MANAGEMENT

Variability in annual recruitment is a life history characteristic of many fish species (Longhurst, 2002; Berkeley *et al.*, 2004; Hsieh *et al.*, 2006). Highly variable or episodic recruitment is a common trait of many long-lived fishes such as *Sebastes* species (rockfishes) (Leaman and Beamish, 1984), Orange Roughy (*Hoplostethus atlanticus*) (Francis, 1992; Koslow *et al.*, 2000), Western Blue Groper *Acheorodus gouldii* (Coulson *et al.*, 2009), and Snapper (*Chrysophrys auratus*) (McGlennon *et al.*, 2000; Fowler and Jennings, 2003).

Recruitment variability can have major implications for fisheries management. As noted by Berkeley *et al.* (2004), the removal of older age classes from a population, termed age class truncation, occurs at even moderate levels of fishing. This, on its own, is of concern to fisheries managers because it is the older fish in a population that are most fecund and these often make a major contribution to total egg production (Hsieh *et al.*, 2006). However, the impacts of age class truncation can be more pronounced for species with high recruitment variability or episodic recruitment. In this context, Koslow (1989) and Longhurst (2002) concluded that the risk of stock collapse will be high if the number of mature age classes falls below the interval between good recruitment events.

In a multi-species recreational fishery, such as the offshore demersal finfish fishery in south-western Australia, one may predict that fishers will tend to focus on species which, at any particular time, are relatively high in abundance. Thus, it may be envisaged that species with high recruitment variability will be most heavily impacted when the individual fish of very strong year classes grow to a size at which they start being able to be caught and retained by fishers. This raises important questions for fisheries managers, such as whether, for moderately-heavily fish stocks, individuals of very strong year classes need protection from becoming quickly-depleted by the heavy targeting by fishers. Recruitment variability becomes particularly important when managers are faced with the need to preserve older year classes when, as in the case of the Western Rock Lobster (*Panulirus cygnus*) fishery in Western Australia in recent years, a series of abnormally poor years of recruitment is experienced. Recruitment variability also has important implications for fishers, as catches of species will reflect that variability, particularly if the exploited portion of the stock comprises a limited number of age classes (Fowler and Jennings, 2003). For managers, there is also a need to be able to communicate to fishers whether their catches are temporarily low simply because of natural recruitment variability, or low because of excessive fishing mortality.

The key temperate, demersal finfish species considered in the model produced in this study, the West Australian Dhufish *Glaucosoma hebraicum* and Snapper *Chrysophrys auratus*, are iconic recreational fish species in south-western Australia and have experienced heavy fishing pressure (*e.g.* Wise *et al.*, 2007). In recent years, there has been considerable concern among fishers and researchers that in these species, recruitment variability may have major implications for their management. Exploration of the potential implications of recruitment variability for the recreational (or commercial) fisheries for these species has, however, been limited. This no doubt reflects, at least in part, the fact that there has been a lack of suitable tools for such exploration, such as the agent-based simulation tool developed in this study. There is also a lack of knowledge among researchers of the ways in which recreational fishers target different fish species and adjust their targets when abundance varies due to recruitment variability.

NEED

Fisheries management is becoming of greater complexity as increasing numbers of recreational fishers target multiple species and switch targets in response to changes in abundance of stocks, and in the context of a growing recognition of the need to sustain stocks within an ecosystem framework. For fisheries scientists, these changes have led to the need for additional training in quantitative skills and the development of experience in computer modelling. For managers, the issues of fisheries management are now demanding an increased understanding of the social and economic consequences of fishing regulations for recreational fisheries, the behavioural responses of recreational fishers to regulations, and the implications of the spatial distribution and movements of fish and fishers. In particular, RecFishWest has identified a need to communicate better to fishers the implications of recruitment variability, and to understand the effectiveness of alternative fisheries regulations that are proposed to ensure the sustainability of those stocks with high variability in levels of annual recruitment.

In common with other countries, fisheries agencies find it difficult to recruit scientists with strong quantitative skills, even from overseas. Development of quantitative skills during postgraduate or postdoctoral studies has been identified as one approach to improving the supply of quantitative scientists, which is a need that must be addressed if Australia is to provide the high-quality research advice that will be needed in the future. The need to develop a simulation tool that will aid communication with recreational fishers and allow exploration of the social and behavioural implications of fishing, recruitment variability and fishing regulations has been identified by RecFishWest. Agent-based models allow investigation of aspects of fisheries at the scale at which individual fishers operate, thereby providing analytical tools that can assist in assessing the implications of fishers' responses to new fishing regulations, a need that will increase as the share of the catch taken by recreational fishers continues to grow.

OBJECTIVES

1. Provide a simulation tool to communicate to fishers the implications of recruitment variability for a fish stock and for the catches of individual recreational fishers.
2. Explore how individual recreational fishers are likely to respond to changes in fish abundance and to changes in commonly-used fisheries regulations.
3. Develop the computer simulation and modelling skills of an early-career fisheries scientist.

METHODS

This section provides a detailed description of the agent-based model and its data inputs. The preliminary simulations that have been undertaken to explore implications of recruitment variability for recreational fishers, and how fishers respond to changes in fish abundance and commonly-used fisheries regulations, are then described.

DESCRIPTION OF THE AGENT-BASED MODEL

Method for describing the model

As ABMs are complex, it is important that each model is described thoroughly to ensure that users can gain a sound understanding of how it works, and also of the underlying assumptions (Grimm and Railsback, 2005). Several protocols have been proposed for describing ABMs (Berec, 2002; Grimm *et al.*, 2006; Triebig and Klügl, 2009). The description given in this report broadly follows the very logical and comprehensive protocol of Grimm *et al*. (2006).

Software platform

The model was developed in VisualBasic.Net (version 3.5 SP1) within Microsoft Visual Studio 2008 (version 9.0.21022.8 RTM) (Microsoft, 2007). The data used by the model are read from Microsoft Excel^{TM} files.

Purpose of the model

The purpose of the ABM is to explore the consequences, *i.e.* in terms of fishers' catches and fisheries management implications, of localised interactions between recreational boat, demersal line fishers and key demersal finfish species, such as *G. hebraicum* and *C. auratus*. The interactions depend on the movement patterns, abundances and a range of aspects of the biology of the fish species, and on the behaviours of recreational fishers.

State variables and scale

The model consists of two interacting types of agents. These are the fish (*G. hebraicum*, *C. auratus* and a third, non-descript species that we have labelled “red herring”) and the recreational, boat-based, demersal line fishers. The agents interact within in a simulated marine reef-system landscape for a specified period (up to 1 year - see below). Each fish agent represents a single fish belonging to one of the three species, whilst each recreational fisher agent represents an individual recreational boat-based fisher. The state variables characterising each fish are a unique integer number that identifies the fish, and its species, age, and sex, whilst the state variable characterising each fisher is a unique integer that identifies the fisher.

The artificial landscape is a neutral landscape generated by a random process and is based on a 128 by 128 cell grid, with each cell considered to represent 100 m^2, and with the landscape thus covering a total area of 12.8 km^2 (Fig. 1). Each cell is considered to represent the area that is typically traversed by an individual fish in a single, 24 hour day. The overall landscape is considered representative of the size of a fishing ground common to a group of fishers using the same boat ramp. Each cell is assigned one of five possible habitats, labelled non-reef, reef edge, reef edge hotspot, reef top, and reef top hotspot.

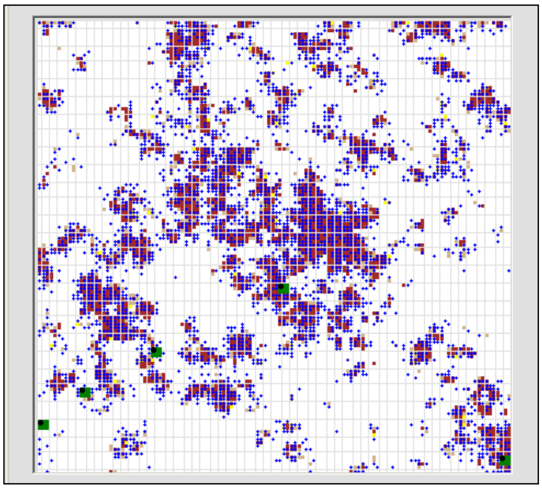


Figure 1 The simulated landscape used in the agent-based model. Each cell represents an area of 100 m^2, and the whole landscape represents an area of 12.8 km^2. The white areas represent non-reef habitat. Blue dots represent individual fish, and the green squares with a black dot represent fishers who are actively fishing.

Process overview and scheduling

The ABM consists of two main sub-models which guide the behaviours of the fish and fishers (see below for more details). Fish agents may experience three event types, and fishers may also experience three event types (Table 1).

Table 1. Fish and fisher agent event types. Detailed descriptions of each event type are provided below.

Fish event type	Fisher event type
Movement	Decision to go fishing
Encounter with a fisher	Commence fishing
Natural mortality	Decision to continue fishing, move or go home

The method used in the model to schedule the various fish and fisher events was adopted from the approach described by Hampton and Majkowski (1987). For each individual fish and fisher in the model, an event is scheduled and added to an event queue. The model processes each event in the queue according to the order in which they were scheduled. Consistent with the description given by Hampton and

Majkowski (1987), the part of the model that performs the task of processing the event queue is referred to as the “simulation engine.” The simulation engine also contains a display grid event to display information to the user at specified intervals during a simulation and a termination event to end the simulation at the required time. The details of how each event is scheduled and the consequences of each event are described below.

The agent-based model program employs an efficient algorithm and data storage structure (AVL Tree) to store and retrieve details required to process the simulation events. The algorithm, invented by Velskii and Landis (1962), was downloaded from the internet.(http://www.planetsourcecode.com/vb/scripts/). The AVL classes within this algorithm were attributed to Jim Harris.

The scheduling of events is also dependent on the pseudo-random number sequence. To generate random numbers, we used a Visual Basic implementation of the Mersenne Twister algorithm (MT19937ar), translated for Visual Basic 2005 by Ron Charlton (see http://www.math.sci.hiroshima-u.ac.jp/˜m-mat/MT/efaq.html). The program had initially been designed and coded in C by Matsumoto and Nishimura (1998) and then translated to VBA by Pablo Mariano Ronchi.

Design concepts

Emergent properties

Emergent properties are those that result from interactions of the agents with each other within the environment (Grimm and Railsback, 2005). Emergent properties of interest in this ABM are the abundance and size and age compositions of fish in catches and in the remaining population of fish, and patterns of fisher behaviour in response to different levels of recruitment variability, fish abundance and management controls.

Agent interactions

Interactions occur between the fish and fisher agents but, as yet in the model, no interactions occur between individuals of the same type. It is thus currently assumed (in the model) that fishers act independently of other fishers and do not share knowledge of good fishing locations. Likewise, as individual fish are independent of other fish, the model does not take into consideration fish reproductive or competitive processes. The behavioural patterns of the fish and fisher agents are guided by a set of logical and probabilistic rules. A stochastic element has been built into each of the rules to allow for variation both between individuals and in the outcomes of decision-making processes.

Adaptability

Adaptability refers to the way in which agents respond to their environment to improve their fitness. Fishers can adapt by improving their knowledge of good fishing locations throughout the course of the simulation. Each fisher has a “list” with a fixed number of “good” fishing locations (*i.e.* as “real” fishers would have in a Global Positioning Satellite system), with each location ranked according to its value as a fishing location, as perceived by that fisher. During the simulation, a fisher can search for new fishing spots. When a new location is found that is perceived to be better than one or more in his/her current list, it can replace one in the list with a lower perceived value, and thus the quality of a fisher’s list of locations can improve over time.

Model outputs

The model outputs a range of statistics and data to the user interface during run time (Fig. 2). These include charts presenting, for each fish species, 1) the age compositions of female and male fish in the population at the beginning of the simulation, 2) those in the remaining population during the simulation and 3) the age and length compositions of female and male fish that are released and retained by fishers. The output data also include charts which present trends in 1) fishing effort, *i.e.* the number of fishers that went fishing, 2) CPUE, (average number of fish retained per trip) and 3) “fisher knowledge”, *i.e.* average (perceived, but not actual) value of the habitats of the fishing locations of the fishing fleet. Other data presented to the user interface during run time include i) the current value of the simulation clock (in days), ii) the total number of fishing trips, iii) total hours fished, iv) number of searches for new fishing locations v) total hours spent searching, vi) proportion of time spent searching, vi) average number of moves by fishers each trip, vii) total number of fish bites received, viii) number of “good” fish bites, ix) numbers of released and x) retained fish, xi) the proportion of fish retained, xii) and the number of times fishers have attained their boat limits for the individual species, and xiii) the mixed-species boat limit. The model outputs the above statistics (to text files), as well as statistics for individual fisher trips, including the number of hours spent fishing and searching, and numbers of fish caught and retained.

