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# A spatially explicit learning model of migratory fish and fishers for evaluating closed areas

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## Abstract

Fisheries models usually characterise the concentrations of fish and the distribution of the fishing fleet by spatial averages over large areas assuming homogeneous spatial characteristics. Many important management questions, such as those related to the spatial effects of closed areas, cannot be addressed by such models. This paper presents a model which describes the spatial movement of individual fish schools and the spatial response of individual fishing boats, and which can be applied on a much finer scale and thus can be used to analyse the scale-dependent development of the fishery. The motion of the fish is based on assumptions about time-dependent gradients in the relative attractiveness of nearby grid cells which motivate migrations based on feeding and spawning factors. The motion of fishing boats is modelled in a similar fashion, with the attractiveness of neighbouring cells based on historical catch records as a function of position and time of year, as well as whether current catch rates are high enough to justify staying in the same cell. Our model showed that marine reserves increase fish biomass but decrease fish catches. It is also indicated that marine reserves are of limited use when not combined with quotas of catches. Our findings also point that transfer rates of fish increase the benefits of marine reserves in terms of fish biomass but decrease fish catches.

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**Keywords:** Fish; Fishers; Closed area; Fleet dynamics; Marine reserves; Spatial behaviour

## 1. Introduction

Much of the difficulty in fisheries modelling and management arises from dealing with very different scales in time, space, and trophic depth (Gessner et al., 2004). Spatial scales are particularly difficult to

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address (Giller et al., 2004), since most fish species are very mobile, and while fishing fleets are also mobile their ability to locate fish aggregations is usually limited to those within a range of several hundred metres (there are some exceptions – surface-schooling fish like menhaden can be located with spotter airplanes). Stock assessments usually deal with the movement of fish by averaging the populations over large areas, typically several hundred square kilometres (e.g., NAFO map) and stock sizes are almost always calculated on an annual basis. These assessments are of limited value to fishers, particularly those who use fixed gear or who are restricted in the region they can fish because they use small boats or are subject to local regulatory restrictions. They also do not provide a suitable basis for assessment of localised management measures, such as marine protected areas (MPAs) and seasonal closures.

An alternate approach is to focus on the spatial distribution of the fish and fishers, and to develop models which focus on the factors affecting their motion, rather than trying to add transport mechanisms to models based on population dynamics and ecological interactions. One way to do this is by the use of cellular automata, which are designed specifically for the modelling of the dynamics of spatial distributions (Wolfram, 1983a; Ermentrout and Edelstein-Keshet, 1993). A cellular automaton is a grid-based discrete time model with rules describing how the occupancy of the grid cells changes from one time step to the next. Usually it is assumed that the contents of each cell depend only on the contents of it and adjoining cells during the previous time step, which provides a discrete representation of the continuous motion of objects (in this case fish and fishing boats) between positions represented by the cells (Wolfram, 1983b). However, the use of cellular automata in ecology can have trivial results when significant biological characteristics are omitted or misinterpreted (Ruxton and Saravia, 1998), so identifying the correct rules for iterating from one time step to the next is of critical importance.

The use of cellular automata is not the only way to address the modelling of spatial aspects of fisheries. One of the earliest approaches was that of Allen and McGlade (1986) who approached the fishery from the perspective of self-organising systems, while Hilborn and Walters (1987) treated the problem from an optimisation viewpoint. Considerable effort has gone into trying to understand the strategy of fishers (Gillis

et al., 1993) but generally not in terms of the interactive dynamics of the movement of fish stocks and the fishing fleet. It is generally accepted that cellular automata are a useful tool when dealing with uncertainty and complex ecological systems (Wu and David, 2002; Wiegand et al., 2004).

Several pelagic fish species migrate from feeding to spawning areas depending on seasonality (Beamish et al., 2005). Since the motion of fish and boats does not follow precise predictable rules, it is common to model it by a stochastic process (Kim, 2003). For fish this attraction depends on environmental factors such as water depth and temperature, and also includes variables to describe changes in preference for spawning sites, feeding areas, and attractive locations (Magnússon et al., 2005). Therefore, the attractiveness of an area for fish movement depends on seasonality taking into account the abovementioned parameters. The motion of the fleet is similar, but with an attraction potential based on the historical record of fish abundance (Gillis et al., 1993; Gillis et al., 1995). Thus, the attraction potential of an area for the fishing fleet is based on a past empirical knowledge of fish biomass records depending on seasonality.

Movement of fish has since long ago been a topic of interest in ecology (Bardach, 1958; Gerking, 1959; Gibson, 1967). Modelling tools for the movement of fish schools are given among others by Huth and Wissel (1992), Vabo and Nottestad (1997) and Stöcker (1999). Modelling fish movement using cellular automata is a well established technique (e.g., Pola, 1985; Stöcker, 1999). There are also studies modelling the learning behaviour of fishers (e.g., Xiao, 2004). However, there are no spatially-explicit learning models on the interaction between fish and fishers. In addition closed areas such as MPAs are becoming a popular measure for fish conservation (Horwood et al., 1998). There are several models evaluating the impacts of closed areas (e.g., Guénette and Pitcher, 1999; Lockwood et al., 2002) but these models are not spatially explicit and they assume homogeneous spatial properties. Furthermore, marine reserves are not always beneficial to fisheries management (Hilborn et al., 2004) and the spatial behaviour is important for the evaluation of closed areas (Smith and Wilen, 2003). It is unclear if closed areas generally increase fish catches (Horwood et al., 1998; Hilborn et al., 2004). Furthermore, it is reported that when fish transfer rates are high the benefits of marine reserves

are decreased (Polacheck, 1990; Guénette and Pitcher, 1999). It is also reported that closed areas will have little effect in fisheries management, if catchability is not regulated too (Horwood et al., 1998).

Given that using traditional modelling approaches it is difficult to evaluate the effects of closures, since there is little information on fish and fishers' spatial dynamics and distribution, we therefore propose the use of spatially explicit modelling tools such as cellular automata as appropriate for addressing this question. We apply a spatially explicit model where fisher's behaviour is based in knowledge of the past fish behaviour. The aim of this model is to provide a spatially explicit learning model for modelling the interaction between migratory fish and fishers and to provide a tool for evaluation of closed areas.

