A multi-agent simulation model of fishery fleet dynamics for the Queensland coral reef line fishery

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Abstract

We present a computational model of fishing fleet dynamics for the Queensland coral reef line fishery. The model runs in a two dimensional space with agents moving between port and the collection of available reefs. The model of rationality is based on the haystack models of game theory, such that the agents are aware of what other boats are doing and seek to maximise yield with consideration of the extent to which they can trust the other boats. The core decision making by the boats depends on three elements: The expected number of fish at a reef, the influence of its peers and the costs involved in making the trip. The software allows graphical visualisation of the emergent dynamics and generates numerous statistical measures by which it can undergo sensitivity analysis and be calibrated against real world datasets.

1 Introduction

There has been a slowly accumulating body of work in building fisheries models that include consideration of the spatial structure of the fishery [1, 2, 11, 10]. Nevertheless, the uptake of such models has been much slower than the general development of spacial models by the ecological modeling community [11]. However, the recent interest in developing networks of marine protected areas has stimulated an unprecedented need for reliable models of fisheries that contain information about the spatial features of the fishery [9, 13].

In all previous modeling efforts the model of rationality exhibited by the human agents lacks certain crucial features. In the seminal model by Allen and McGlade, for example, they employee a boundedly rational model of the fisherman based on the notion that the probability of a fisherman switching species to harvest is dependent on their expected profit. The fishermen base this calculation on their knowledge of the relative market price and availability of species, and their knowledge of fish location depends on information exchange between vessels. Their calculations of expected fish includes consideration of the number of vessels currently exploiting a location, but not explicit consideration of who those vessels are [1].

This trend of basing the rationality of agents upon a socially blind calculation of expected utility continues to the present day with models of Sanchirico [11, 10]. In this form the models captures the essential economic considerations, yet the entire issue of social structure that is a common theme in human decision making is absent. Agents do not differentiate between the identity of individual boats when making movement choices (although some models make allowances for these distinctions in information trading [1]). Although it may be argued that no model can be said to adequately capture all aspects of its real world counterparts, we feel that by ignoring the element of potential competition and cooperation a model cannot hope to adequately capture any serious economic scenario.

Game theory offers a rich framework for exploring issues of agent interaction with the possibility for many types of social contracts to emerge as agents seek to optimise their payoffs. The history of game theory applied to fisheries modeling has been typically for addressing the problem of the 'tragedy of the commons'. This is regardless of whether the analysis is of static or dynamic games. Typically these models do not take into consideration the spatial elements of the fishery, and notion of strategy is merely the choice of fishing effort [3]. What is obviously required is a game theoretic structure which takes into consideration the spatial elements of the scenario. This requirement is satisfied by the Haystack game, which appears uniquely suited to the reef fisheries situation.

The Haystack model emerged as a tool for illustrating the potential importance of spatially distributed sub-populations in the evolution of cooperation. The name haystack model comes from a game in which mice must choose a haystack to settle in. Their evolutionary success depends on the nature of the other mice that settle with them [12]. Since then it has become a general game theoretic model for studying strategy choice in the exploitation of public goods [4].

In these games the payoffs to agents are often dependent on the number and nature of others who settle with them. In many simulations of the haystack game, the players have a set preferences for the players with whom they would like to cohabit a haystack. In this regard we consider the movement of fishing fleets viewable as a haystack game. The boats have the capacity to be influenced in their movements by their knowledge of other's decisions. This may be driven by numerous aspects; who they expect to have most information about fish stocks, or perhaps the extent to which they trust another vessel not to over-harvest a location.

In this paper we present a computational model being developed to model the movement of a fishing fleet on the Queensland coral reef line fishery. The model is an adaptive multi-agent system in which the fleet of boats makes decisions about which reef to visit on the basis of three elements: The expected number of fish at a reef, the influence of its peers and the costs involved in making the trip. Each of these elements is weighted by a separate coefficient which may be varied across simulations. The agents themselves begin with random peer influence vectors, but adjust these in line with the amount of fish they are able to catch (effectively a payoff). Over time we collect a number of different performance statistics, distribution of time spent at each of the reefs, the sustained yield of the entire fleet and distribution of yield across the fleet.

The long term goal of the project is to develop a general simulation framework for studying the dynamics of fishing fleets and the fluctuations of fish stocks in a fishery using game theoretic models of the decision making by agents within the fishing fleet. The model will have general applicability for testing theories about specific fisheries, as well as studying these bioeconomic systems in general.