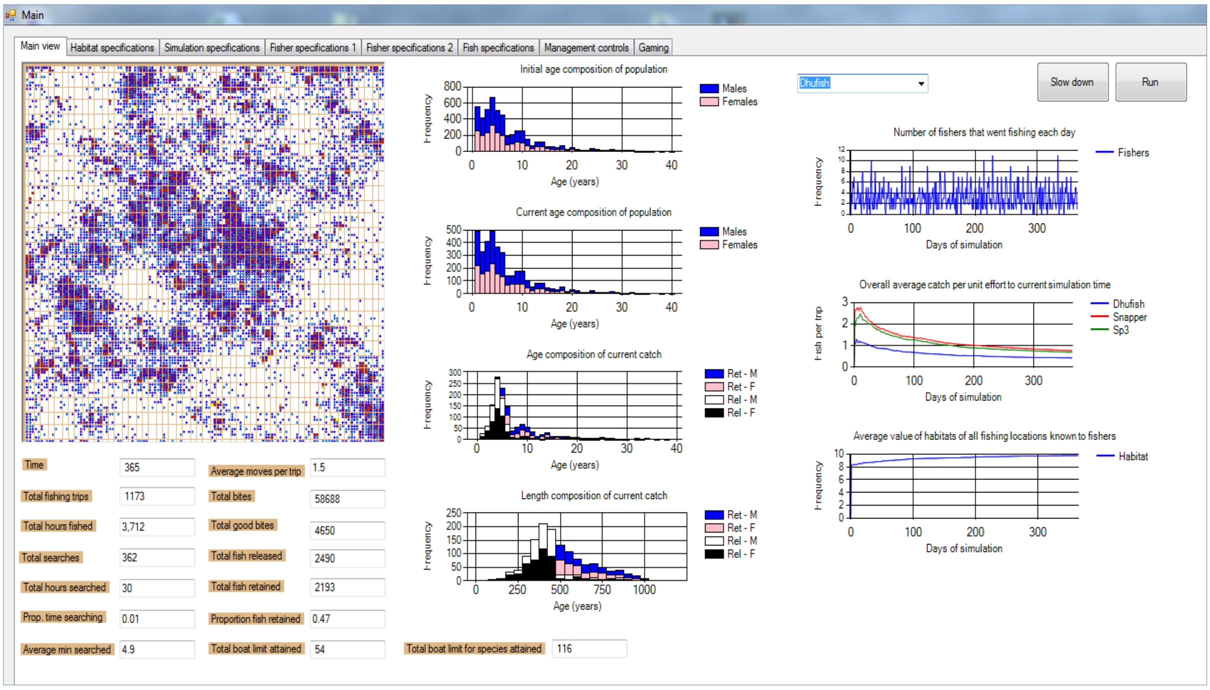


Figure 2. Main program form for displaying the results of simulations to users.

Initialisation

Initialisation of a model run involves 1) setting the simulation clock to the starting value for the simulation (currently specified as 0 days), 2) reading all default values for the model parameters from an external Microsoft Excel^{TM} data file, 3) setting up the landscape grid, with each cell being assigned one of the five habitat types, and 4) creating the fish and fisher agents. Steps 3-4 are described in more detail below.

Setting up the artificial landscape

The model landscape over which the fish and fisher agents move is a fractal landscape generated using the diamond-square algorithm (Miller, 1986). The landscape contains five habitat types, namely non-reef, reef top, reef top hotspots (caves within the reef platform), reef edge, and reef edge hotspots (caves and ledges in the reef edge). The diamond square algorithm creates an artificial landscape according to values specified for the proportions of each of the five habitat types in the landscape grid, and habitat patchiness. Values for habitat patchiness vary between 0 and 1, with 1 producing landscapes containing large continuous areas of reef and values approaching zero producing landscapes containing many, highly fragmented reef habitats.

Creation of fish agents

The fish are created employing age composition data (for an exploited fish population) for the females and males of each species. These data are read in from an external file and used to create a random age composition sample for each species, according to the specified number of individuals for each fish species. The samples are generated employing the algorithm genmul, available online from RANLIB within NETLIB (http://www.netlib.no) (Devroye, 1986), which generates observed samples from a multinomial distribution. (See below regarding source of input data).

Once fish are created, they are placed on the landscape grid randomly according to their "habitat preferences" (based on parameters derived from a recreational fisher survey, see Appendix). An event is then scheduled for each fish, which may be a movement, fisher encounter or natural mortality event (see Table 1).

Create fisher agents

Each of the fishers in the fishing fleet is created with a knowledge base of fishing locations, *i.e.* a collection containing a set number of such locations. Each location in the collection is assigned a value according to the fisher's perception of its worth for catching fish (based on noisy observations of the habitat at that location and on parameters derived from the fisher survey). The values of each habitat type to fishers as a fishing location, which range from 1 (very poor) to 10 (excellent), are assumed to be the same for all fishers. A fishing location is considered “good” if the fisher has assigned it a value which lies above a specified threshold level (Fig. 6).

Allocation of each of the fishing locations known to each fisher prior to the commencement of a simulation involves 1) randomly selecting a cell, 2) undertaking a “random walk” in the immediate vicinity of that cell for a specified number of steps and 3) selecting the cell with the highest perceived habitat value as the fishing location to be allocated to the fisher. This process is then repeated to allocate all of the specified number of known fishing locations to all fishers. The likelihood of fishers identifying correctly each of the true habitat types is determined in the program according to a probability matrix (based on the results of the fisher survey). The values which are entered into the matrix for cases when fishers have incorrectly identified the true habitat type of a cell are distributed equally across the four incorrect habitat types.

The final stage in creating the fisher agents is to schedule a decision for each fisher to determine, at that time, whether to go fishing, or stay at home.

Input

Input data are required to 1) generate the landscape, 2) create the fish and fisher agents, 3) to parameterise the decision rules of the agents and 4) schedule a program termination time.

Input data for generation of a landscape

The data required for generating artificial landscapes include values for the proportions of each habitat in the landscape grid, and a value for habitat patchiness (Fig. 3). The landscape parameters can be modified at the commencement of simulation runs.

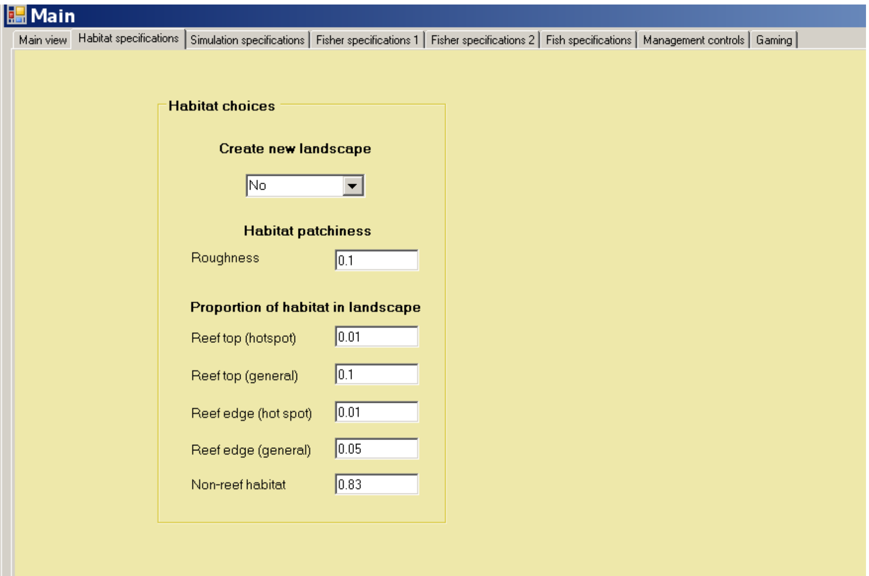


Figure 3. Form displaying values of parameters used by the model to generate an artifical landscape.

Input data for fish agents

The data required to generate the fish agents include age composition data (for a population of fish) and a range of specified biological parameters.

To generate the required age composition data, we used an external single species, single area, length, age and sex-structured model (currently being developed by S. Hesp, E. Fisher & N. Hall for FRDC 2008/006). The model can generate such data for female and male fish in an exploited population under an existing management regime, *i.e.* a combination of possible bag, boat and size limits, temporal and/or spatial fishery closures, and quotas, and with a specified level of recruitment variability. This external model constitutes the operating model for a Management

Strategy Evaluation (MSE) program, for which a full description will be provided in the final report for FRDC 2008/006 at the end of 2010.

Other data required for fish agents include 1) values for the number of fish to be generated, 2) von Bertalanffy growth parameters and the standard deviation of the lengths at age, 3) maximum age, 4) logistic parameters for gear selectivity, 5) probability of capture if the fish encounters a fisher and is large enough to be fully-selected into the fishery, 6) probability of death following capture and release (*i.e.* if the fish is undersize or the boat limit for that species has been attained) due to fishing-induced baurotrama, and 7) probabilities of movement from each of the five habitat types. The values for each of these parameters are displayed to the user on a form and can be modified before the commencement of a new simulation (Fig. 4). Graphs showing the trends in growth and size-selectivity of the three species are displayed to help users visualise the input data.

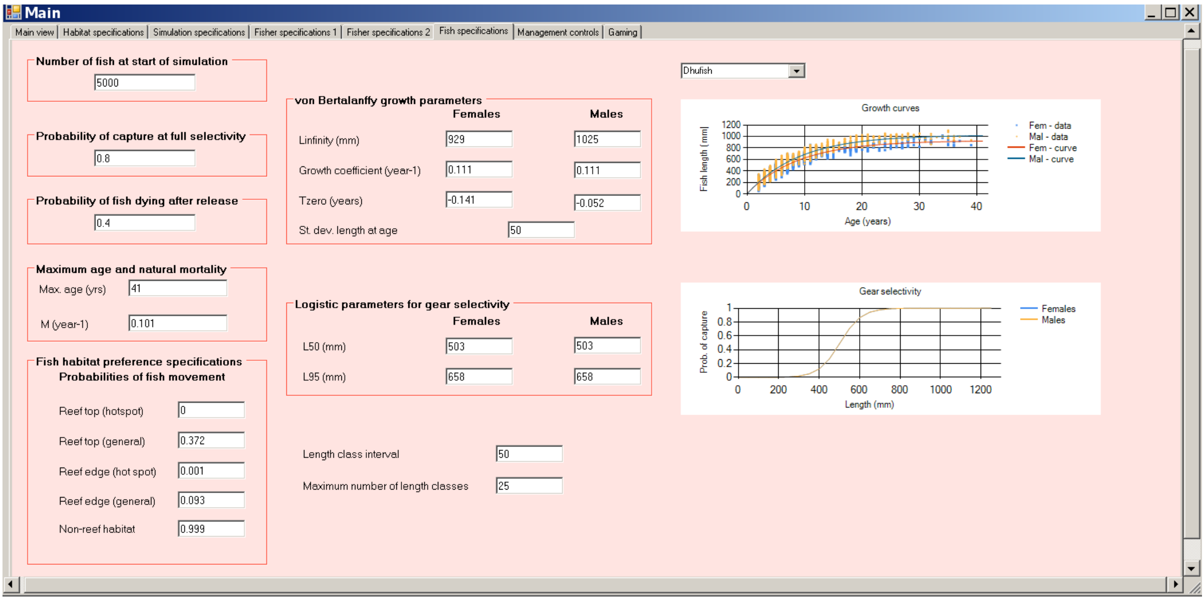


Figure 4. Form displaying values of parameters used by the model which describe the abundance, and aspects of the biology and movement parameters of each of the fish species. Two graphs are displayed to the right of the form to help users visualise the data inputs for fish.

Data inputs for fisher agents

Data required for fisher agents include values for 1) the number of fishers in the fishing fleet, 2) the probability of a fisher undertaking a search after moving from a fishing location, 3) the total number of fishing locations and initial number of “good” fishing locations known to each fisher, 4) threshold value above which the fisher perceives the habitat type to be a good habitat for fishing 5) perceived value of each habitat type to fishers for catching fish, 6) the minimum size of fish that produce “good” bites, 7) matrix describing the probabilities of fishers identifying correctly each of the five habitat types and, if not, the probabilities of the remaining habitat types being (incorrectly) identified as the perceived habitat, 8) logistic parameters to describe the relationship between the time elapsed since the last fishing trip and the probability that the fisher will go fishing and 9) logistic parameters to describe the relationship between time elapsed since the commencement of a fishing trip and the probability of the fisher going home. As for the parameters for fish, the values for each of the fisher parameters are displayed to the user on a form and can be modified before the commencement of a new simulation (Fig. 5a,b). Graphs are provided to help users visualise the data for describing the relationships between (i) probability, whilst fishing, of staying at the same location and bite rate, (ii) probability of a fisher deciding to go fishing and the number of days elapsed since the last fishing trip and (iii) probability of a fisher deciding to go home and the number of hours elapsed since the commencement of the fishing trip.