## 2. Problem formulation

The model represents a small spatial marine area by a rectangular grid of cells. Each cell is characterised by the initial number of schools and a number of fishing boats which is considered fixed in the model. The state of the cells (fish schools and fishing boats) changes on a daily basis through a set of rules involving the current state of each cell and its eight adjacent cells.

For both the fish schools and the fishing fleet the movement between cells at each time step is determined by a set of attractiveness potentials. For fish the attractiveness is an indication of the known migration patterns – for example, at the onset of the spawning period the regions preferred for spawning become more attractive and the areas where the fish had been previously, presumably the areas where they could feed and grow best, lose attractiveness. During the daily iterative calculations the fish sense the relative attractiveness of adjoining cells and move in the direction of the cells which are most attractive. In other words, migration is not described as a process of moving to a known distant location, but rather a matter of sensing local gradients in the attractiveness of cells in the immediate neighbourhood and moving preferentially towards the most adjoining attractive cells. This mechanism offers a way not only to model seasonal migration, but also to include detailed habitat effects based on bathymetry,

water column characteristics, bottom type, and other local effects. Such characteristics of fish movement have been identified in large scale (Humston et al., 2000) and micro scale (Edgar et al., 2004) fishery systems, in pelagic fish (Brill et al., 1999) as well as in reef fish and tropical fish (Sheaves et al., 1999; Chapman and Kramer, 2000).

The same general mechanism applies to the fishing fleet. They are assumed to stay in the same cell as long as they are catching fish, but if the catch rate is too low they move towards the neighbouring cells in which historically fish has been most abundant. They do not steam to a distant fishing ground in this model, but only move as far as an adjoining cell on a daily basis.

These movement mechanisms are not strictly deterministic, as a degree of randomness is introduced. In other words, fish schools and fishing boats generally move to the cells which are most attractive according to a probability distribution which favours the more attractive cells but also admits a finite probability of moving to a somewhat less attractive cell. This offers a means for allowing the fleet to spread out, since boats do not prefer to concentrate on the same fishing ground even if they have identical expectations of where they will catch the most fish, but avoids having to model explicitly the tendency for the fleet to cover a larger area. The extent to which the fleet and fish stocks spread can be controlled by a parameter which specifies that a certain number of the less attractive cells will not be occupied on the next time step, that is to say that the probabilities of moving to the least attractive cells is automatically set to zero.

Fish migrations are driven by a number of biological and oceanographic factors which vary from one stock to another. Some fish seem to feed continuously and follow their food supply, spawning wherever they happen to be feeding during the spawning season, while others have well-defined spawning areas and sometimes stop feeding in order to move to these areas. Food supplies can depend on water temperature, upwelling, and a host of other factors. In this model we simply assume that the areas where fish are likely to go at different times of year are known without considering the underlying mechanisms and model fish migrations so as to match experimental observations.

There are no ecological considerations in the model – feeding and natural mortality are treated as fixed and do not involve models of prey and predators.

### 3. Assumptions and limitations of the model

Because this model is intended primarily to provide a means for describing the spatial dynamics of fish and fishers, a number of simplifications have been made in the present formulation.

Most fisheries involve dozens of different commercial species, a variety of fishing techniques, and a very varied mix of catches either because the fishery is deliberately a mixed one or because there is unavoidable by catch in a directed fishery. However, in this model we consider only one stock of fish and a single uniform fishing fleet. A second simplification is that there are seasonal migrations for spawning, but the recruitment process is represented only by continuous incrementation in the biomass of fish. This is due in part to the fact that the stock is not age-structured. Furthermore, there are no ecological interactions, which would of course involve introducing additional species to the model. We assume that the fish migrate to preferred feeding grounds, but the presence of food in those areas is represented by a fixed annual cycle rather than by dynamic modelling of the food web. A similar but more sophisticated approach to modelling areas of attractiveness under uncertainty is proposed by Arnot et al. (2004).

Similarly the behaviour of the fishing fleet is highly simplified, and we assume that boats rely entirely on information on current catches in their present locations or on historical records of fish distribution. This ignores the fact that some fishers cooperate and advise each other by radio, or that in some cases (mainly near-surface schooling species) the fishery even uses spotter planes to locate fish concentrations within large areas. Furthermore, we assume that all fishers have access to the same information, namely the historical distribution of fish in all areas – this is of course not the case in real fisheries.

A further drastic assumption is that boats can fish continuously – we do not keep track of how full their holds are and do not calculate steaming time to port. In this way we can deal only with the number of boats in each cell without having to maintain catch records for individual boats. We included another simplification by basing the historical distribution of fish on that for an unexploited stock. We do this by running the model for 100 years without any fishing mortality and storing the result in a “database” of fish concentrations in each cell on a monthly basis to which all the fishers have

access. It would of course be more realistic to update this database continuously during the period when there is fishing.

While there is a body of literature dealing with strategies of fishing and bioeconomic models of where boats go (Hilborn, 1985; Sampson, 1991; Gillis et al., 1995), in this paper we assume that the fishers are simply looking for fish and we do not take into account steaming time or economic factors. We also did not include a wide range of environmental effects and other factors affecting the dynamics of the fishery. In our current modelling approach we ignore such refinements as group fishing tactics in order to optimise the combined fleet catch, as described by Lane (1988) and Sampson (1994). However, parameterisation of the model is a greater problem, since the basic structure of the model involves the probabilities that fish and fishing boats will move from where they are to a nearby location, and these cannot be determined from first principles. The only practical alternative is to estimate these parameters by inverse modelling, namely finding values for the attractiveness coefficients which give rise to reasonable output, and this has been done in calibrating the present version of the model.

### 4. Implementation

#### 4.1. Characteristics of the map

The model is based on a grid of square cells. We represent land and closed areas by sets of rectangles which are closed, respectively, to fish and boats, and just to boats. These rectangles are defined in simple text files where two pairs of coordinates represent opposite corners of each rectangular area. The size of the grid can also be modified. For the simulations shown here a grid of  $90 \times 100$  (9000 cells) has been used. Periodic boundary conditions which are used in many cellular automata implementations (Wolfram, 1983a) have been omitted as not relevant of fish or fishing boats movement.

