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Framework for a space-time resource and fisher model to assess CPUE-abundance relationships

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Abstract: We describe a new integrated resource-fisher operating model (RESFIM – **RES**ource-**F**isher **I**ntegrated **M**odel) developed to examine how adequately CPUE indexes resource abundance. The model for the first time links resource movement and fisher behaviour, an approach lacking in most current individual-based models employed to examine CPUE-abundance relationships. For each resource movement scenario, namely (a) random movements between locations; (b) habitat attraction; (c) habitat attraction + density dependence; and (d) environmental conditions, RESFIM simulates daily resource dynamics and behaviour of fishers harvesting the resource, the latter using a Bayesian belief network (BBN) which determines where fishers will harvest. The decision on where to harvest is based on factors that include information sharing, use of acoustics and environmental conditions.

Keywords: *fish movement, fisher behaviour, individual based model, CPUE, hyperstability*

1. INTRODUCTION

Fisheries assessment models usually assume CPUE to be linearly related to abundance, i.e. fishing effort is randomly distributed and the catchability coefficient constant in space and time (Hilborn and Walters 1987, 1992). While this assumption may be reasonable for a virgin fishery, it could be invalid as a fishery develops and harvesting becomes non-random. A key to understand CPUE-abundance relationships is to determine the extent of the fisher's ability to locate areas of greatest abundance, and how it interacts with resource habitat selection (Harley *et al.* 2001). While fisher behaviour has led to concerns regarding the use of CPUE as an index of abundance, most studies have omitted this factor and have instead focused on the influence of spatial stock redistribution on CPUE-abundance relationships (Gillis *et al.* 1993; Dunn and Doonan 1997). Various theoretical, linear and non-linear CPUE-abundance relationships have been investigated in fisheries (Richards and Schnute 1986). While linear forms constitute the most common, non-linear forms can lead to hyperdepletion or, more often, hyperstability. The need for spatially explicit models that dynamically simulate mobile agents through time has increased in recent years. However, while most use ecosystem or fleet behaviour, very few have included fisher behaviour (e.g. Dreyfus-León 1999; Maury and Gascuel 1999; Dreyfus-León and Kleiber 2001; Little *et al.* 2004) or examined how different resource-fisher scenarios may influence CPUE-abundance linearity in space and time (Fonteneau and Richard 2003; Gaertner and Dreyfus-León 2004). In this paper we describe a general framework for an integrated resource-fisher operating model (RESource-Fisher Integrated Model; RESFIM) to assess how CPUE indices compare with "true" abundance. The resource and fisher sub-models are integrated to form the basis of daily movements of a resource and harvesting activities of fishers, based on general fleet and species movement characteristics. The resource sub-model incorporates the main characteristics of a fishery, such as spatial resource movement and recruitment, but excludes age and length structure. The fisher sub-model incorporates several types of behaviour employed to locate the resource, including local environmental conditions and information sharing, and employs a Bayesian belief network (BBN) to determine harvest location.

2. MODEL DESCRIPTION AND METHODS

2.1. Model Description

RESFIM comprises resource and fisher sub-models designed to capture the dynamics of both resource and fishers (Fig. 1). The model assumes that (i) environmental conditions influence both resource and fisher sub-models; and (ii) these sub-models are linked during harvesting via a catch equation. The resource sub-model incorporates space-time movements and biological processes relating to a resource (e.g. recruitment, spawning, movement and catch) whereas the fisher sub-model incorporates different fisher behaviours which involve moving to harvest locations. RESFIM was written in Microsoft Visual Basic 6.0 and adopts a two dimensional spatial structure.

2.2. Environmental Conditions

Simulated sea surface temperatures (SSTs) are employed as a proxy for environmental conditions to characterize resource movement and fisher behaviour. SSTs have been closely linked to fisheries CPUE (e.g. Chen *et al.* 2005; Zainuddin *et al.* 2006), and associated to resource movement either empirically (e.g. Brill *et al.* 1999; Cotton *et al.* 2005) or via simulation (Colbourne *et al.* 1997).

2.3. Resource Sub-Model

Biomass (B) for area (A), year (y), location (c) and time step (t) is estimated via a space-time model modified from a delay difference equation of Smith (1993):

$$B_{A,y,t+1,c} = s_A B_{A,y,t,c} + R_{A,y,t,c} + B^{\bullet\to c}_{A,y,t+1,c} - C_{A,y,t,c} \tag{1}$$

where R is the recruitment biomass, C catch, s "survival" incorporating growth and natural mortality, and $B^{\bullet\to c}$ net biomass distributed to and from harvest location c. Harvest location is analogous to a fishing ground, while A surrounds harvest locations. Recruitment may occur in more than one season and is described by the Beverton-Holt (1957) stock-recruitment function. Yearly stochastic recruitment (R_y) is distributed intra-annually based on an equal proportional allocation method (Quinn and Deriso 1999) and evenly across locations. Vessel catches are based on the catch equation:

$$C^{v}_{A,y,t,c} = q^{v}_{A,y,t,c} E^{v}_{A,y,t,c} B_{A,y,t,c} \tag{2}$$

where v vessel and E effort. Catchability coefficient (CC) for vessel v $\left(q^{v}_{A,y,t,c}\right)$ is defined as:

$$q^{v}_{A,y,t,c} = \bar{q}_{y} q^{v} q_{A,y,t,c} \tag{3}$$

where $\bar{q}_{y}$ is the overall fleet CC in year y and is log-normally distributed with μ_y mean and σ_y^2 variance. Also q^{v}, CC for vessel v, is log-normally distributed with μ_v mean and σ_v^2 variance and may vary in time to reflect improvements in navigational or electronic fish detection devices (e.g. GPS; echo-sounder) and fishing gears. The spatial CC $q_{A,y,t,c}$ may differ between locations, and depend on environmental cues expressed as a second order polynomial.