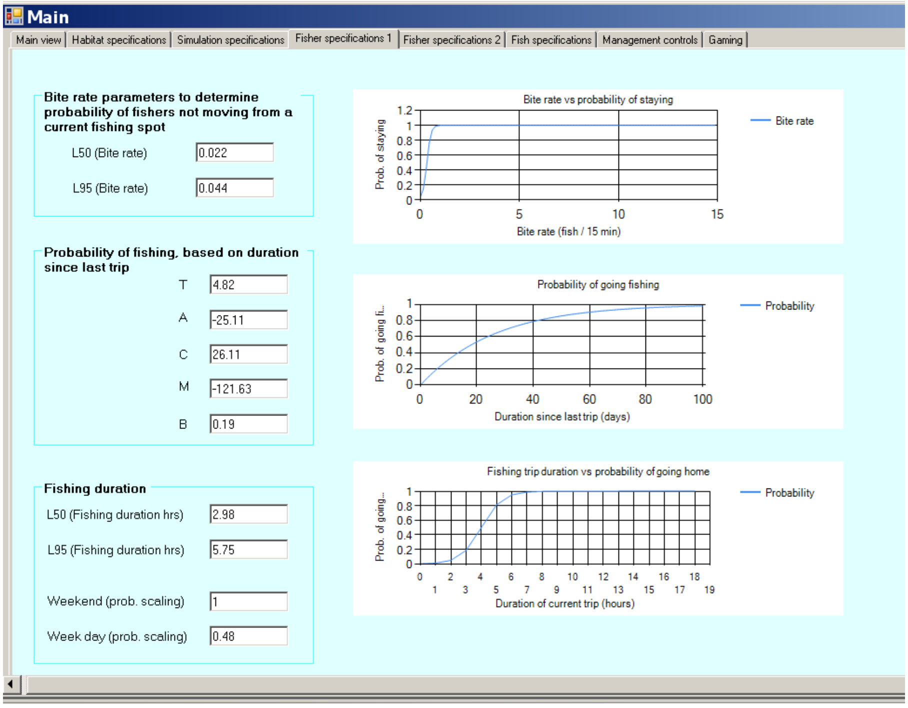
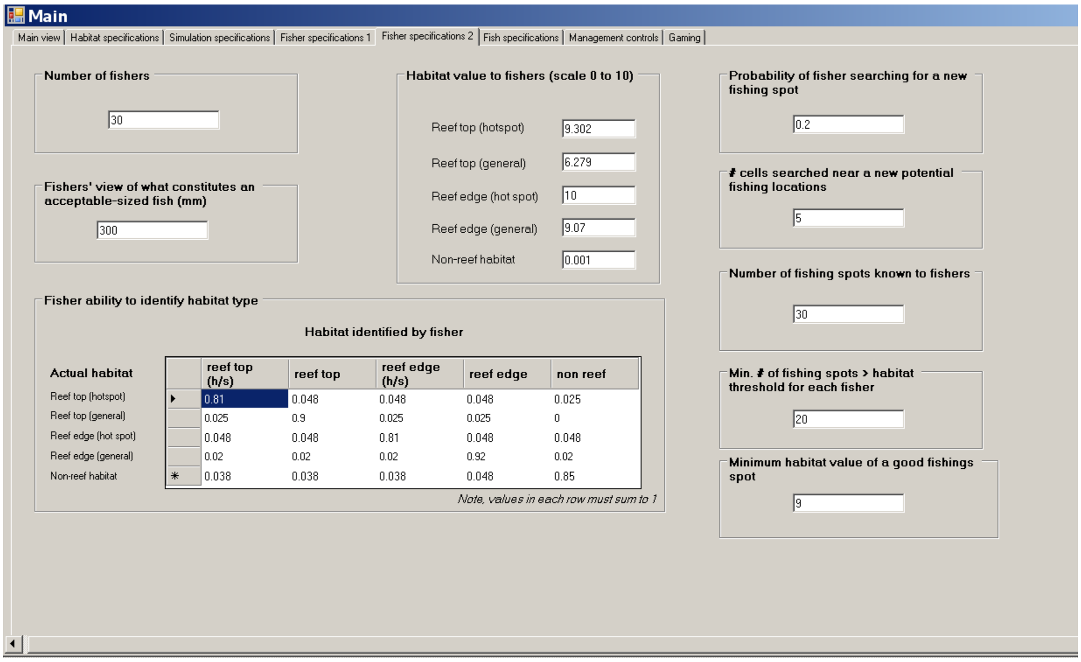


Figure 5a. Form displaying values of parameters used by the model, specifying aspects related to fisher behaviour. Several graphs are displayed to the right of the form to help users visualise the input data.



Actual habitat	reef top (h/s)	reef top	reef edge (h/s)	reef edge	non reef
Reef top (hotspot)	0.81	0.048	0.048	0.048	0.025
Reef top (general)	0.025	0.9	0.025	0.025	0
Reef edge (hot spot)	0.048	0.048	0.81	0.048	0.048
Reef edge (general)	0.02	0.02	0.02	0.92	0.02
Non-reef habitat	0.038	0.038	0.038	0.048	0.85

Figure 5b. Form displaying values of parameters used by the model, which describe a range of aspects of the fishers, and their knowledge and behaviours.

Data inputs for commonly-used fisheries management controls

The model currently considers several forms of management control, a minimum legal length of fish for retention, and boat limits, for individual species, and a mixed boat limit (Fig. 6). As the model is extended beyond the current project, further controls will be implemented. The agent-based model is ideally suited to be used to explore the influence of both temporal and spatial controls on recreational fisher behaviour.

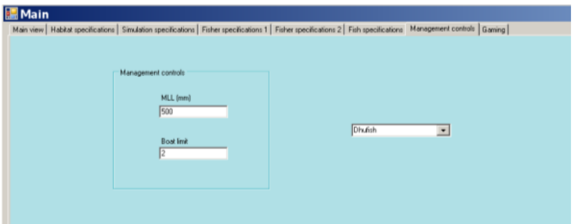


Figure 6. Form displaying values of parameters for management controls.

Sub-models

Fish sub-model

The rules of fish agent behaviour correspond to three event types, *i.e.* a fish movement event, a fish encounter with a fisher event, and a natural mortality event. The scheduling of each event type and the consequences of each event are described below by the event pathway diagram (Fig. 7) and associated description.

1. *Fish movement event*

Scheduling: *Dependent of instantaneous rate of fish movement*

The instantaneous rate (day^{-1}) of fish moving from a given habitat type, $R_{FishMovement}$, is calculated as:

$$R_{FishMovement} = -\ln(1 - P_{FishMovement}),$$

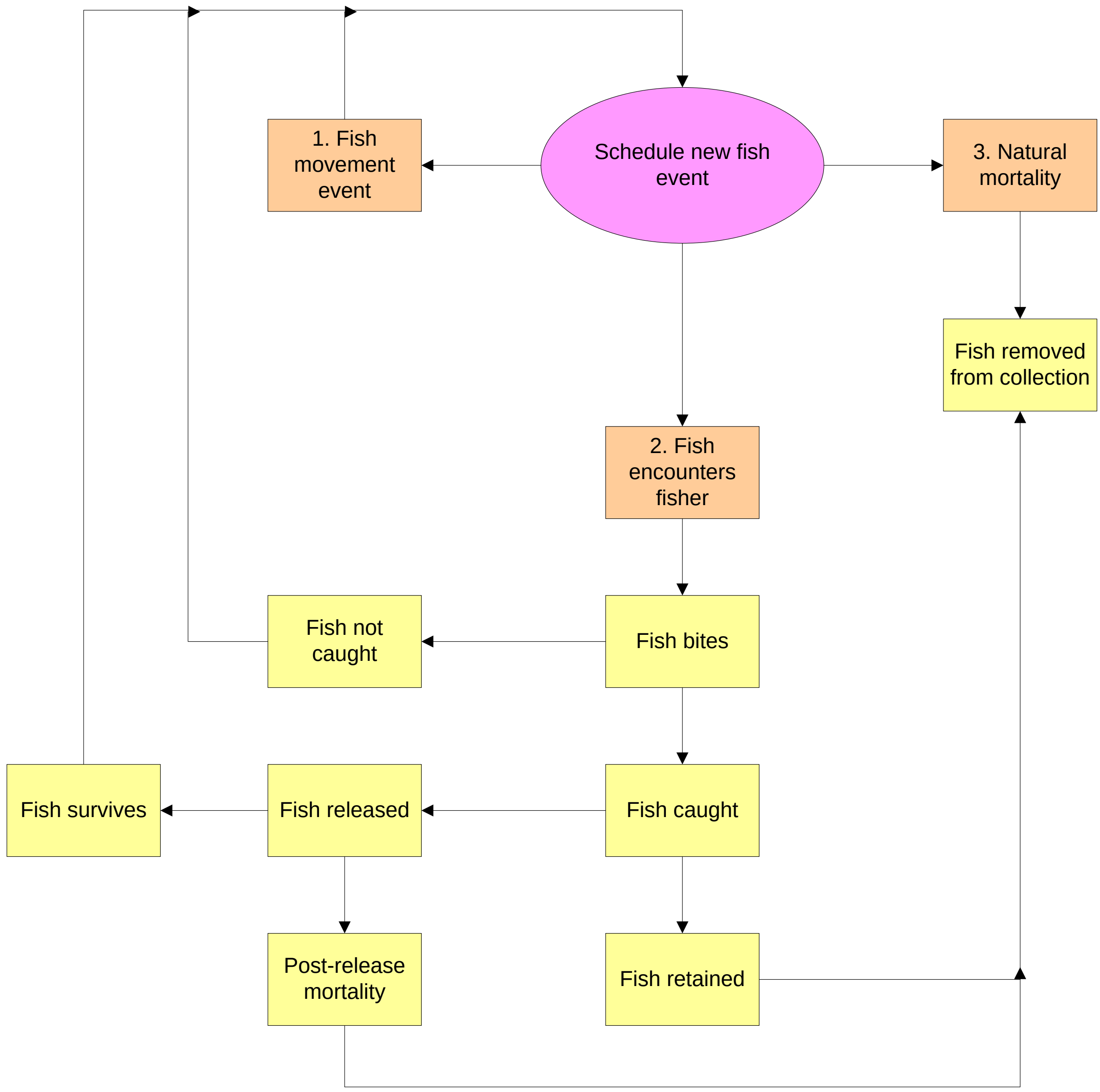


Figure 7. Fish agent sub-model describing the possible fates of fish at each of the three main event types (fish movement, fisher encounter and natural mortality).

where $P_{FishMovement}$ is the probability of fish moving from that habitat type, and ln is the natural logarithm.

The scheduled time till the fish movement event, $T_{TillFishMovement}$, is then determined as:

$$T_{TillFishMovement} = -\ln(1-r)/R_{FishMovement} ,$$

where *r* is a uniform random number between 0 and 1.

The scheduled simulation time of the fish movement, $T_{FishMovement}$, is:

$T_{FishMovement} = T_{SimClock} + T_{TillFishMovement}$,

where $T_{SimClock}$ is the current value of time for the simulation clock.

Note that if a fish (or a fisher) moves outside the grid, that fish will re-enter the grid at the corresponding location on the opposite edge of the grid.

2. *Fish encounters fisher event*

Scheduling: *Dependent on number of fishers currently occupying same grid cell as fish (see below)*

The encounter rate between a fish and a fisher, $R_{FisherEncounter}$, which depends on the number of fishers currently occupying the same grid cell as that fish, $N_{FishersInCell}$, is calculated as:

$$R_{Encounter} = [-ln(1-P_{Encounter})]N_{FishersInCell} ,$$

where $P_{Encounter}$ is the probability (set as a constant) of a fish encountering a fisher in the same cell as itself over 24 hours. Note that, as $R_{Encounter}$ depends on $N_{FishersInCell}$, the events for fish in a cell are rescheduled every time a fisher enters or leaves that cell.

The time of the fish encounter with a fisher event, $T_{Encounter}$, is given as:

$$T_{Encounter} = [ln(1-r)]/R_{Encounter} .$$

$T_{Encounter}$ is then adjusted to determine the probability of encountering a fisher within the next 15 minutes of the current time of the simulation, $T_{SimClock}$, *i.e.*

$$T_{Encounter} = T_{SimClock} - T_{Encounter} /(0.25 * 24).$$

When a fish encounters a fisher, the fish may or may be caught by the fisher and, if so, retained or released. If caught and released, the fish may survive or die (see Fig. 7 and below).

i) *Fish bites and is caught*

The probability that a fish is caught once it has encountered a fisher is dependent on the length at age of the fish and its size-dependent selectivity to the fishing gear. For a given species, $L_{t,s}$, the length at age t for a fish of sex s, is determined from the von Bertalanffy growth equation, *i.e.*,

$$L_{t,s} = L_{\infty,s}\{1 - exp[-k_s(t - t_{0,s})]\} + \varepsilon ,$$

where for each sex, $L_{\infty,s}$ is the asymptotic length (mm), k_S is the growth coefficient (year^{-1}), $t_{0,s}$ is the hypothetical age at zero length, and ε is the observation error. For each species, random observation error was generated according to a specified value for the standard deviation for the lengths at age, $stdev$, and randomly-drawn values from the inverse of the cumulative distribution of the standard normal probability density function, using a Visual Basic.net implementation of a function equivalent to the normsinv() function of Microsoft Excel™, *i.e.*

$$\varepsilon = stdev\ (normsinv(r)).$$

The algorithm employed to compute the values from the inverse of above cumulative distribution is that of Peter J. Acklam (http://home.online.no/~pjacklam/notes/invnorm/index.html), adapted for Visual Basic by Christian d'Heureuse (http://www.source-code.biz).

For each species, the probability that a fish of length L (mm) will be selected by the fishing gear, S_L is given as:

$$s_L = 1/\{1 + exp[-\ln(19)\,(L - L_{50})/(L_{95} - L_{50})]\},$$

where $\ln$ is the natural logarithm, and L_{50} and L_{95} are the lengths in mm at which 50 and 95% of fish, respectively, are selected by the fishing gear.

The probability that a fish at full selectivity (for that species) will be caught on biting $P_{BiteCapture}$, is determined as:

$$P_{BiteCapture} = S_L\left(P_{Capture}\right),$$

where $P_{Capture}$ is a specified constant.

ii) *Fish is retained or released*

If a fish is caught by a fisher, it will be retained by the fisher if it is larger than the minimum legal length for retention specified for the fish species and if that fisher has not yet attained the boat limit for that species. If retained, the fish is removed from the fish collection.

iii) *Fish suffers post-release mortality*

Following capture and release, the probability of a fish dying is specified as the constant $P_{ReleaseDeath}$. If the fish dies, the fish is removed from the fish collection.

3. *Fish natural mortality event*

Scheduling: *Random assignment, depending on instantaneous rate of natural mortality (see below)*

For a given species, individuals may be assigned a time of natural death during the simulation, T_M, scheduled as:

$$T_M = T_{SimClock} + [-\ln(1-r)/(M/365.25)] ,$$

where M is the instantaneous rate of natural mortality (year^{-1}) for that species, as estimated by insertion of the maximum recorded age for the species (as determined in past studies) into Hoenig's (1983) equation for fish.