The actual size of the area modelled is arbitrary, but given the assumptions of the model there are some restrictions that must be respected if the results are to have any semblance of realism. If we model the North Sea with a  $90 \times 100$  cell grid then each cell is approximately 7 km on a side and has an area of about  $50 \text{ km}^2$ .

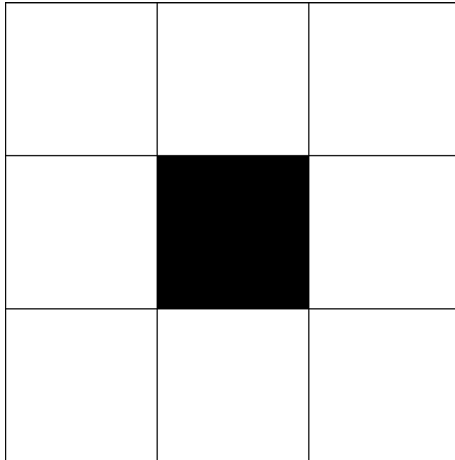


Fig. 1. Representation of a cell and its neighbourhood.

This is plausible with a daily time step, meaning that the fish schools and boats might move about 7 km/d, although of course they can move much more than that.

#### 4.2. Fish movement

Fish movement is based in centres of attraction (e.g., feeding–spawning areas) that are activated according to seasonality. The attractiveness potentials are entered as rectangles of attraction and smoothed by Gaussian distributions of width which can be specified by the user to tune the strength and range of the attractiveness gradients. There can be multiple centres of attraction, and the strength of attraction is also a user-controlled variable. The subsequent movement of fish schools is determined by the neighbouring cells. For each cell on which a fish school is located, we examine the attractiveness of the eight adjacent cells as shown in Fig. 1.

These nine cells are referred to as the neighbourhood of the cell to be updated and include the cell itself. The attractiveness of the current cell, which determines the likelihood of not moving to another cell, is multiplied by  $W_f$ , which is the unwillingness of fish to move to another cell.  $W_f$  is an input parameter and varies according to the behaviour of the fish modelled. Some fish schools tend to move faster while others tend to remain longer in one place, which is represented by different values of  $W_f$ . The probability of moving to any of the other eight adjacent cells is based on their attractiveness potentials, and of course the probability of moving

to the most attractive cell is highest. The probability of moving to the least attractive cells can be set to zero by adjusting a user parameter, which limits the degree to which the stock spreads. The probability of moving to a cell which is land is of course zero, and fish schools that occupy the same cell can join together and form larger fish schools up to a certain threshold value. If the combined biomass of the fish schools in a cell exceeds that threshold, then the schools do not merge.

The dispersion of the fish can be controlled by limiting the number of cells  $N_c$  that they can move to. This too is a parameter that can be set by the user in a text input file, and basically it keeps fish from moving to a specified number of the least attractive cells. This assures that fish schools will either stay at their current location, or if they move they will go to a location which is at least marginally more attractive than the current one.

When two temporary areas of attraction are given, such as a feeding and a spawning area, fish seasonally migrate from one area to the other. It is also possible that multiple centres of attraction are active at one time (e.g., several feeding areas). In short, the user can specify the rectangular area of attraction, the days of the year that the area of attractiveness is active and the strength of attraction of that area (Fig. 2).

#### 4.3. Fish recruitment

In our modelling approach, age structure is ignored and there is no seasonality to recruitment, so a constant population growth rate could be used. However, for flexibility in future development we define a differential growth rate  $g = R - M$  as the difference between a recruitment rate  $R$  and a natural mortality  $M$ , which can be defined separately at a later stage. A stochastic element is included so that the actual growth rate varies slightly about the mean.

A density-dependent recruitment term is also included, reflecting the logistic growth of populations. Thus, the actual growth expression used in the model is  $G = RB - MB$  where  $G$  is the total population growth,  $B$  is the biomass, and  $\beta$  is a constant roughly equal to one divided by the maximum biomass (more precisely,  $\beta = (1 - M/R)/B_{\max}$ ). For heavily exploited populations the density-dependent correction  $\beta B$  is small, but it plays an important role in initialising the model with an unfished stock.

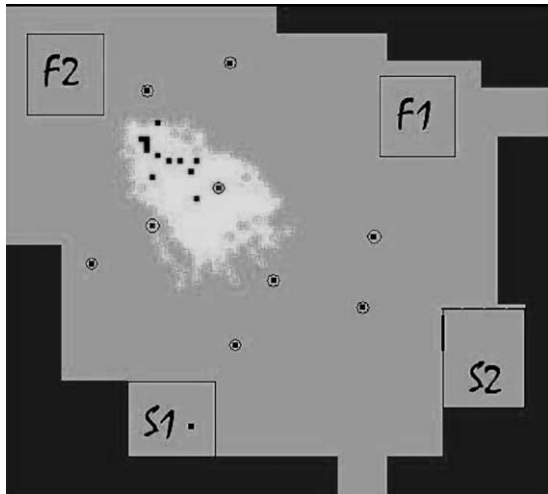


Fig. 2. Snapshot of the motion of fish schools and boats. The dark areas represent land, and the four areas F1, F2, S1 and S2 represent seasonal feeding (F) and spawning grounds (S) which are centers of attraction. The light area shows a temporary attraction to feeding ground F2, and the dots represent schools of migrating fish. The circled dots represent fishing boats.

Since  $R$  and  $M$  are not modelled independently at this stage, we have simplified the structure of the model by neglecting natural mortality (i.e.,  $M=0$ ) so that  $\beta=1/B_{\max}$  and  $G=RB \times (1 - B/B_{\max})$ . In the simulations used for this paper the biomass is approximately half of  $B_{\max}$ .