2 The Model

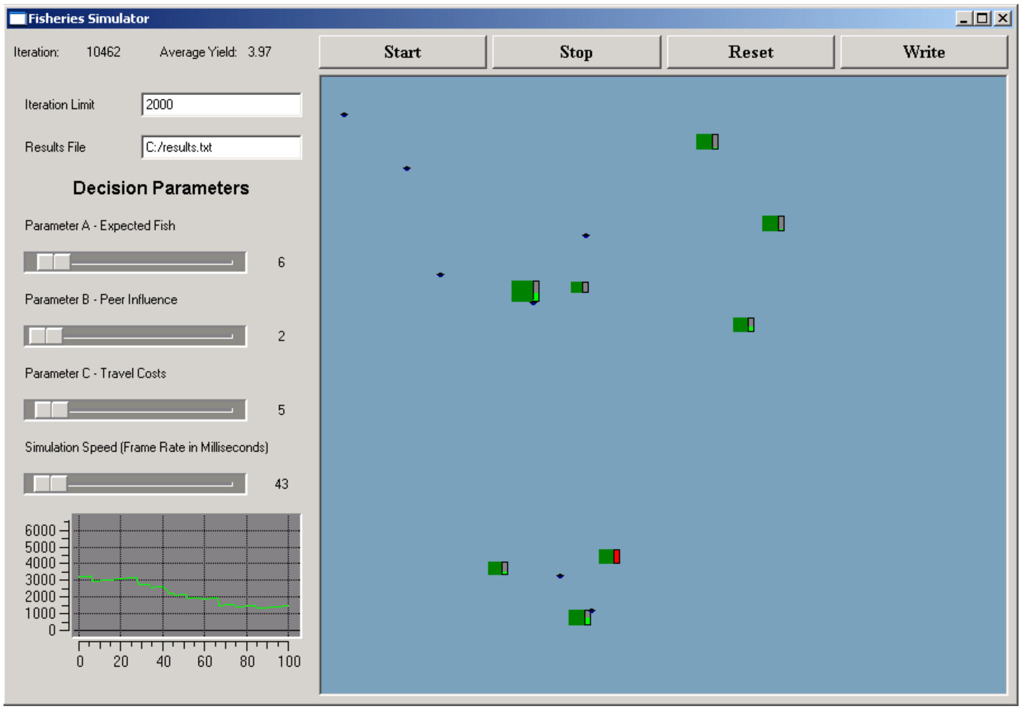
The model consists of a two dimensional space over which there is a distribution of reefs and a corresponding fish population. The fish population is has its own underlying dynamics based on ecological modeling, and discussed in detail in Section 2.4. Of course the fish population is also affected by the activities of the fishing fleet, the harvest of the fleet is likewise proportional to the available fish stock. Crucially, if fish stock drops below a certain threshold an extinction event may occur with a probability dependent on the exact proportion left.

Each boat in the fleet must obtain fish by moving between the port and each of the reefs. The amount of fish a boat can catch will be proportional to not only the amount of fish at the location, but also the other boats on the reef. A boat may decide to return to port at any stage with a probability proportional to the fullness of its hull. Once the boat has a full load it must return to port to offload. Each boat has specified parameters for hull size, speed and crew size, however the speed of the boats varies with the amount of load they are carrying. Each boat also has a parameter controlling what it regards as an acceptable size catch in a time period, which will cause it to reevaluate the reef at which it will fish.

The application has been implemented in C++ using the QT cross platform GUI library and the QWT library of technical widgets [7].

2.1 Main Simulation Loop

These essential components to the simulation are put together into a central simulation loop that controls the activity of boats and reefs in a synchronised fashion. This central loop has the



Iteration: 10462 Average Yield: 3.97

Iteration Limit 2000

Results File C:/results.txt

Decision Parameters

Parameter A - Expected Fish 6

Parameter B - Peer Influence 2

Parameter C - Travel Costs 5

Simulation Speed (Frame Rate in Milliseconds) 43

Figure 1: Screen shot of the fisheries simulation package. The graphical display shows position of each boat in the fleet with a small black icon. Each reef is a shown as green square, with an area proportional to its capacity. The barometer on their right hand side of each reef displays current fish stock (red indicates that the fish population on a reef has gone extinct). The line chart in the lower left shows the fluctuations in total fish stock of the fishery. The decision function coefficients are controlled with three of the sliders on the left hand control panel.