Fisher sub-model

The decisions and subsequent actions of the recreational fishers are described by three main event types, a fisher decision to fish event, a fisher decision to commence fishing on day event, and a fisher checkpoint event. There are two subcategories of fisher checkpoint events, depending on whether the fisher is fishing or is currently searching for a new fishing location. The fisher decision pathways are described by Figure 8 and further below.

1. *Fisher decision to fish event*
Scheduling: *10 pm daily*

The probability of a fisher deciding to go fishing on a given day, $P_{Fishing}$, as a function of the number of days elapsed since the fisher's last trip, D, is described using Richards' generalised logistic equation (Richards, 1959), *i.e.*

$$P_{Fishing} = A + \left[C/\left(1 + exp^{-B(D-M)^{1/T}}\right)\right],$$

where A is the lower asymptote, K is the upper asymptote, A is the "growth" rate, and M is the time of maximum growth. The Richards curve, which is typically used for growth modelling, is an extended and more flexible form of the logistic equation.

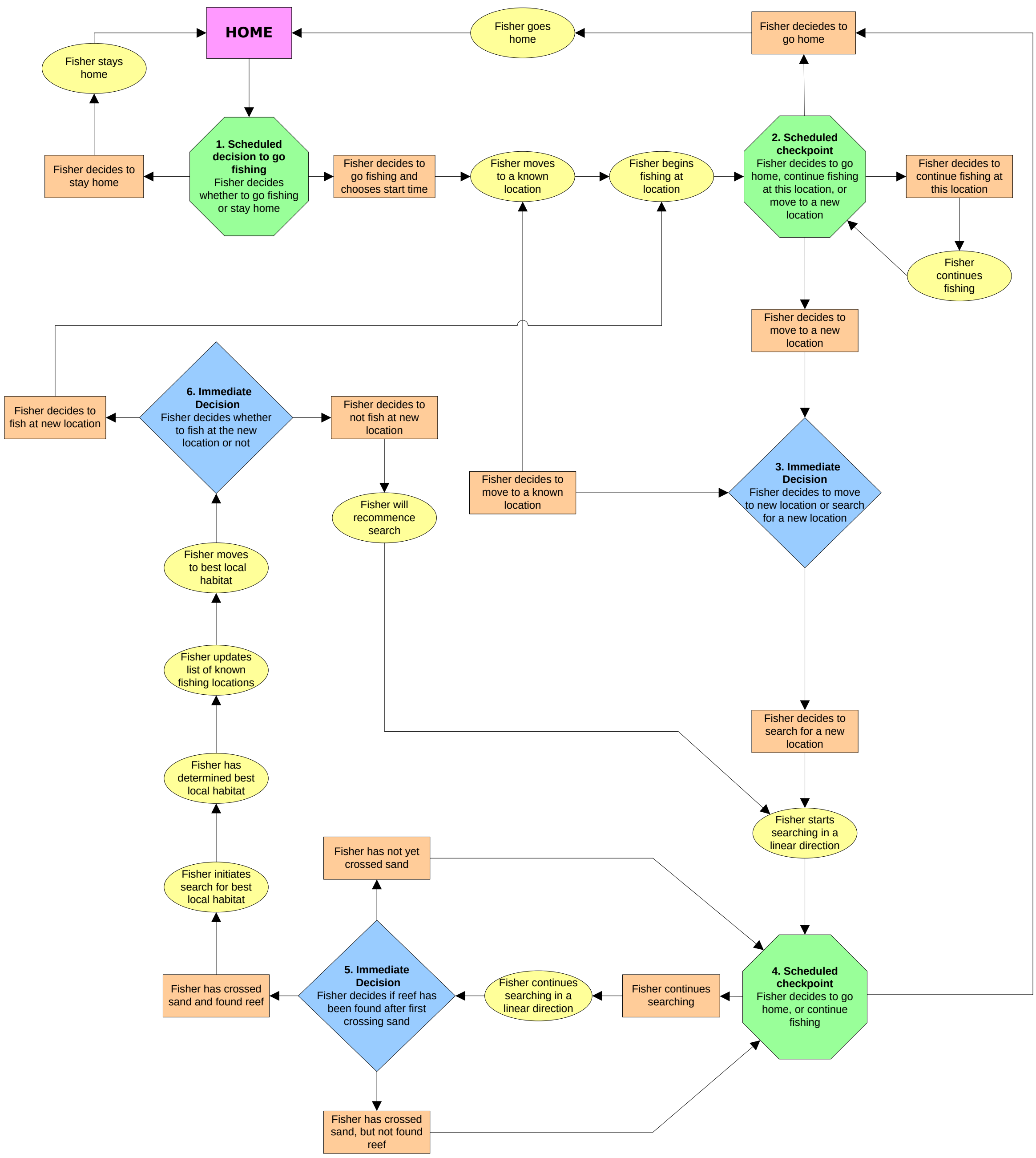


Figure 8. Fisher agent decision pathways. Numbers correspond to the six fisher decision points of the fisher sub-model. Octagons indicate a review checkpoint, diamonds represent an immediate decision in relation to fishing, rectangles represent the outcomes of a decision and ovals represent the actions taken by the fisher.

$P_{Fishing}$ is then scaled depending on whether the day is a working day or a weekend day. If a decision is made to go fishing, a "fisher commences fishing on day" event is scheduled for a (random) time between 6 am and 12 noon the following day.

2. *Fisher decision to commence fishing on day event*

Scheduling: *Random time between 6 am and 12 noon following a fisher decision to fish event.*

The processing of a "fisher commences fishing on day" event involves the placement of the fisher on the landscape grid at a random fishing location known to the fisher (*i.e.* from that fisher's list of known fishing locations), commencement of fishing and the scheduling of a fisher checkpoint event (for 15 minutes after the commencement of fishing).

3. *Fisher checkpoint event* (type I)

Fisher decides to continue fishing, go home or move to a new fishing location.

Scheduling*: Random time every 10-20 min whilst fishing*.

(i) Decision to continue fishing

The probability of the fisher continuing to fish at the same location, $P_{StayInCell}$, as a function of bite rate (min^{-1}), B_{Rate} is calculated as:

$$P_{StayInCell} = \{1 + exp[-\ln(19)(B_{Rate} - B_{Rate\,50})/(B_{Rate\,95} - B_{Rate\,50})]\},$$

where $B_{Rate\,50}$ and $B_{Rate\,95}$ are the number of "good" bites (min^{-1}) at which 50% and 95%, respectively, of fishers will decide to stay at the current fishing location. Determination as to whether a bite is a "good" bite is made according to the size of the fish (that is biting).

(ii) Decision to return home

The same form of logistic equation is used to relate current fishing trip duration, T_{Trip}, to the probability of a fisher returning home, $P_{ReturnHome}$. This latter parameter is thus calculated as:

$$P_{ReturnHome} = \{1 + exp[-\ln(19)(T_{Trip} - T_{Trip\,50})/(T_{Trip\,95} - T_{Trip\,50})]\},$$

where $T_{Trip\,50}$ and $T_{Trip\,95}$ are the number of hours after which 50 and 95% of fishers, respectively, will return home. Alternatively, a fisher will automatically return home if the "mixed species" boat limit has been attained. Currently, the model considers the two key target species to be included in the mixed species boat limit.

(iii) Decision to move to a new fishing location

P_{Move}, the probability of a fisher moving to a new fishing location is determined as:

$$P_{Move} = 1 - P_{StayInCell}$$

A fisher may move either to a known fishing location, or commence a search to find a new location. The probability of a fisher deciding to begin searching for a new fishing location, P_{Search}, is set as a constant. Fishers commence searching by moving in a random linear direction to a new cell.

4 – *Fisher checkpoint event (search mode)*

Scheduling*: every 1 min whilst searching*.

(i) Decision whether reef has been encountered, after first encountering sand

A fisher must move sufficiently far from a previous fishing location for the new location to represent a different fishing spot. The process by which this is assumed to occur involves fishers moving far enough from their previous fishing location to encounter a non-reef habitat, before then encountering a new reef (Fig. 8). At each 1 minute checkpoint, the fisher decides whether non-reef habitat has been encountered and, if so, whether a new reef habitat has then been encountered. Note that if a fisher (or fish) moves outside the grid, the fisher will re-enter the grid at the corresponding location on the opposite edge of the grid.

Once a fisher encounters a new reef (and thus potential new fishing location), that fisher first undertakes a local search, *i.e.* a random walk, for a specified number of cells, to determine the cell with the (perceived) best habitat in the local vicinity of the newly-found reef. The fisher's collection of fishing spots is then updated, with the new location replacing an existing poorer location, which is always that with the poorest value as a fishing spot. After updating the collection, the fisher then decides whether to fish at the new location, or whether to recommence searching (Fig. 8).

(ii) Decision to fish new location or previously-known location

A newly-found location is fished if the fisher's perceived value of the habitat lies above the habitat value specified as the minimum for a good fishing location, otherwise the fisher will commence a new search (Fig. 8).

Gaming

The model has been extended to allow users to explore further the consequences of fisher behaviours through "gaming". If desired, the user can select "Gaming on", by selecting to display a user form called Gaming. When gaming is initiated, certain behaviours of one of the fishers in the fishing fleet are able to be controlled by the user. These behaviours include 1) the time intervals between fisher decision checkpoints, 2) the bite rates sufficient for a fisher to decide to continue fishing at the same location, 3) trip duration and 4) how often fishers decide to search for new habitats. A range of fishing and catch statistics are provided to the user during and at the end of the simulation, allowing users to compare the influence of their specifications on the success of their fisher agent.

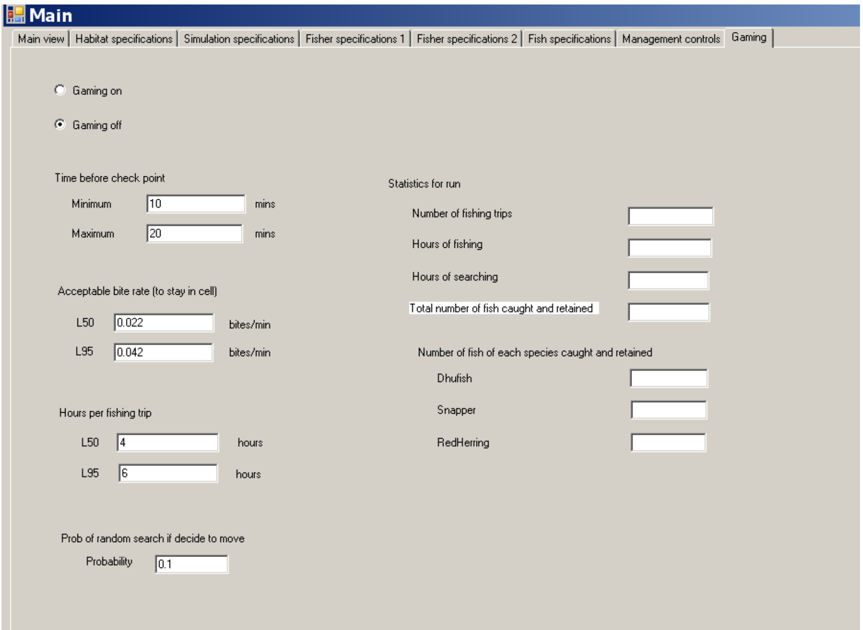


Figure 8. “Gaming” form enabling users to alter parameters for one of the fishers in the fishing fleet, and to compare that fisher’s fishing success against other fishers.

Installing and running the model

The model is run from an .exe file, freely-available from http//:www.cffrfisheriesmodelling.net/. Instructions on how to download and run the program are provided on the website.

The model is very simple to run. Indeed, all that is required is for the application to be opened, and for the user to press “Run” on the first form that opens automatically. However, the user can, if desired, explore all the data inputs of the model by switching between forms. Furthermore, the parameter values in the external

Microsoft Excel™ files can be altered to enable further investigation of the ways in which the model parameters influence results of simulations.

PRELIMINARY SIMULATIONS EMPLOYING THE AGENT-BASED MODEL

A series of simulations have been run to demonstrate the types of information that are output by the model, and to explore the influences of 1) recruitment variability, 2) fish abundance and 3) management controls on the fish populations, fisher catches and fisher behaviours.

Input data and parameter values used for simulations

i) Age composition data for creating fish agents

As described above, we have used an external MSE model (being developed for FRDC 2008/006) to produce the age composition data required by the agent-based model to create the fish agents. These data are intended to be representative of populations of West Australian Dhufish (*Glaucosoma hebraicum*) with low recruitment variability and high recruitment variability, of Snapper (*Chrysophrys auratus*) with episodic recruitment and d) of Silver Trevally (*Pseudocaranx georgianus*) with low recruitment variability (*i.e.* referred to as “Red Herring” in the model) (Fig. 9).