The daily stochastic update of the fish biomass is made via the following procedure: in each time step, a uniform random number  $u$  in  $[0, 1]$  is used. If  $u$  is between  $[0, 1/3]$  then the growth rate of that day equals to  $0.999G$ . If  $u$  is between  $[1/3, 2/3]$  then the growth rate of that day will be equal to  $G$ . If  $u$  is between  $[2/3, 1]$  then the growth rate of that day will equal to  $1.001G$ . Doing so, we assure that on average the growth rate will follow the logistic growth rate however, there are stochastic variations of the growth of biomass on a smaller time scale. Also the yearly based growth rate  $G$  is updated on a daily basis using the compound interest formula.

#### 4.4. Vessel movement

The movement of fishing boats is modelled similarly to that of fish schools, but with some obvious differences. Although the attractiveness of different cells for

fish is part of the model input and can be changed as often as desired, even daily, the attractiveness of cells for fishing boats is the result of the initialisation simulation and is calculated on a monthly basis. The probability of staying in the current cell depends on the presence of fish. Boats are excluded from closed areas – these closures can be temporary, but in the simulations shown here they are permanent.

An additional characteristic of the fishing fleet is the willingness of boats to move. Boats that are catching fish have an incentive to stay where they are, but if they think that there are more fish in an adjoining cell (based on the historical simulated database of fish abundance) they may decide to move, and their willingness to move depends on how ready they are to accept the risk of giving up known catches in their present location for the chance of higher catches elsewhere.

We also restrict the number of boats that can occupy the same cell,  $E_{\max}$ . This is an input parameter and depends on the size of the cells and other factors. For the simulations shown here the maximum number of boats in a cell is three. It is assumed that even if several boats occupy the same cell they are fishing independently. Fishing boats cannot enter closed areas. Closed areas are entered as rectangles. We have included the effect of closed areas in the model by setting the attractiveness to fishing boats of these areas to zero even if there are fish present.

#### 4.5. Fishing mortalities

When a fish school and a fishing boat are present at the same cell then the fishing boat will catch some fish resulting in fishing mortalities. Fishing mortality  $Z$  is computed with a version of the usual catch equation  $Z=qE$  where  $q$  is a catchability coefficient and  $E$  is the effort as measured by the number of boats in each cell – each boat represents one unit of effort in this model. The effort  $E$  and fishing mortality  $Z$  are computed separately for each cell, so the catch per cell is given by  $Z=qEB$  where  $B$  is the biomass of fish in the cell. This value is subtracted from the total fish biomass and recorded as part of the total catch.

#### 4.6. Initialisation

To run the model it is necessary to specify an initial fish biomass and number of fish schools. The fish are

Table 1  
Summary of models' input parameters

Fish characteristics	
$W_f$	Unwillingness of fish to move
$G (G = R - M)$	Growth rate (growth = recruitment – natural mortality)
$B_{\max}$	Maximum fish biomass that the system can sustain
$N_c$	Maximum number of adjacent cells for which the probability of moving is greater than zero. This value affects the degree of dispersal of fish schools, $N_c \leq 9$ .
$B$	Total initial fish biomass
$N_s$	Initial number of fish schools
$S_{\max}$	Maximum size of a fish school. Schools can merge only if the total biomass within a cell is less than $S_{\max}$
Boat characteristics	
$Q$	Catchability coefficient
$E_{\text{total}}$	Number of fishing boats
$W_b$	Unwillingness of fishing boats to move
$W_c$	Unwillingness of fishing boats to move if they are currently catching fish
$E_{\max}$	Maximum number of fishing boats in one cell
Characteristics of attractiveness	
Number of areas of attractiveness	Upper left and down right coordinates of the area of attractiveness (spawning, feeding areas, etc.)
$S_g$	Width of Gaussian smoothing functions
$I_f$	Strength of attractiveness potential
Map and simulation time	
Number of squares needed to describe form of coastline	Upper left and down right coordinates of the closed squares
Number of closed areas	Upper left and down right coordinates of the closed squares
$L_{\text{sim}}$	Number of simulation years

divided into schools of equal biomass and distributed randomly on the grid, on cells that do not contain other fish schools and are not land. We run the model for during a period of time without interaction between fish and fishing boats. During these simulation years only natural fish mortality is included and there is no fishing mortality. In the results presented in this paper we used a 110-year period of simulation without fish-fishers interaction. The first 10 years are discarded, since we found that it was the time needed for the system to reach a steady state. Subsequently, we kept monthly records of the average fish biomass for each cell during the 100 simulation years. We treat this as a fish distribution database which is used to determine the attractiveness of each cell for fishing boats – the fishing boats are assumed to prefer to fish in places where historical records and experience show that there are usually fish. After the 110-year simulation without fishing boats is completed, fishing boats are randomly distributed on cells that are empty, that are not land or closed areas, and that do not contain any other fishing

boats. Sequentially, the fleet is activated and begins to catch fish.

#### 4.7. Technical aspects – summary of input parameters

The model was programmed in Borland C++ and makes extensive use of object-oriented techniques (Silvert, 1993; Fortin et al., 2003). Table 1 summarises the input parameters for the model, which are entered in text files and can be changed by the user without recompiling the model.

## 5. Methods

The output of the model generates continuous animation on a daily basis in colour of the motion of fish schools and boats. Figures presented in this paper are black-and-white snapshots of the general pattern of the simulations. In the actual simulations the fish schools

and boats are represented by dots of different colours, but in the figures of this paper the boats have been circled to distinguish them. Land is represented by the black areas and water is represented by various lighter shades of grey. The different shades represent areas of various degrees of attractiveness to boats that vary through the year on a monthly basis. The seasonal boat attractiveness is represented by gradients of grey – the lighter shades represent more attractive areas, so the boats move generally towards areas with lighter shades (Fig. 2). We also keep record of total fish biomass on each day as well as fishing mortalities.

A simulation scenario that we run was to test whether closed areas increase fish catches. In order to do so, we run a simulation without a closed area and sequentially another simulation using the same input parameters. The closed area was placed at a spawning area. Therefore, during spawning period at the spawning area there were no fishing mortalities. During this simulation run, we used only one feeding area and one spawning area (Fig. 3).