following structure, at each time step:

Algorithm 1 Simulation Control Loop

```
while $iteration < Limit$ do
    for $boat$ in $Fleet$ do
        if $boatInTransit$ then
            Continue toward destination
        else if $boatInPort$ then
            Sell the haul
            Run Procedure 'Decision Function'
        else if $randomHeadHomeCheck$ then
            Head for port
        else if $currentReefHasFishstockWithinThreshold$ then
            Harvest Fish
            if $harvestLessThanAcceptableLimit$ then
                Run Procedure 'Decision Function'
            end if
        else
            Run Procedure 'Decision Function'
        end if
    end for
    for $reef$ in $Fishery$ do
        Update fish stock using growth model
    end for
end while
```

The procedure 'Decision Function' is the core of the decision making process for the boats in the fleet. It involves evaluating equation 1 for each of the reefs and choosing the reef with maximum result. The amount of influence that each of the other boats had in this decision is stored and once the boat arrives at its new destination and begins to harvest, the peer influence vector is updated in line with how much fish the boat is able to catch, using the simple reinforcement dynamics outlined in Section 2.3.

2.2 Decision Function

The essence of the multi agent simulation is the decision function by which the boats choose reefs to visit. The decision function is a composite of three essential elements; the expected fish, the influence of their peers and the travel costs.

Each of the boats has some information about the location of fish. However it is not perfect, each boat has an accuracy parameter which governs the accuracy of information it receives about fish stocks in each of the reefs. This parameter is adjusted as the simulation continues so that the distribution of accuracy reflects market share. The assumption being that information is obtained by having access to the best technologies.

The boats have a vector of peer influence, which represents their tendency to follow each other boat in the fleet. In evaluating each reef, the agent sums the influence of all other boats that are currently at or sailing to that reef.

Finally the agent takes into consideration the distance to each reef, with the assumption that traveling costs in the form of petrol and wages are directly proportional to distance.

The decision function is implemented thus, an agent examines each i of the R reefs, and takes the maximum of $Dest_i$ given as:

$$Dest_i = A \times f_i + B \times \sum_{j=1}^{N} D_{ji} \cdot I_j - C \times d_i \tag{1}$$

Where the parameters A, B and C are coefficients weighting the three components of the decision rule. The value f_i is the number of fish the agent expects to find at location i. The sum with index j from 1 to N is over the number of boats in the fleet. The N by R matrix D contains destination information for the entire fleet, with the form entry D_ij is equal to one iff boat j is headed for reef i and zero otherwise. The value d_i is the Euclidean distance to the reef from the boats current location.

Each boat in the fleet has an information accuracy parameter, which reflects the reliability of their information about fish stock levels at each reef. When making the decision the number of expected fish f_i is calculated by generating a random number between $-fishStock/2$ to $fishStock/2$ and multiplying this by the boat's accuracy term. Thus the higher the accuracy the closer the expected fish will be to the real fishStock. This differs from models in which information about fish stocks are obtained by information sharing among vessels [1]. However, these models tend to make assumptions about access to immediate high quality information that are not supported by empirical studies [6].

2.3 Reinforcement Learning

Each of the boats in the fleet maintains a vector of values that indicate the extent to which their decisions will be influenced by each of the other boats in the fleet. This vector is initialized with random values between zero and one. After a boat makes a decision to visit a particular reef, it maintains a separate vector of all the boats in the fleet who had also chosen that reef at that time. When the boat arrives at the reef it calculates the amount by which it updates the influence vector as follows. The difference between the real and expected fish stock is calculated D_e^r. This is then divided by the reefs capacity to scale it in proportion to the reef size. Finally the change is then given a hard threshold so it must lay in the range -0.5 to 0.5. This change term is then added to all entries in the peer influence vector that correspond to boats that were moving to the same reef.

As such the reinforcement dynamics will tend to support relatively naive boats coming to trust boats with higher quality information. However, due to the fact that these naive boats are as likely to overestimate as underestimate the fish stock, the reinforcement dynamics may never settle into equilibriums.

The reinforcement dynamics could potentially be modified to introduce a stag hunt component so that in some sense boats will tend to follow boats that do not quickly consume all fish stock on a reef. In other words boats will avoid those others with a tendency to over-fish.