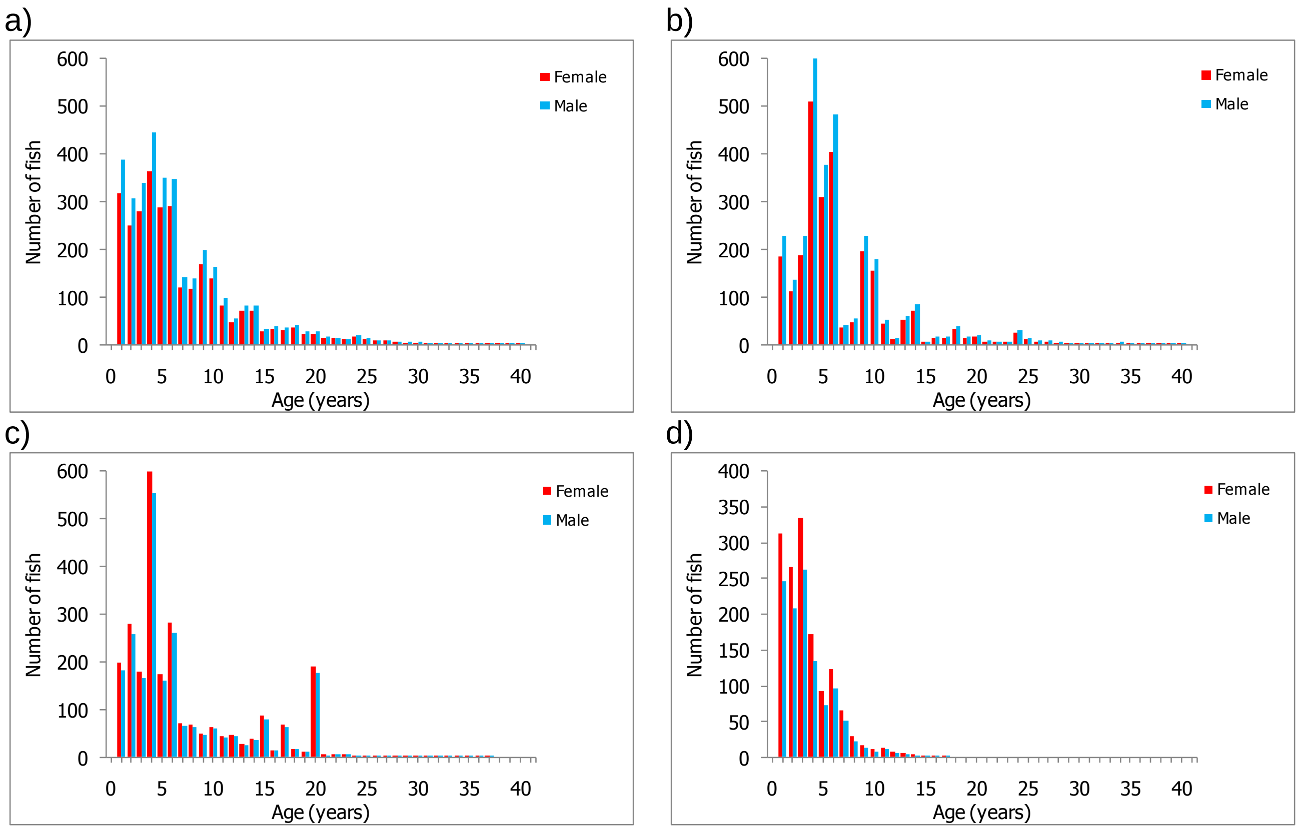


Figure 9. Age composition data for West Australian Dhufish (*Glaucosoma hebraicum*) with a) low recruitment variability and b) high recruitment variability, of c) Snapper (*Chyrsophrys auratus*) with episodic recruitment and d) of Silver Trevally (*Psuedocaranx georgianus*) with low recruitment variability.

Note that, as with the agent-based model, the MSE model employs the random number generator MTRandom (a Visual Basic implementation of the Mersenne Twister algorithm). When generating age composition data using the MSE program, separate random number generators, using different values for their seeds, were used for the different species to ensure that each species had a different recruitment series. However, common values of seeds were used to generate age composition data for the low and high recruitment variability populations of *G. hebraicum* to control for random effects when exploring the influence of different levels of recruitment variability in this species. Note also that the values of the von Bertalanffy growth parameters, maximum ages and levels of exploitation for the three fish populations that were input into the MSE model to produce age composition data were the same as those used in the agent-based model to create the fish agents.

i) Fish and fisher agent parameters

The values of the parameters for fish and fishers in the model simulations are derived from a range of sources, including scientific literature, the results of a recreational fisher survey, or as specified by A. Hesp. An analysis of the recreational fisher survey data is provided in a recently-completed Honours thesis by R. Burch at Murdoch University. Further surveys and analyses are being undertaken by C. Tink for her PhD thesis. The values and sources of all parameter values for fish are presented in Table 2 (see also Fig. 4, for West Australian Dhufish). The fisher parameters (see Figs 5 and 6) were derived from the recreational fisher survey data other than the following, which were specified by A. Hesp: 1) Number of fishers, 2) logistic bite rate parameters 3) number of fishing locations, 4) minimum number of good fishing locations and 5) minimum threshold for habitat value of a good fishing location.

Table 2. Values of fish species parameters used in the simulations. Superscript numbers refer to the relevant data source for each parameter (listed below the table).

Species	West Australian Dhufish	Snapper	"Red Herring" (Silver Trevally)
		Maximum age and mortality	
Maximum age (years)	41[1]	38[6]	18[8]
M (year^{-1})	0.101[1]	0.109[6]	0.232[8]
ProbOfDeathAfterRelease	0.4[2]	0.2[2]	0.05[2]
		Growth parameters	
$L_{\infty\ (Females)}$ (mm)	929[1]	1150[6]	477[8]
$L_{\infty\ (Males)}$ (mm)	1025[1]	0.12[6]	0.24[8]
$k_{(Females)}$ (yr^{-1})	0.111[1]	-0.41[6]	-0.37[8]
$k_{(Males)}$ (yr^{-1})	0.111[1]	1127[6]	459[8]
$t_{0\ (Females)}$ (yr)	-0.141[1]	0.12[6]	0.27[8]
$t_{0\ (Males)}$ (yr)	-0.052[1]	-0.46[6]	-0.22[8]
StDevLengthAtAge	10[2]	10[2]	25[28]
		Gear selectivity parameters	
$L_{50\ (Females)}$ (mm)	503[3]	372[7]	290[9]
$L_{95\ (Males)}$ (mm)	658[3]	480[7]	441[9]
ProbOfCaptureAtFullSelectivity	0.8[2]	0.8[2]	0.8[2]
		Fish movement parameters	
ProbOfMoving (ReefTopHotspots)		0.069[4]	
ProbOfMoving (ReefTop)		0.448[4]	
ProbOfMoving (ReefEdgeHotspots)		0.001[4]	
ProbOfMoving (ReefEdge)		0.969[4]	
ProbOfMoving (NonReef)		0.999[4]	
		Management parameters	
Minimum legal length (mm)	500[5]	410[5]	250[5]
Boat limit (fish)	2[5]	4[2] *	16[2] *
Mixed species boat limit (fish)		6 (2 West Australian Dhufish, 4 Snapper) [2]	
		Fish abundance	
Number of fish	5000[2]	5000[2]	5000[2]

Data sources: 1. Hesp *et al.* (2002), 2. Specified by A. Hesp, 3. A. Hesp, unpublished data, 4. Determined from the results of recreational fisher survey (undertaken in this project) 5. Department of Fisheries, Western Australia, Recreational fishing regulations for the west coast bioregion 6. Lenanton *et al.* (2009) – based on results of research by M. Moran, C. Wakefield and G. Jackson, 7. C. Wakefield, unpublished data, 8. Farmer *et al.* (2005), 9. D. French, unpublished data.

*Specified by A. Hesp as a boat limit no longer exists for these species in Western Australia. Values specified = twice the current bag limit. Note that the number of West Australian Dhufish in one of the simulations differed (reduced to 2500 fish), to explore the implications of changes in abundance in a population of this species.

Simulations

(i) Recruitment variability

Effects of recruitment variability were explored by running two simulations for which the level of recruitment variability in one species, *G. hebraicum*, differed markedly. Thus, simulations differed by employing the age composition data for *G. hebraicum* displayed in Fig. 9a (low recruitment variability) and Fig. 9b (high recruitment variability). All other factors in the two simulations were kept constant, including the seeds for the random number generators, to control for random effects.

(i) Changes in fish abundance

The implications, for the fishery, of a change in fish abundance of a population of one species, *G. hebraicum*, was explored by comparing the results of the first simulation above (in which 5000 fish were created for a population of *G. hebraicum* with low recruitment variability), and a simulation in which only 2500 individuals of this species (with low recruitment variability) were created.

(i) Changes in common management controls

The possible implications of a change in the minimum legal length for retention (MLL) of a species was explored by comparing the results of the first simulation with another in which the MLL for *G. hebraicum* was raised from 500 mm to 650 mm. Finally, the results of the first simulation were compared with another in which the boat limit for *G. hebraicum* was lowered from 2 to 1 fish per day to investigate the possible effects of changing the boat limit for a species.

RESULTS/DISCUSSION

The results presented below, which are intended to illustrate the outputs that the model produces, are obtained from single trials for scenarios for which the level of recruitment variability or abundance of *G. hebraicum* is high or low, or for which certain management controls have been altered. As the model is developed further, the results obtained for different scenarios will be subjected to a more detailed exploration using a larger number of simulation trials. Although an interpretation has been provided of the results presented below, the conclusions that will be drawn from the future more extensive exploration are likely to differ slightly from those presented in this document.

Implications of recruitment variability

(Simulation 1 vs 2)

The age compositions for the populations of West Australian Dhufish (*Glaucosoma hebraicum*), Snapper (*Chrysophrys auratus*) and "Red Herring" (employing data for Silver Trevally, *Psuedocaranx georgianus*) at the end of the simulations resembled those generated for these species prior to the commencement of simulations, except that the numbers of fish in all of the age classes had declined through natural mortality and, for older ages classes, also through fishing mortality (Figs 10-12). Except for the younger age classes not (or only partially) recruited into the fishery (*i.e.* below ~ 6 years for West Australian Dhufish, ~ 4 years for Snapper and 3 years for Red Herring), the age compositions for the individuals of each species in catches reflected the age compositions of their populations. Thus, for example, in the simulation for *G. hebraicum* with high recruitment variability, the retained catches of

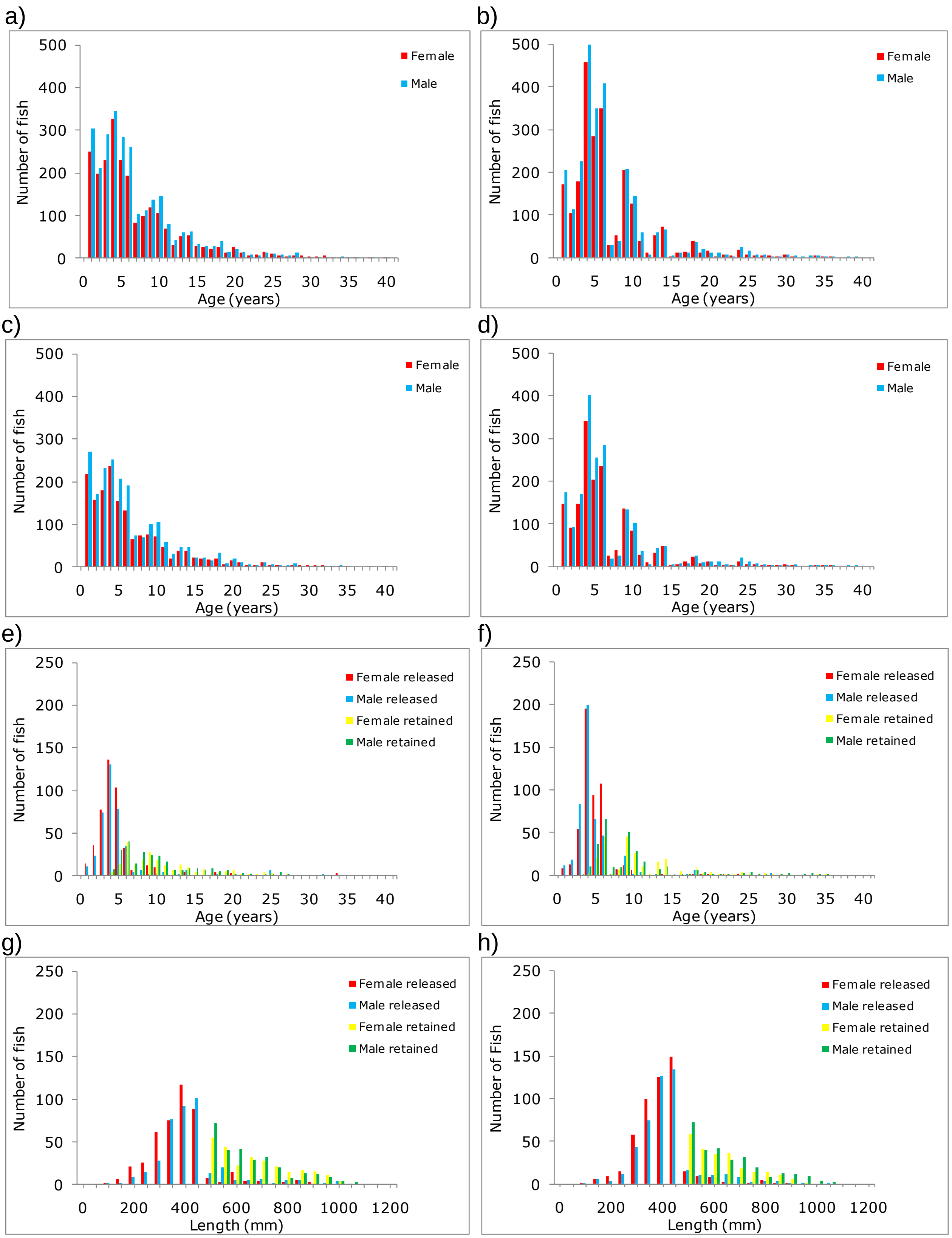


Figure 10. Results of simulations 1 (*Glaucosoma hebraicum* with low recruitment variability) *vs* simulation 2 (*G. hebraicum* with high recruitment variability). (a,b) Age compositions for the populations of *G. hebraicum* at the beginning and (c,d) end of the simulations, and the age (e,f) and length compositions (g,h) of *G. hebraicum* in catches.. Figures on left and right display results for simulations 1 and 2, respectively