Often the benefits of closed areas are reported to be lower than expected (Smith and Wilen, 2003). In addition, it is reported that closed areas will have little effect in fisheries management, if catchability is not regulated too (Horwood et al., 1998). In order to test

the combined effects of closed areas and catchability, we run a simulation without closures. Thereafter we run a simulation with the same input parameters as before but with a closed area located on a spawning area and with 25% higher catchability than before (Fig. 4).

It is reported that when fish transfer rates are high (i.e., fish that move fast and usually are large-sized), the benefits of marine reserves are decreased (Polacheck, 1990; Guénette and Pitcher, 1999). Given that the studies that reported this result were not spatially explicit and were not based on a learning fishers behavior, we examined if this is valid when fishers are “more intelligent” in their behavior in the model. In other words we tested if the effect of closed areas is limited when fish moves fast but fishers move on a similar pace with the fish too. We achieved that by running a simulation with slower moving fish (fish unwillingness to move was high) and slower moving fishers (vessel unwillingness to move was equally high too). Sequentially, we performed another simulation with the same input parameters as before but with fish that moves 20% faster (fish unwillingness to move was 20% less than before). We also modified fishers’ unwillingness to move by 20% too. In both simulation runs the closed area was located at the same area which was a spawning area. All the other model input parameters were

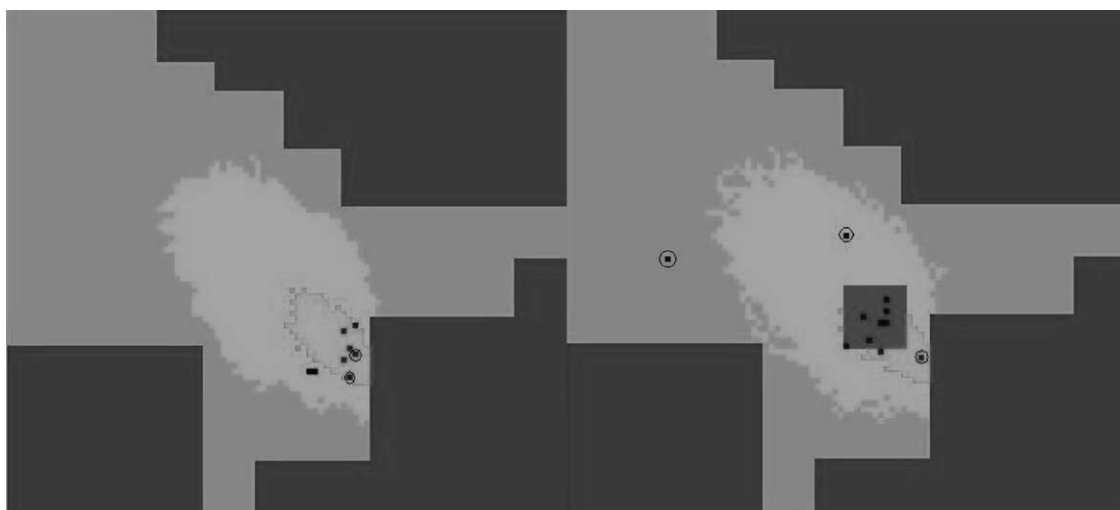


Fig. 3. Snapshots of simulation runs without (left picture) and with a closed area (right picture). The closed area is located on a spawning area. Land is depicted with black color. The zone of attraction for the fish is close to the shore (spawning area) and the boats (circled dots) are close to the fish schools (left picture). When a closed area is introduced, most of the fish schools are inside the closed area, while the boats are outside (right picture). Both simulations were carried out with the same input parameters and the feeding area is located on the upper left end.

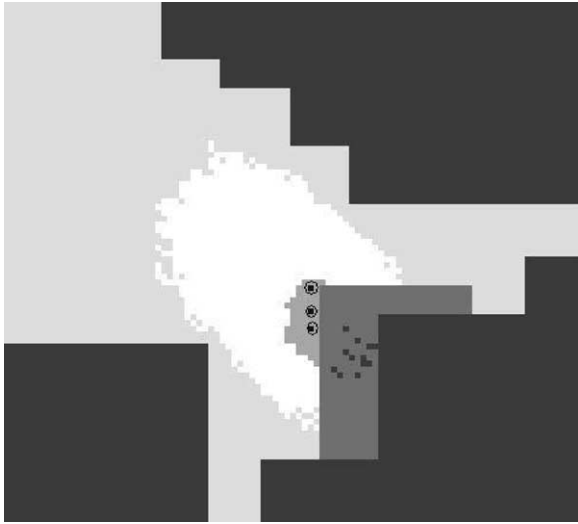


Fig. 4. Simulation snapshot during the spawning season. The spawning area is closed to the fishers. When closed areas are introduced at feeding or spawning areas (that are areas of attraction for fish) fishing boats tend to fish close to the border of these areas.

kept constant in both simulation runs. In both simulations fish had a feeding and a spawning area as areas of attraction (totally two areas of attraction).

## 6. Results

Fish and fishers behaviour was generally very realistic. When only one area of attraction is active at a time (one feeding and one spawning area), fish movement is dispersed over an imaginary line that connects these two areas of attractiveness depending on seasonality. When multiple centres of attraction are active at the same time, some fish follows a trajectory connecting these areas of attractiveness, while some other develop some more “favourite” areas and move more locally. Vessel movement is generally realistic too. Fishing boats generally follow seasonal fish migration too. When closed areas are introduced at feeding or spawning areas (that are areas of attraction for fish) fishing boats tended to fish close to the border of these areas.

The model under circumstances develops also unrealistic behaviour. When the initial fish biomass that is introduced is too high fishing boats seem to be lost.

There are several fishing boats that are trying to catch fish at areas that fish biomass is too low during that month. Another problem that occurs is that when too many areas of attraction are active at the same time (usually more than eight), fish seems to be confused too. In that case fish does not migrate but usually develops chaotic local micromovements.

According to our results, closed areas increased fish biomass but also decreased fish catches (Fig. 5). In the simulation run where there was no closed area, mean fish biomass was 25380 t ( $\pm 1360$ ) meanwhile when the spawning area was closed to fishers mean fish biomass was 26300 t ( $\pm 1290$ ). Mean fish catches were 680 t per year ( $\pm 61$ ) without any closures meanwhile with the introduction of the closed area decreased to 580 t ( $\pm 53$ ).