2.4 Population Dynamics

The fish populations at each of the reefs in the simulation are modeled as renewable resources with a purely compensatory growth function. The discrete standard logistic function is used for this purpose, the change in fish stock X is determined by

$$X_{t+1} = X_t + r \times X_t \times (1 - \frac{X_t}{K}) \tag{2}$$

Where K is the carry capacity of the reef and r is the intrinsic growth rate. The value of r determines the quality of the population's intrinsic dynamics, values greater than 2.570 result in deterministic chaos while values less than or equal to 1 result in a steady asymptotic approach to K [5].

In line with standard fisheries modeling we take the harvest rate to be proportional to the effort expended and the density of fish in the reef [5]. In our model the effort expended is proportional to the size of the boat, and its corresponding crew, and the time spent at the fishery.

An expression for the yield given these assumption is

$$H(E, X) = qEX \tag{3}$$

When combined with the discrete logistic growth model this is known as the Schafer model, after the biologist M.B.Schafer who used it to model Pacific tuna fisheries. It can be shown that the sustained yield for such a model is given by

$$Y = qKE(1 - \frac{qE}{r}) \tag{4}$$

It is important to note that if the effort expended on harvest is too large, $E > \frac{r}{q}$, then the population will be exhausted. Hence a critical function of such modeling the exploitation of renewable resources is to answer the question of how much effort to expend in order to maximise sustained yield and not eliminate natural resources.

In the early numerical models effort remained an illusive property, a single value that was understood to incorporate all investment of capital and labor into the industry. We may use the above equation to find a estimate the achievable sustained yield for a fishery, yet because the effort is merely an abstract theoretical construct, it fails to provide clear guidance for how to implement such a sustained yield.

In our model there are numerous parameters that can be interpreted as contributing to effort. For example, the size and total hull capacity of the fleet, which can be interpreted as a representation of the investment of capital as well as the amount of labor being invested due to the fact that crew size is proportional to boat size. The information quality parameter for fish stock sizes, can be taken as an indication of investment in research and technology. In future versions of the model we intend to allow the boats the capacity to grant shore leave between ventures, influenced by the current expected yields. The proportion of time that a boat remains at port between trips will also qualify as an inverse contributor to effort.

The breakdown of effort into numerous separate parameters immediately suggests the research topic of investigating the achievement of an optimal balance between these elements in order to maximise the sustained yield. The size and capacity of a fleet and the amount of shore leave between voyages, must be adjusted in proportion to the capacity of the fishery as well as industrial relations requirements.

3 Conclusion

The current model is still being developed and is not yet in a state that it can serve as a basis for informative simulations. Our next immediate goal is to calibrate the existing model with data for the Queensland coral reef fishery and test the statistical properties of the fishing fleet behaviour for coherence with our dataset. From that point we will be looking to extend the model in a variety of ways to increase the flexibility and realism of the models.

We will be extending the flexibility of the software to allow easy modification of all parameters relating to the physical layout of the reefs, the underlying population dynamics of the fishery and the fundamental configuration of the boats in the fleet. The configuration of boats will be extended to allow simulators to choose between different definitions of rationality, for example, between the current Reinforcement learning, Boundedly rational behaviour Preset influence matrices or Explicit rule based behaviour.

We will be extending the economic characteristics of the model so that the profits made by the boats are dependent upon an artificial market whose statistical properties can be adjusted by the simulator. With this extension we will follow the individual prosperity of the boats and allow them to leave and enter the game depending on economic success.

We will look at extending the game theoretic concerns so that there can be be greater capacity for cooperation and defection within the game, for example in the exchange of information and the formation of spontaneous agreements on divided exploitation of available fish stock.

Finally we will be modifying the software so that it can function explicitly for modeling management scenarios, by allow the selection of certain reefs as fishing reserves. Including a model of population spawning between reserves. We will then add the capacity for the definition of economic regulators such as the definitions of Total Allowable Catch (TAC) and the capacity for introducing fines on vessels for transgressions.

We note that many of these features have been modeled by Hall [8] using a dynamic open access fishery model of the interaction between fisheries, tourism and agricultural run off. Hall however only considers very stylised spatial features of the problem and does not model spatial dynamics explicitly.

The long term goal is to have the software function as a general modeling framework for reef line fisheries, such that all the specific details of a particular physical system can be entered into the system and a variety of game theoretic scenarios tested against real datasets.

Acknowledgments

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