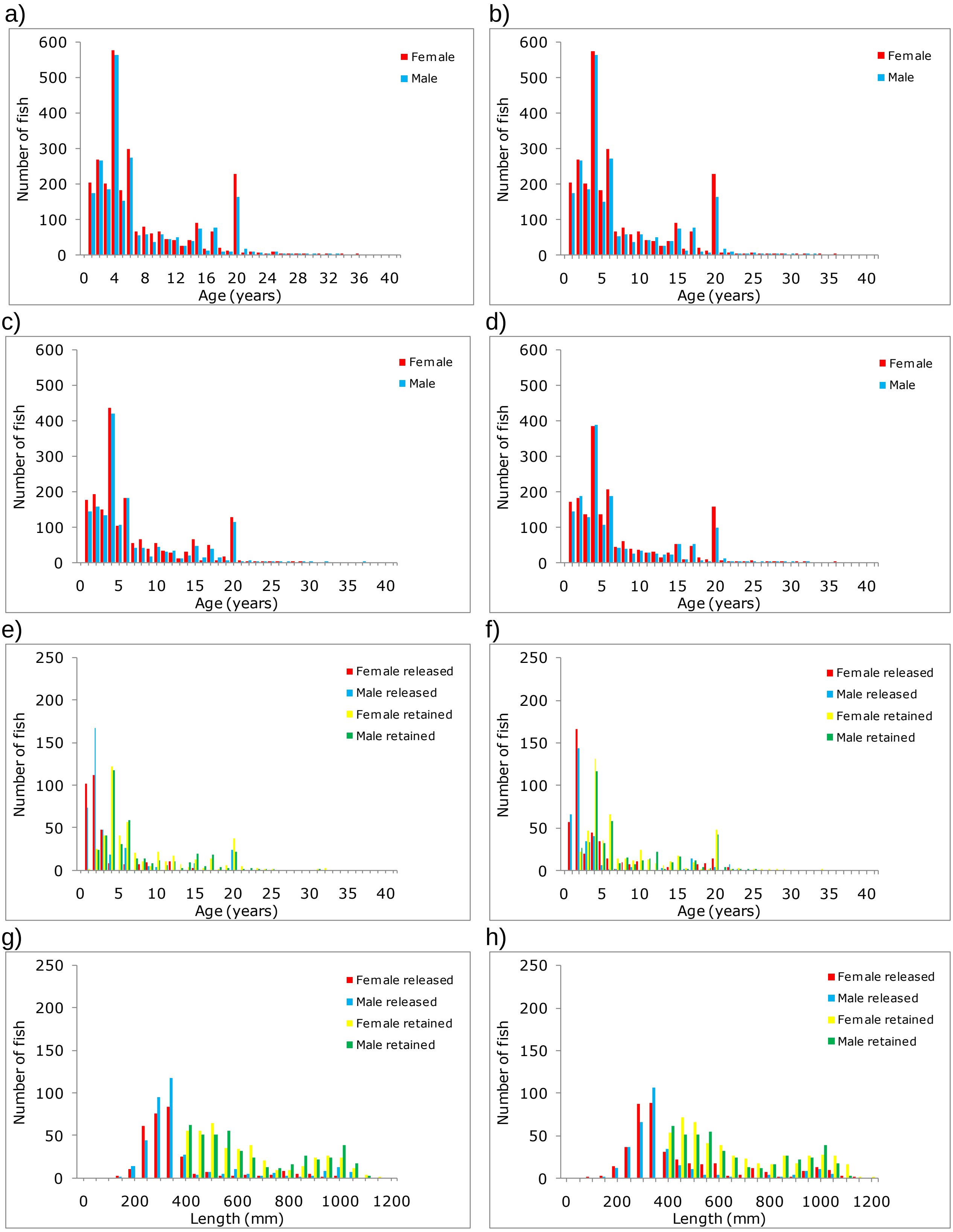


Figure 11. Results of simulations 1 (*Glaucosoma hebraicum* with low recruitment variability) *vs* simulation 2 (*G. hebraicum* with high recruitment variability). (a,b) Age compositions for the populations of *C. auratus* at the beginning and (c,d) end of the simulations, and the age (e,f) and length compositions (g,h) of *C. auratus* in catches. Figures on left and right display results for simulations 1 and 2, respectively.

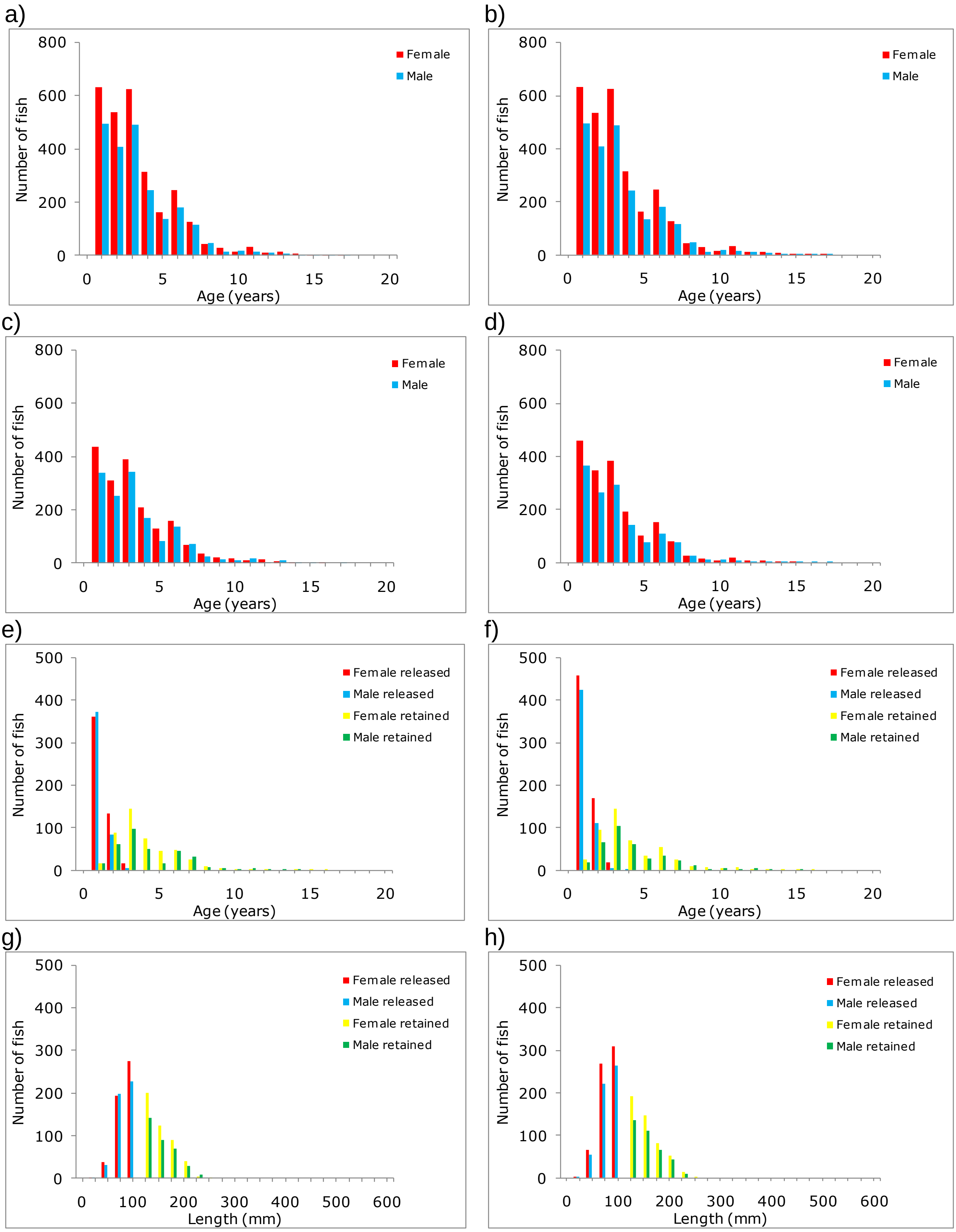


Figure 12. Results of simulations 1 (*Glaucosoma hebraicum* with low recruitment variability) *vs* simulation 2 (*G. hebraicum* with high recruitment variability). (a,b) Age compositions for the populations of Red Herring at the beginning and (c,d) end of the simulations, and the age (e,f) and length compositions (g,h) of Red Herring in catches. Figures on left and right display results for simulations 1 and 2, respectively.

this species were dominated by 7, 9 and 10 year old fish, which were very abundant in the initial population (Fig. 10). Likewise, 4, 6 and 20 year old fish, which were abundant in the *C. auratus* population, were most frequently caught by fishers (Fig. 11). The length compositions demonstrated that the majority of *G. hebraicum* caught by fishers were released, whereas most Snapper and about half of the Red Herring captured were retained, reflecting the different patterns of growth and size restrictions for these species (Figs 10-12).

Fishers caught and retained slightly more *G. hebraicum* (520 fish) in the simulation for the high recruitment variability population of this species than was the case for the low recruitment variability population (493 fish). Furthermore, the daily bag limit for *G. hebraicum* was attained on several more trips in that former simulation (129 vs 116) (Table 3). As the proportion of fish above 5 years (*i.e.* age at which individuals start becoming recruited into the fishery) was similar for the two simulations (~47%), the slightly greater catches for the *G. hebraicum* population with high recruitment variability can be explained by the slightly greater time that fishers spent fishing for fish of that population (3,799 vs 3,712 hours) and the stochastic nature of the simulations.

The simulations also demonstrated that recruitment variability has the potential to influence fisher behaviours. In the simulation for *G. hebraicum* with high recruitment variability, fishers received more bites (5,405 vs 4,650) from good-sized (> 400 mm) fish, presumably reflecting the presence of a relatively large number of fish of 4-5 year old fish with lengths just below the minimum legal length limit (Fig 10). As a consequence of the improved bite rates, fishers undertook fewer searches for new

Table 3. Statistics generated by the agent-based model for five simulations in which certain parameters for the West Australian Dhufish *Glaucosoma hebraicum* were altered. The statistics provide information on activities of fishers whilst fishing, the numbers of fish bites received by fishers and fish caught, released and retained, and the number of times fishers attained their boat limits.

	Simulation Number				
Statistics	**1**	**2**	**3**	**4**	**5**
Total fishing trips	1,173	1,169	1,183	1,195	1,136
Total hours fished	3,712	3,799	4,164	3,842	3,651
Total searches	362	309	491	358	361
Total hours searched	30	27	39	29	27
Proportion time searching	0.01	0.01	0.01	0.01	0.01
Average minute searched	4.9	5.2	4.7	4.8	4.5
Average moves per trip	1.5	1.4	1.9	1.4	1.5
Fish bites	58,688	56,959	44,431	60,859	53,083
Good fish bites	4,650	5,405	3,561	5,480	4,665
Fish released	2,490	2,903	2,417	3,151	2,681
Fish retained	2,193	2,318	2,250	1,988	2,062
Proportion of fish retained	0.47	0.44	0.48	0.39	0.43
Dhufish released	838	983	456	1381	1046
Snapper released	681	729	807	728	640
Red Herring released	971	1191	972	1042	995
Dhufish retained	493	520	316	307	370
Snapper retained	898	945	904	835	909
Red Herring retained	802	853	825	846	783
CPUE (retained Dhufish)	0.44	0.42	0.27	0.26	0.33
CPUE (retained Snapper)	0.80	0.76	0.78	0.70	0.80
CPUE (retained Red Herring)	0.73	0.68	0.71	0.71	0.69
Multi-species boat limit attained	54	64	34	22	90
Boat limit attained for Dhufish	116	129	54	54	370
Boat limit attained for Snapper	56	54	62	39	59
Boat limit attained for Red Herring	0	0	0	0	0

Details of simulations:

Simulation 1; Initial abundance = 5,000 fish, recruitment variability = low, MLL = 500 mm, Boat limit for Dhufish = 2 fish day^{-1}.
Simulation 2; Initial abundance = 5,000 fish, recruitment variability = high, MLL = 500 mm, Boat limit for Dhufish = 2 fish day^{-1}.
Simulation 3; Initial abundance = 2,500 fish, recruitment variability = low, MLL = 500 mm, Boat limit for Dhufish = 2 fish day^{-1}.
Simulation 4; Initial abundance = 5,000 fish, recruitment variability = low, MLL = 650 mm, Boat limit for Dhufish = 2 fish day^{-1}.
Simulation 5; Initial abundance = 5,000 fish, recruitment variability = low, MLL = 500 mm, Boat limit for Dhufish = 1 fish day^{-1}.

fishing locations (309 vs 362 searches) (Table 3), and spent longer fishing, and this, in turn, was accompanied by greater catches of the other two species.

In summary, the simulations for recruitment variability demonstrated that, by its impact, at any particular time, on the abundance of individuals of certain sizes, recruitment variability can influence the behaviours of fishers which can have implications for that and other species in the fishery. It should be noted, however, that at this time, the possibility of a relationship between fish length and depth, and thus the ability of fishers to target larger fish, has not been investigated. The possibility that the presence of larger fish in a grid cell may reduce the catchability of smaller fish (of either the same or different species) in that cell also has not been investigated.