When no areas were closed to fishers and fish catches were normal, fish biomass per year was 25380 t ( $\pm 1360$ ). Fish catches per year were 680 t ( $\pm 61$ ). With the introduction of a closed area located on a spawning area and with a 20% higher catchability, mean fish biomass per year was 25030 t ( $\pm 1410$ ) and mean fish catches per year were 720 ( $\pm 66$ ) t. Thus, closing an area and increasing fish catchability by 25% resulted in a reduced a mean fish biomass 300 t per year but it increased fish catches by 40 t per year (Fig. 6).

Fish that moved at slower pace had mean annual total biomass 26100 t ( $\pm 1330$ ), meanwhile 20% faster moving fish had on average 26300 t per year total biomass ( $\pm 1290$ ). Fish catches for slower moving fish were 603 t per year ( $\pm 53$ ). However, fish catches in the case of faster moving fish were 580 t per year ( $\pm 53$ ). Therefore, a closed area located on a spawning area resulted in slightly higher fish biomass per year on average in the case of faster moving fish but in lower fish catches (Fig. 7).

## 7. Discussion

Even though the model is based in inverse modelling due to the absence of data of fish biomass per cell, our results are in agreement with Hutton et al. (2004) who reported that seasonal migrations of fish from spawning to feeding areas are well followed by fishers. However, in the model when initial fish biomass was too high during the “learning” simulation period vessels seemed to be lost trying to catch fish in wrong

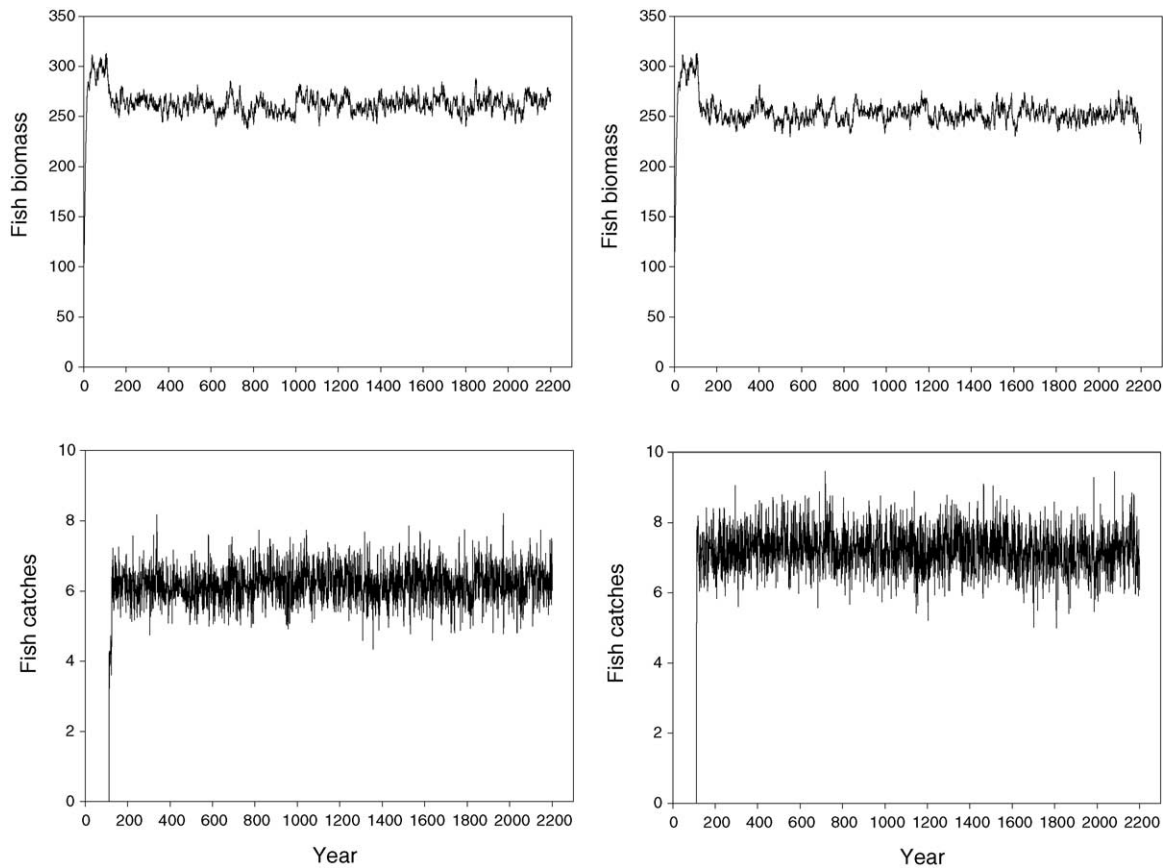


Fig. 5. Total fish biomass (upper graphs) and fish catches (lower graphs) in  $10^2$  metric t for 2200 years of simulation. Graphs on the left show fish biomass and fish catches of a simulation that does not include a closed area. Graphs on the right show fish biomass and fish catches of a simulation using the same initial conditions as the previous one but with a closed area that is located on a spawning area. Fish catches start from year 110 due to the learning period.

places. That is due to the fact that during the 100-year “learning” simulation period there are no fishing mortalities. Therefore, fish population is limited only by natural mortalities. As a result during the “learning” period fish population is larger than it would be in reality, and therefore, fish schools will be present at less attractive areas due to the fact that attractive areas will be overpopulated. Given that the mean fish biomass per cell on a monthly basis of the 100-year “learning” period are used as the attractiveness potential of vessel movement, fishers will tend to fish at places that there was fish during the learning period but when fishing mortalities are introduced, fish population is lower and present mainly at the most attractive areas since these areas are not overcrowded. However, this problem was

avoided in the simulations presented by setting initial fish biomass that did not exceed 40% of the maximum expected fish biomass.