2.3.1. Resource Movement

Resource movement is simulated under four categories: random, habitat attraction, density dependence and environmental conditions. No movement occurs outside the spatial boundaries, i.e. the population is closed.

Random A randomly distributed resource is generated from a uniform U[0,1] distribution.

Habitat attraction Pertains to a schooling resource which moves between preferred locations either daily, or seasonally to account for seasonal shifts in abundance. Greater movement towards attractive locations can also occur during particular times of year (e.g. spawning aggregations on seamounts or rocky reefs). This is achieved by utilizing a probability density function (pdf) of a normally distributed random variable with mean μ_s and standard deviation σ_s, for season s, where $s \in [1, 4]$.

Habitat attraction + density dependence Pertains to a highly mobile resource that forms dense aggregations (e.g. in relation to food availability) by moving daily to preferred locations which are influenced by local density relative to local carrying capacity. This is achieved by employing movement and dispersion rate parameters to maintain the spatial carrying capacity of a location. This scenario follows the suggestion that the spatial distribution of a resource may be density-dependent (MacCall 1990), as in the case of the Atlantic cod commercial fishery (Swain and Wade 1993).

Environmental conditions A space-time first order autoregressive (AR) model simulates daily SSTs and short-term variability. Parameters account for uni-directional N-S space-time correlations, so that SST at a location and time step are related to that of its nearest neighbour (NN) in a previous time step. A resource moves towards locations where SSTs are most favourable (e.g. warmer SST) and avoids SST-unfavourable locations.

2.4. Fisher Sub-Model

This sub-model simulates interactions between fisher behaviour and resource movement. Behaviour types comprise six likely harvesting strategies adopted daily by commercial fishers, with fishers using either the same strategy to determine where to harvest on any particular day (homogeneous), or different harvesting strategies (heterogeneous) (Fig. 1). A fisher first decides each day whether or not to harvest before choosing harvest location. Each fisher returns to home port after a single shot with one gear type in one location, and a constant steaming time is assumed. Fishers may harvest at the same location simultaneously, provided there is available resource. However, a resource cannot be completely harvested at any location in any time step.

2.4.1. Homogeneous Fisher Behaviour

Random Harvest location is random each day.

Individual Employs a BBN (Pearl 1986, 1988) that allows decisions made by fishers to be modelled in response to different levels of information and knowledge of resource. Information is primarily based on daily CPUE, and used to determine fisher's probability of selecting a harvest location. It is updated recursively so CPUE changes are accounted for, i.e. a discounted CPUE is computed as a daily weighted average, where greater weight is placed on most recent observations (i.e. personal experiences and/or those of other fishers) than those in the past. Weight may be altered to satisfy the degree to which each fisher places emphasis on both current and past observations. Probability of harvesting in a particular location increases or decreases if CPUE falls above or below a discounted weighted average, respectively. This ensures that harvesting accounts for CPUE changes relative to a fishers' historical knowledge.

Acoustics Echo-sounder information coupled with the previous year's CPUE is employed to select harvest location, i.e. a location is harvested if predicted CPUE on a day falls within 10% of the observed CPUE closest to the same day in the previous year. If predicted CPUE falls below the lower limit, the fisher moves to first NN location to determine whether to harvest based on predicted location's CPUE. If no harvesting takes place, a NN search is repeated until a decision to harvest in NN location is made.

Environmental conditions A fisher determines where to harvest based on predictions from a second order polynomial of the previous year's CPUE and SST. Harvesting takes place where predicted CPUE is maximum providing this corresponds to current SST and, if not, where predicted CPUE is closest to maximum. The model is updated annually to allow for changes in relative resource depletion.

Information sharing A pdf-learning regime and information from other fishers are used to determine where to harvest. The pdf is updated daily using historical CPUE and information shared by other fishers using a link matrix which incorporates the degree of sharing. The matrix does not describe a causal mechanism for information exchange between fishers, but implicitly uses information gained from other fishers. Harvesting location is then chosen based on each fisher's updated pdf. The same amount of information sharing takes place for all fishers during each fishing trip. It is more likely that a fisher will harvest in locations where CPUE of several fishers has been greatest.

Perfect information Assumes perfect knowledge of spatial resource distribution, so fishers move to locations with greatest available biomass.

2.4.2. Heterogeneous Fisher Behaviour

Fishers use different strategies which may differ between fishers, but there is no switching of strategies during harvesting. For example three fishers employ acoustics, four rely on environmental conditions and three share information before deciding where to harvest.