Implications of changes in fish abundance

(Simulation 1 vs 3)

As would be expected, a reduction in the number *G. hebraicum* resulted in fewer individuals of this species being caught. A halving of the abundance of individuals in the *G. hebraicum* population resulted in the number of caught and released *G. hebraicum* being reduced by 46% and the number of individuals caught and retained being reduced by 36% (Table 3). The reduced abundance of *G. hebraicum* was accompanied by an increase in fishing time (by 452 hours), a greater number of searches (491 vs 362), reflecting lower bite rates, and a greater number of moves to new fishing locations (1.9 vs 1.5 moves per trip). Although the greater fishing activity for the simulation with lower *G. hebraicum* abundance resulted in more *C. auratus* being caught and released (807 vs 681 fish), a similar number of the latter species were caught and retained (904 vs 898 fish). The lower abundance of *G. hebraicum* resulted in far fewer fishers attaining their boat limits for that species, and the mixed boat limit for *G. hebraicum* and *C. auratus* (Table 3). Thus, the simulations indicate that a change in the abundance of a species can have a major impact on the dynamics of a fishery, by influencing catches of that and other species, impacting bite rates and thus, in turn, the targeting behaviours of fishers (Table 3).

Implications of changes in common management controls

Change in the minimum legal length for retention

(Simulation 1 vs 4)

An increase in the minimum legal length (MLL) from 500 to 650 mm for *G. hebraicum* led to marked increase in the number of individuals of this species caught and released (1381 vs 838 fish) and a large reduction in the number caught and retained (307 vs 493 fish) (Table 3). Consequently, the boat limit for *G. hebraicum* was achieved less often (*i.e.* 54 vs 116 trips) and the same was true for the mixed boat limit for this species and *C. auratus* (22 vs 54 trips). Increasing the MLL did not have a major impact on the catches of Snapper and Red Herring (Table 3).

Although an increase in the MLL for *G. hebraicum* reduced the abundance of legal-sized fish, this did not lead to greater moving and searching by fishers (unlike the previous simulation in which the overall abundance of this species was reduced). In the current simulation for an increased MLL for *G. hebraicum*, the number of good bites received by fishers was higher (5,480) than in any previous simulation, reflecting the greater abundance of sub legal-sized West Australian Dhufish. The greater abundance of sub-legal sized *G. hebraicum* > 400 mm, in combination with the model’s assumption that fishers will not move from a fishing location whilst encountering an acceptable bite rate, helps to account for the lack of any marked increase in the number of movements and searches by fishers (Table 3).

Thus, the simulations indicated that increasing the MLL for a species is likely to greatly affect the catches of that species, with relatively far fewer fish being retained, and much larger numbers being released (some of which may die due to fishing-induced barotraumas). The preliminary simulations did not predict that a change in the MLL for *G. hebraicum* will impact greatly on other fish species or the behaviours of fishers. However, it is important to recognise that other factors, such as recruitment variability, will impact on the degree to which a change in the MLL influences fishers and their catches at any one time, depending on the abundances of fish belonging to the younger and older age classes.

Change in the boat limit for a species

(Simulation 1 vs 5)

Halving the boat limit for *G. hebraicum* resulted in a marked reduction (493 to 370 fish) in the number of this species caught and retained by fishers, and an increase in the number caught and released (838 to 1046 fish) (Table 3). A substantial number of those released fish (325 fish) were above the MLL, and thus represent fish that had been caught by fishers after having attained their boat limit for *G. hebraicum*. As a consequence of the boat limit reduction for *G. hebraicum*, fishers attained the boat limit for this species far more often (from 116 to 370 of all trips) and the same was true for the mixed boat limit (from 54 to 90 of the trips). Although the mixed boat limit was attained more frequently by fishers in the simulation for which the boat limit for *G. hebraicum* was halved, similar numbers of *C. auratus* were caught in the two simulations (898 vs 909 fish), reflecting the fact that fishers spent similar time fishing and searching.

Summary of findings and their implications

In brief, the simulations showed that, at any time, recruitment variability influences the relative abundance of individuals of a species in different size classes which, in turn, can influence catches of that species. The model predicts that when the abundance of recruited individuals of a species is low, *e.g.* as may occur when fishing pressure has been heavy (or because of recruitment variability), this can influence the targeting behaviours of fishers, and thus have consequences for other species in the fishery. Increasing the MLL and reducing the boat limit for *G. hebraicum* greatly affected the simulated catches of this species, with far fewer fish being retained and more being released. Although such a situation may have some benefits for a fishery, issues associated with discard mortality, high-grading and negative impacts on the experience of recreational fishers would, of course, also need to be considered. Catch and release mortality is a factor is taken into account by the model but further development is required to generate statistics to explore the consequences of such release mortality.

Over the next two years, we will be extending and exploring the model further to undertake more detailed investigations of the implications of recruitment variability, fish abundance and management for recreational fisheries. Important variables known to influence fisher behaviours, such as water depth and species “depth preferences” and weather and its impacts on fishers, will be incorporated into the model. The model is ideally suited to exploring the consequences of spatial and temporal management controls. The consequences of alternative assumptions about the ways in which fishers target particular fish species in a multi-species fishery will be explored and broader implications of recruitment variability for the sustainability of a fishery (*i.e.* average effects) will be investigated by running multiple simulations for fish species with different series of recruitments.

In summary, this study represents one of very few to have used simulation approaches to explore the potential implications of different responses by recreational fishers to management. It is the first to focus on a recreational, boat-based line fishery in Western Australia. The relevance of this type of research for fisheries management is highlighted, for example, by the statement of Branch *et al.* (2006) that as almost all regulatory action affects the fishing fleets pursuing the fish, studies of the behaviours of fishers should be as important a part of fisheries science as studies of fish ecology and population dynamics. Likewise, Haapasaari *et al.* (2007) state that effective management must consider fishers' reactions to such management, and Hilborn (1985) and Jentoft *et al.* (1998) note that a failure to understand and manage the behaviours of fishers has contributed to many fisheries problems. Pereira and Hansen (2003) highlight that key aspects which pose particular challenges for managing recreational fisheries are a lack of knowledge of the ways in which recreational fishers target fish species and how their fishing effort varies spatially and temporally. The agent-based model developed in this study thus provides an excellent tool to facilitate the development of more effective management plans for recreational fisheries.

BENEFITS AND ADOPTION

As outlined in the original application, this project was initiated by RecFishWest, who identified the need for a simulation tool, such as the agent-based model developed in this study, to assist recreational fishers in understanding issues related to recruitment variability in finfish, and associated implications of different types of fishing regulations. Our project application also outlined the key need to develop fisheries scientists with strong quantitative skills.

The agent-based model developed in this study is a tool that can potentially be used for a range of beneficial purposes. These include 1) communicating to recreational fishers the implications, for their catches and sustainability of fish stocks, of variable recruitment of fishes and different management, 2) predicting the behavioural responses of fishers to different fisheries regulations to facilitate the development of management plans which provide maximum benefit for the conservation of fish stocks while minimising, to as great an extent as possible, disruption to fishers, and 3) as an educational tools for students of fisheries biology, fish stock assessment and/or fisheries management. The simulation tool will be of benefit to fisheries researchers and managers of Australian fisheries agencies (particularly DoF, WA), and researchers at other universities and institutions.

This project has benefitted greatly several early-career research scientists, who were introduced to concepts related to simulation and fisheries modelling. The continued mentoring of this group of students/early-career fisheries researchers will be of future benefit to agencies such as DoF.

The agent-based model software will be made freely available over the internet. The project investigators will advertise the results of the study and availability of the model by continued interaction with fishers and RecFishWest and DoF, postings on RecFishWest's internet fishing forum, “Hotbite”, and local fishing magazines such as Western Angler.

FURTHER DEVELOPMENT

The agent-based model developed in this study will continue to be improved and extended, with more detailed exploration and testing of the model by C. Tink over the next two years (for her PhD). Model development will focus on a range of areas, including 1) optimising the efficiency of model routines to enhance program speed, 2) introducing additional factors known to influence the distribution and behaviours of fish and fishers, 3) improving the data inputs for the fishery of current focus of the model (the recreational, demersal finfish fishery of Perth coastal waters) and 4) enhancing the applicability of the model for other fisheries.

Optimising the efficiency of model routines

By their nature, ABMs are very computer intensive, and this has the potential to constrain their usefulness (Breckling *et al.*, 2006). For this reason, we invested considerable time implementing an efficient algorithm (AVL tree) for storing and retrieving information required to schedule and process the events of the simulation. A full simulation now takes about one and a half hours on a standard desktop or notebook computer, which thus makes the program very accessible (*i.e.* for a simulation representing 1 year in the fishery, with the area represented by a grid size of 128 x 128 cells, and with 15,000 fish, and 30 fishers who fish regularly). However, we are aware that introducing additional factors into the model (see below) is likely to reduce program speed and thus we are exploring ways in which to optimise program efficiency.

Additional factors in the model

Water depth and weather

The results of our survey and focus group discussion with recreational fishers revealed that depth and weather are important factors influencing the dynamics of recreational fisheries. We are exploring alternatives for modifying the code to enable generation of landscapes which incorporate bathymetric information. Once depth is incorporated, individuals of fish species will be placed over the landscape in proportion to the estimated relative abundances of different species at various depth intervals (as estimated from the survey). We then intend to incorporate variables for weather (wind speed and swell), which will influence the decisions of fishers of when to go fishing, and where to fish. An exploration of interactions between management, weather and depth-related fisher, fish-targeting behaviours may provide useful insights for managers on the effectiveness of different management controls.

Fish schooling and migratory behaviours

As a component of her PhD study, C. Tink will be exploring implications of fish schooling and migratory behaviours. Agent-based modelling is well-suited to such explorations, and a number of approaches have been used (*e.g.* see review of Parrish *et al.*, 2002).

Factors influencing decisions of fishers to go fishing

In discussions with industry stakeholders, it became clear that an exploration of other factors influencing the decisions of recreational fishers to go fishing would be valuable for fisheries managers. One aspect highlighted in those discussions was the influence of the mining boom(s) in Western Australia. Thus, it was considered that an increasing number of recreational fishers are likely to be “cashed up, fly in and fly out” mining workers, who have considerable spare time during periods of the year when traditionally, most fishers were working, *i.e.* during the week, outside of traditional holiday periods.

Applicability of the model for other fisheries

As discussed in the background section (of this report) on agent-based modelling, a disadvantage of ABMs is that they are often difficult to adapt to systems other than those for which they were originally designed (Murdoch et al., 1992; Grimm, 1999). However, in our discussions with fishery stakeholders, it became apparent that, with a few modifications, our model could be applicable for a range of recreational wetline fisheries and commercial fisheries.

PLANNED OUTCOMES

Planned outcomes as stated in the original application

(1) Recreational fishers will be better informed and more able to consider and discuss the effects of recruitment variability on their catches and the implications of that variability for the sustainability of fish stocks. The simulation tool that is developed will assist in communicating how recruitment variability affects catches and the consequences for fish stocks.

(2) Recreational fishers, fisheries scientists and fishery managers will understand

better the likely response of individual fishers to alternative fisheries regulations and be better able to develop effective management strategies. By simulating the response of individual fishers to changes in abundance and in activity in response to fisheries regulations, the overall average response can be assessed.

(3) By providing training and experience in the development of an agent-based computer simulation model of the interaction between individual fishers and individual fish from a stock with high recruitment variability, an early-career fisheries scientist equipped with quantitative skills will become available for recruitment to one of Australia's Fisheries Agencies or the fishing industry.

(4) Fisheries managers will benefit from improved advice on the social implications associated with alternative fisheries management regulations, such as the impact on different groups of fishers. The simulation model will explore the implications of fishing at a local scale and the interactions of individual fish with their habitat, thereby supplementing the results obtained from traditional, whole-of-fishery models.

Planned outcomes 1 and 2

The simulation tool which has been developed in this study provides a range of graphics and figures to convey how different levels of recruitment variability, fish abundance and biology, fisher behaviours and management interact to influence the age and size compositions and abundance of fish in simulated catches (and in the fish population).

Recreational fishers will be made aware that the program and information about the project are available from a website, by means of a workshop held with fishers (run by the project investigators and RecFishWest), by advertising (on RecFishWest's website), and by “word of mouth”. They will be able to use the program to explore how different levels of fish abundance and recruitment variability, and different management are likely to influence their catches and the sustainability of fish populations. Alternatively, fishers will be able to use the “gaming” option in the program, allowing users to alter the behaviours of one of the fishers in the fishing fleet and explore how the fishing success of that fisher compares with the rest of the fleet.

During the project, the project investigators held a survey and focus group discussion evening (at RecFishWest) with a group of keen and experienced recreational fishers who catch demersal finfish species in Perth coastal waters. During that evening, fishers were made aware of the project and its aims, and contributed to the project by providing survey data. Soon after the completion of the project, the investigators will contact those fishers (through RecFishWest) and provide them feedback on how the project has progressed. A colleague at Murdoch University (Dr Howard Gill) is kindly arranging a survey and discussion evening with a second group of fishes in the Mandurah region. As the research progresses beyond the FRDC project, we will continue to interact with fishers to inform them of the results of the project and the new model.

Planned outcome 3.

As planned, this project led to several early-career fisheries researchers being introduced to computer simulation and modelling techniques. Furthermore, N. Hall provided excellent mentoring for the PI, increasing his modelling skills and experience. B. Chuwen continues to develop his quantitative skills in the fisheries area and has been introduced to computer programming and simulation. Honours student R. Burch produced an excellent Honours thesis on agent-based modelling and has expressed an interest in furthering her studies in fisheries science. C. Tink is continuing with her PhD studies on agent-based modelling. The current project thus achieved its aim of helping to make available a greater pool of recruits for Australian fisheries agencies of young fisheries scientists with strong quantitative skills.

Planned outcome 4.

The agent-based model that has been developed in this project explores implications of fishing at a local scale, and the interactions of individual fish with their habitat. The current model provides predictions of the ways in which fishers are likely to respond to certain management controls, which will be of benefit to managers. With continued development, the model will become a useful supplement to traditional, whole of fishery models as a means for providing management advice. For example, agent-based models can potentially provide a greater environmental and social context within which to place the results of traditional whole of fishery models.