Our model failed to live up to the reality when more than eight areas of attraction were introduced (for example four spawning and four feeding areas). This is due to the fact that in our model fish “thinks” that should pass through all active areas of attraction. In other words when two feeding areas are active at a time, fish will try to pass through both of them. In reality fish will stay at a feeding area at the feeding season as long as there is prey available. Since there are no prey-predator interactions and no food stocks in the model we modelled fish migrating behaviour instead. Therefore, when many areas of attraction are

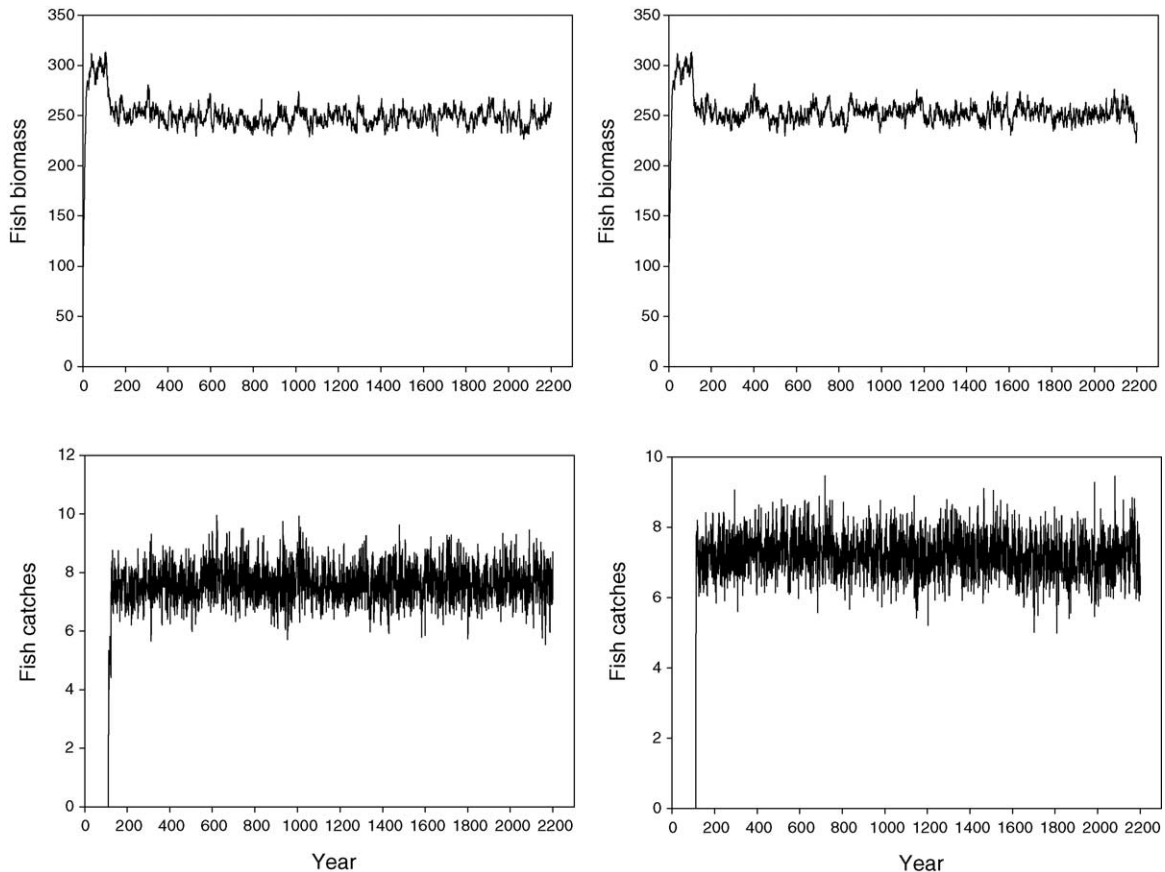


Fig. 6. Total fish biomass (upper graphs) and fish catches (lower graphs) in  $10^2$  metric t for 2200 years of simulation. Graphs on the left show fish biomass and fish catches of a simulation that does not include a closed area and with normal catchability. Graphs on the right show fish biomass and fish catches of a simulation using the same initial conditions as the previous one but with a closed area located on a spawning area and with 25% higher catchability. Fish catches start from year 110 due to the learning period.

active at a time fish is confused and model response is unrealistic.

There is a debate on whether closed areas increase fish catches (Horwood et al., 1998; Hilborn et al., 2004). Hoffmann and Dolmer (2000) in a study in a fjord system in Denmark found that closing an area had no long-term effects on the distribution of fish and epibenthic invertebrates. Frank et al. (2000) studying the Scotian Shelf found that “evaluation of the effectiveness of the closed area revealed that the management objective was not fully met”. However, it was also found that “the closed area does appear to have had some benefit to groundfish species in terms of increased abundance”. According to our findings closed areas increase fish biomass and

decrease fish catches. Interestingly when the spawning area was closed to fishers, mean fish biomass was higher but the variance was lower. Therefore, it seems that indeed closed areas create a fish population buffer. Furthermore, the relative increase of the fish biomass when the spawning area was closed shows  $((26300 - 25380)/25380 = 0.04)$  which a 4% increase is. The relative decrease of fish catches was  $((580 - 680)/680 = -0.15)$  or a 15% decrease. That means that based on the learning behaviour of fishers, heavy fishing activity was taking place at the spawning area that was closed on the second simulation run. This result is in agreement with Russ and Alcalá (1996) which reported that marine reserves export adult fish biomass.