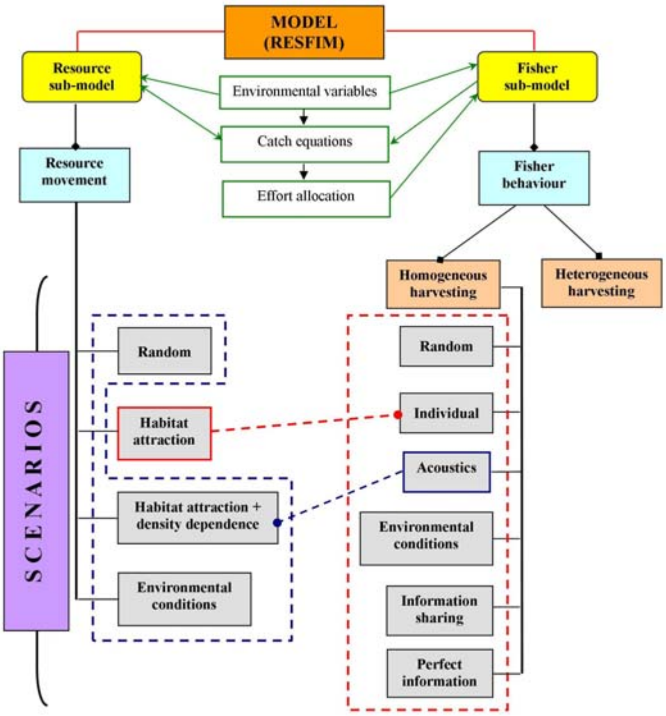

Figure 1. Flow diagram of the general model structure of RESFIM (see text for details). Examples of modeled scenarios include resource movement across fisher behaviours (red dashed lines) and fisher behaviour across resource movements (blue dashed lines).

3. DISCUSSION

RESFIM was developed to simulate a number of resource movements-explicit fisher behaviour scenarios aiming to examine CPUE-abundance relationships for fisheries exploiting mobile resources. Model outputs could be employed to identify which scenarios are likely to produce hyperstable, hyperdepleted or linear relationships. More importantly, RESFIM can be used to evaluate whether CPUE-abundance linearity can be reasonably assumed under different resource movement-fisher behaviour combinations, and to determine under which circumstances CPUE indices fail to correctly interpret fishery-wide abundance trends.

As well as RESFIM, a number of simulation models incorporate both resource dynamics and explicit fisher behaviour, including the generic space-time model SHADY (Maury and Gascuel 1999) and ELFSim (Little *et al*. 2004). While all three models have different mathematical forms, RESFIM shares similarities with SHADY at the resource sub-model level and with ELFSim at the fisher sub-model level. For example, RESFIM harvest scenarios allow fishers to use environmental conditions, historical CPUE and/or acoustics to determine where to harvest, with fishers forming homogeneous or heterogeneous groups. By contrast, SHADY includes resource movement scenarios for migrating vs. non-migrating resources, as well as environment and a fishing fleet in the context of marine protected areas for general fish stocks (Maury and Gascuel 1999). Moreover, RESFIM incorporates uncertainty of the resource biomass at each harvest location, whereas SHADY allows fishers to randomly access a "fraction" of the total number of cells before harvesting in the most abundant cell. This "fraction" can be changed to allow fishers to have perfect knowledge of abundance in all harvest locations, and is based on the ideal free distribution (IFD) theory of Fretwell and Lucas (1969) that assumes a predator has perfect knowledge of resource profitability and aims to maximize it. This "perfect information" fisher behaviour type is also used in RESFIM but, unlike SHADY, it also incorporates additional behaviours which assume that true abundance is unknown.

Similarities between RESFIM and ELFSim include the use of (a) BBNs to propagate fisher behaviour in time, (b) a discount factor which down weights historical information, and (c) information sharing to decide where to harvest (Little *et al*. 2004). However, unlike ELFSim, the RESFIM resource sub-model is not age, sex or size structured, and harvesting takes place over trawl grounds instead of individual reefs. Moreover, RESFIM assumes that the two variables used by ELFSim to estimate expected profitability, i.e. distance from home port and movement costs, are constant. Also, the updating procedure of RESFIM's fisher sub-model is performed daily and not monthly as with ELFSim, i.e. profitability estimates from RESFIM are based on daily rather than monthly CPUE.

Another space-time simulation model which incorporates fisher dynamics based on the IFD theory, and resource movement based on advection and diffusion rates (MacCall 1990) is that used in tuna and billfish fisheries (Fonteneau and Richard 2003). As with RESFIM, this model simulates space-time dynamics of a target species to examine CPUE-abundance relationships. However, unlike RESFIM which only simulates target species and can be used to determine CPUE-abundance relationships for a 10-year period, the Fonteneau and Richard (2003) model simulates space-time dynamics of target and by-catch species, and can only used at the local scale (a small subset of grids) for a year. Moreover, unlike the latter, RESFIM's fisher sub-model is not based on the IFD theory so outputs can be used to examine CPUE-abundance relationships when perfect information on resource abundance is unknown.

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