CONCLUSION

This project has achieved its objectives and resulted in the development of a modelling tool that can be used to communicate to fishers the implications of recruitment variability for their catches and the sustainability of fish. A group of keen and experienced recreational fishers contributed to the success of the project by providing key data in a survey to determine how those fishers target offshore demersal finfish species in coastal waters of south-western Australia.

The agent-based model produced in this project enables explorations of the consequences of localised interactions between recreational boat, demersal line fishers and key demersal finfish species for fishers' catches and fisheries management. The model is thus ideally suited for investigating how individual recreational fishers are likely to respond to changes in fish abundance and to changes in commonly-used fisheries regulations. In this regard, the model has potential to be of great benefit for providing advice to managers when developing future plans for recreational fisheries.

A series of preliminary simulations provided insights as to how fishers are likely to respond to the affects of recruitment variability, changes in the abundance of a species and changes in the management controls for that species (in a multi-species fishery). Recruitment variability is predicted to strongly influence the catches of fishers because it can markedly alter the relative abundance of fish of different sizes in a fishery at any one time. When the abundance of such fish is low, fishers are predicted to fish longer and thereby attempt to maintain their catch rate for that species, which may thus, in turn, also impact on other species in the fishery. A change in the relative abundance of a species through fishing, for example, is predicted to have similar effects. The simulations indicated that increasing the MLL and or reducing the boat limit for a species will have a marked influence on the catches of that species, with far fewer fish being retained and many more being released.

The simulations undertaken thus far already demonstrate the great potential of the model developed in this study for exploring consequences of recruitment variability, and changes in fish abundance and management for multi-species fisheries.

This project provided an excellent vehicle for training several early career fisheries scientists at Murdoch University's Centre for Fish and Fisheries Research in computer simulation and modelling techniques. Studies related to the agent-based model produced in this study will continue beyond the current FRDC project. These studies will lead to further enhancement of the modelling skills of several early career fisheries researchers, and an improved model of increased benefit to researchers and fish industry stakeholders.

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APPENDIX 1. INTELLECTUAL PROPERTY

The information produced in the study is not suited to commercialisation.

APPENDIX 2. STAFF

Alex Hesp

Norm Hall

Ben Chuwen

Research students: Rowena Burch (Hons) and Calais Tink (PhD)

APPENDIX 3 - RECREATIONAL FISHER SURVEY

Background: This survey was prepared for a range of purposes, including i) helping to inform and parameterise the agent-based model, ii) obtaining information to extend the model in the future, iii) further knowledge of how fishers target demersal finfish species in south-western Australia and iv) document recreational fisher knowledge of the habitats and movements of West Australian Dhufish and Snapper. A description and analysis of the survey data (for *G. hebraicum*) are provided in Chapter 2 of R. Burch's Honours thesis, entitled "Description and parameterisation of an agent-based model to explore the implications of recruitment variability for the recreational fishery for West Australian Dhufish, *Glaucosoma hebraicum*" (will be available from the Murdoch University library). C. Tink will be undertaking further surveys in the future for her PhD on agent-based modelling.

1. Over the last 12 months, how many times do you think you would have gone fishing from a boat? (Please enter number in box to the right). ☐

2. Please tick the most appropriate box for each of the following statements?

	Never	**Some-times**	**Often**	**Most times**	**Every time**
When I went fishing over the last 12 months, I fished from a boat	☐	☐	☐	☐	☐
When I went boat fishing over the last 12 months, I caught **Dhufish**	☐	☐	☐	☐	☐
When I went boat fishing over the last 12 months, I caught **Snapper**	☐	☐	☐	☐	☐
When I went boat fishing over the last 12 months, I fished on weekends	☐	☐	☐	☐	☐

3. On your last boat fishing trip, how many people were on the boat and actively fishing? (Please enter number in box to the right). ☐

4. On your most recent boat fishing trip, how long did you spend fishing? (Specifically, how much time did you spend on the water, between having arrived at your first fishing location and having left from your final fishing location to travel home)
(Please tick only **one** box):

- 1 – 2 hours ☐
- 3 – 4 hours ☐
- 5 – 6 hours ☐
- 7 – 8 hours ☐
- 9 – 10 hours ☐
- 11 – 12 hours ☐
- More than 12 hours ☐

5. If you went boat fishing at one of your favourite fishing locations, how long would you stay there if you were not getting any "good" bites from a fish?
(By good bites, we mean bites from a fish likely to be big enough that you would keep them, if you caught those fish) Please tick only **one** box:

- Less than 5 minutes ☐
- 5 – 10 minutes ☐
- 10 – 15 minutes ☐
- 15 – 20 minutes ☐
- 20 – 30 minutes ☐
- 30 minutes – 1 hour ☐
- Rarely or never move ☐

6. If you went boat fishing at a location where you have never fished before, how long would you stay there if you were not getting any "good" bites from fish.
(By good bites, we mean bites from a fish likely to be big enough that you would keep them, if you caught those fish) Please tick only **one** box:

- Less than 5 minutes ☐
- 5 – 10 minutes ☐
- 10 – 15 minutes ☐
- 15 – 20 minutes ☐
- 20 – 30 minutes ☐
- 30 minutes – 1 hour ☐
- Rarely or never move ☐

7. Which times of the day do you consider best for catching **Dhufish**?
(Please tick multiple boxes if required):

- Sunrise/ early morning ☐
- Mid morning ☐
- Mid day ☐
- Mid afternoon ☐
- Late afternoon/sunset ☐
- Night ☐
- I use a lunar (or solunar) chart ☐
- No particular time is best ☐
- Not sure – I rarely catch Dhufish ☐

8. Which times of the day do you consider best for catching **Snapper**?
(Please tick multiple boxes if required):

- Sunrise/ early morning ☐
- Mid morning ☐
- Mid day ☐
- Mid afternoon ☐
- Late afternoon/sunset ☐
- Night ☐
- I use a lunar (or solunar) chart ☐
- No particular time is best ☐
- Not sure – I rarely catch snapper ☐

9. On my last boat fishing trip:
(Please tick only **one** box)

- I was mainly aiming to catch **Dhufish** ☐
- I was mainly aiming to catch **Snapper** ☐
- I was mainly aiming to catch **fish species other than Dhufish or Snapper** ☐
- I was aiming to catch a **mix of fish species including Dhufish or Snapper** ☐

10. On your last boat fishing trip, did you catch and retain the bag limit for **Dhufish**?
(bag limit = 2 fish per day)

Yes ☐

No ☐

11. On your last boat fishing trip, did you catch and retain the bag limit for **Snapper**?
(bag limit = 2 fish per day, with 1 fish over 700mm)

Yes ☐

No ☐

12. On your last boat fishing trip, which times of the day were you actively fishing?
(Please tick multiple boxes if required):

- Sunrise/ early morning ☐
- Mid morning ☐
- Mid day ☐
- Mid afternoon ☐
- Late afternoon/sunset ☐
- Night ☐

13. When you go boat fishing, what percentage of your time do you spend using the two types of fishing methods listed below?
(**Note:** If you fish by both methods, the percentages should add up to 100%):

Line fishing (using a handline, rod and line, line with snapper or mechanical winch) ☐

Spearfishing ☐

14. When fishing for **Dhufish**, what percentage of your time do you spend: (**Note:** If you fish using more than one of the methods listed below, the percentages should add up to 100%):

Fishing using an anchor	☐
Drift fishing with a sea anchor	☐
Drift fishing without a sea anchor	☐
I never target Dhufish when I go fishing	☐

15. When fishing for **Snapper**, what percentage of your time do you spend: (**Note:** If you fish using more than one of the methods listed below, the percentages should add up to 100%)

Fishing using an anchor	☐
Drift fishing with a sea anchor	☐
Drift fishing without a sea anchor	☐
I never target Dhufish when I go fishing	☐

16. In your opinion, how skilled are you at identifying each of the following habitat types using an echo sounder:
(Please enter a value ranging from 0 = not skilled at all to 10 = extremely skilled):

Non-reef habitat	☐
Reef edge	☐
Reef top	☐
Reef caves/crevices	☐

17. How good do you think the following habitats are for catching **Dhufish**?

	Poor	Average	Good	Very Good	Excellent
Sand more than 20 m away from reef	☐	☐	☐	☐	☐
Sand within 20 m of reef	☐	☐	☐	☐	☐
Reef top	☐	☐	☐	☐	☐
Reef edge	☐	☐	☐	☐	☐
Caves found on the reef edge	☐	☐	☐	☐	☐
Caves found over the reef	☐	☐	☐	☐	☐
Isolated reef "lumps"	☐	☐	☐	☐	☐

18. How good do you think the following habitats are for catching **Snapper**?

	Poor	Average	Good	Very Good	Excellent
Sand more than 20 m from reef	☐	☐	☐	☐	☐
Sand within 20 m of reef	☐	☐	☐	☐	☐
Reef top	☐	☐	☐	☐	☐
Reef edge	☐	☐	☐	☐	☐
Caves found on the reef edge	☐	☐	☐	☐	☐
Caves found over the reef	☐	☐	☐	☐	☐
Isolated reef "lumps"	☐	☐	☐	☐	☐

19. Do you have a GPS?

Yes ☐

No ☐

20 **a)** If you answered "**YES**" to Q19. , how many fishing spots do you have marked in your GPS? ☐

b) What percentage of your collection of fishing spots marked in your GPS do you consider to be very good fishing locations that you would visit regularly? (0% = none, 100% = all of the fishing spots) ☐

21. In what water depths would you mostly target **Dhufish**?
(Please tick only **<u>one</u>** box):

- Less than 15 meters ☐
- 15 – 25 meters ☐
- 25 – 35 meters ☐
- 35 – 55 meters ☐
- 55 – 95 meters ☐
- More than 95 meters ☐
- Not sure – I never target dhufish ☐

22. In what water depths would you mostly target **Snapper**?
(Please tick only **<u>one</u>** box):

- Less than 15 meters ☐
- 15 – 25 meters ☐
- 25 – 35 meters ☐
- 35 – 55 meters ☐
- 55 – 95 meters ☐
- More than 95 meters ☐
- Not sure – I never target snapper ☐

23. How important is the weather in influencing your decisions as to whether you would go boat fishing on a particular day?
(Please tick only **one** box)

The weather almost never stops me going fishing ☐

The weather sometimes stops me going fishing ☐

I only go boat fishing when the weather is very calm ☐

24. I would cancel a boat fishing trip if:
(Please tick only **one** box)

Forecasted wind strength is 10-20 knots and/or swell greater than 1.5 m ☐

Forecasted wind strength is 20-30 knots and/or swell greater than 2.5 m ☐

Only if a weather warning is current ☐

25. I would start boat fishing earlier and/or stop boat fishing if there is a:
(Please tick only **one** box)

10 – 20 knot sea breeze ☐

20 – 30 knot sea breeze ☐

Greater than 30 knot sea breeze ☐

26. On your most recent boat fishing trip, how far offshore did you travel before you started fishing?

Less than 5 km	☐
5 – 10 km	☐
10 – 15 km	☐
15 – 20 km	☐
20 – 25 km	☐
25 – 30 km	☐
More than 30 km	☐

27. Does the weather you encounter when boat fishing strongly influence how far you are prepared to travel offshore to go to a fishing spot?

Yes	☐
No	☐

28. If you answered "**YES**" to Q27., please answer the following:

i) On a calm day, I would travel up to_____________km offshore.

ii) On a day of moderate conditions, I would travel up to _____________km offshore.

iii) On a rough day, I would travel up to _____________km offshore.

29. Do you **Strongly Disagree**, **Disagree**, **Agree** or **Strongly Agree** with the following statements?

	Strongly Disagree	**Disagree**	**Neutral**	**Agree**	**Strongly Agree**
I have many fishing spots on my GPS, but of these, there are a few which I visit far more frequently than the others, because those few spots provide exceptional fishing	☐	☐	☐	☐	☐
The areas I tend to start fishing on a particular fishing trip are often those where, on my previous fishing trip, I had good success	☐	☐	☐	☐	☐
I often fish in areas which friends have recommended?	☐	☐	☐	☐	☐
I use nautical charts, or other charts (such as those available from tackle shops with approximate coordinates of fishing locations) as a guide to help me start searching for new fishing spots	☐	☐	☐	☐	☐
I use information available from the internet to locate new fishing locations	☐	☐	☐	☐	☐
I often use depth contour and/or other inbuilt information in my GPS to locate new fishing spots	☐	☐	☐	☐	☐

End of survey

GENERAL DEMOGRAPHIC INFORMATION ON SURVEY PARTICPANTS

1. Are you:

Male ☐

Female ☐

2. Aged between:

18 – 29 years ☐

30 – 44 years ☐

45 – 59 years ☐

Over 59 years ☐

3. What is your current postcode?

Post Code ☐

4. How long have you been fishing?

0 – 2 years ☐

2 – 10 years ☐

More than 10 years ☐

5. Do you live in a household that owns a boat used for recreational fishing?

Yes ☐

No ☐

Please provide any comments you would like to make regarding the survey or any additional information you would like to give? Some suggested areas on which you may wish to comment:

1.) Any aspects you feel should have been included in the survey and why
2.) What you understand about the habitats of Dhufish and Snapper and their movements
3.) How you use your knowledge about Dhufish and Snapper to increase your fishing success
4.) What do you do differently to target Dhufish vs Snapper?
    i) Fish at different times of the day for the different species,
    ii) Use different fishing techniques,
    iii) Fish over different habitats?
5) What features on an echo sounder are most indicative of the best habitats for Dhufish and Snapper, and why (that is, what do those features indicate to you about the habitat)