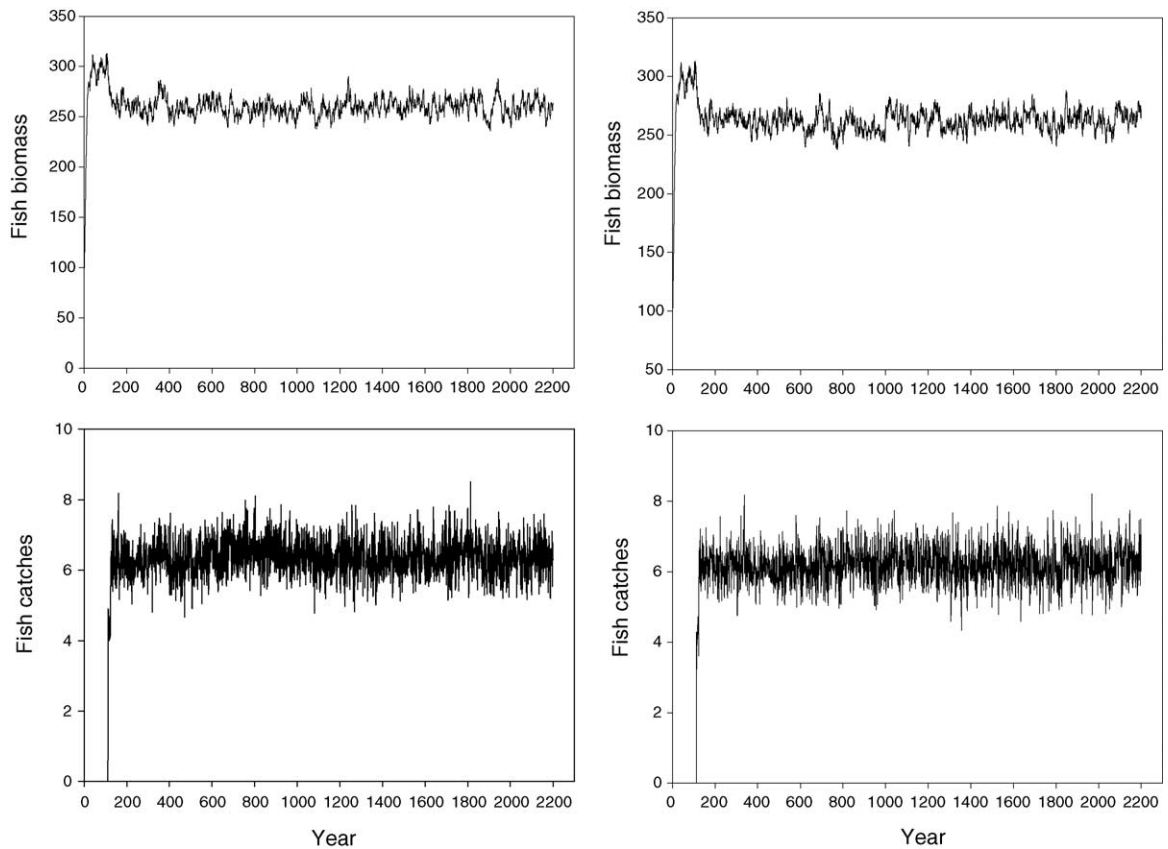


Fig. 7. Total fish biomass (upper graphs) and fish catches (lower graphs) in  $10^2$  metric t for 2200 years of simulation. Graphs on the left show fish biomass and fish catches of a simulation with slower moving fish. Graphs on the right show fish biomass and fish catches of a simulation using the same initial conditions as the previous one but fish and fishers move on average 20% faster than before. In both simulations the spawning area was closed to fishers. Fish catches start from year 110 due to the learning period.

However, the abovementioned results are valid only when fisheries are not regulated by quotas. Our results show that when an area is closed but there are no catch regulations fish biomass is reduced and fish catches are increased, resulting in the opposite outcome than the one desired for fisheries. Thus, this complies with the results of Horwood et al. (1998) that “a displacement of the fleet from one locality to another will generally have little effect if the same quota is taken”.

Our spatially explicit evaluation of the benefits of marine reserves showed that when fishers are “intelligent” in the models basing their fishing spatial preferences on past fish behaviour, transfer rates of fish increased the benefits of marine reserves in terms of total fish biomass. Higher fish transfer rates decreased fish catches. It seems that faster moving fish used the

closed area more effectively. That is probably due to the fact that fish need to feed and reproduce. Therefore, during feeding and spawning season fish will most likely be located at some specific areas. On the meantime, when not in the feeding or spawning season, fish will migrate. However, faster moving fish will develop a more unpredictable behaviour due to higher swimming velocity. That makes fish with higher transfer rates more difficult to detect from fishers, and therefore, more difficult to catch. This result is in contrast with the findings of Polacheck (1990) and Guénette and Pitcher (1999) which found that transfer rates of fish decreased the benefits of marine reserves. However, Guénette and Pitcher (1999) tested the benefits of the reserve size as a proportion of the total area. Spatial homogeneity was assumed and there was no spatial

information on where exactly the marine reserve was located (e.g., it would make no difference if a spawning area was closed or just an area of equal size at a random location). We therefore believe that spatially explicit information as well as the “learning” behavior of fishers are the key factors for the difference in our results.

The work described in this paper is only a preliminary attempt based in inverse modelling rather than real data. The next step is clearly to fit this generic model to a specific fishery by using real parameters based on field data. This could be achieved by using satellite data to map the observed distribution of fishing vessels around closed areas (Rijnsdorp et al., 2001). It is also possible to expand the model to include several different stocks of fish and different components of the fishing fleet (as well as fixed gear fisheries). Many simplifying assumptions have been made in developing the present form of the model, such as constant recruitment, but developing a more realistic representation of fish dynamics is mainly a matter of more programming – these simplifications are not essential parts of the model. In particular, the motivation of fishers and the bioeconomic dynamics of the fishing fleet are critical factors in determining fishing strategy (Hilborn, 1985) and these are not dealt with in the present paper.

Climate change is an issue of current concern, and this model could be modified to reflect effects that now seem to be affecting fisheries. For example, warming of the North Sea seems to be driving stocks further north, and thus, changing their accessibility to different components of the fishery. It has been suggested that the recent declines in cod landings in the North Sea are only partly due to reduction in cod biomass, and that part of the resource is now too far North to be accessible to the traditional fleet (Brander, 2003; Brander et al., 2003). This model could be modified to permit the regions of attractiveness to change over time, and to see how the fishery is affected if the fish distributions change while the fishing fleet continues to rely on past experience.

A model like this one cannot of course replace traditional fisheries models based on population dynamics since a very simplified representation of recruitment and natural mortality is used. The purpose of this modelling approach is to provide a tool for analysing the spatial dynamics of the fishery and to evaluate the effect of marine protected areas and other closures, both temporary and permanent. For such applications we think

that the method of cellular automata could prove very valuable.

*Notice:* The pseudo-code of the model is available upon request.

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