Using an Agent-Based, Object-Oriented Model to test the performance of Catch Per Unit of Effort as an estimator of fish abundance in small-scale, multispecies fisheries

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ABSTRACT

An object oriented, agent-based model is developed and used to help explain the dynamics of the interaction between individual fishing units and individual fish in a small scale fishery, and how these interactions influence the estimation of catch per unit of effort (CPUE) as an abundance index. The model allows animals to have individual characteristics and interact spatially with one another. A fleet exerts fishing effort on the available fish stocks. Each vessel has individual characteristics including a varying propensity toward risk taking, and based on this factor, will alter targeting behavior (selectivity) to maximize revenue. Various scenarios are explored and suggest that while standardizing CPUE may be practical and lead to unbiased estimator of abundance for large-scale fisheries targeting a single species, the same estimators are unlikely to perform as well on data derived from small-scale commercial fisheries. Fleets from these fisheries frequently redistribute fishing effort across multiple species and gears causing changes in catchability that are difficult to incorporate in traditional CPUE standardization procedures. A disaggregated, individual vessel-based analysis can be implemented in order to evaluate the robustness of such estimators.

KEY WORDS: agent-based model, CPUE, small-scale fishery

Análisis de la Captura por Unidad de Esfuerzo como Perito Imparcial de la Abundancia en Pesquerías de Comerciales de Pequeña escala en el Caribe

Desarollamos y usamos un modelo basado en agentes, y con programación orientada a objetos para ayudar a explicar la dinámica de las interacciones entre peces y embarcaciones de una pesqueria de pequeña escala, y cómo estas interacciones influencian la estimacion de índices de abundancia basados en la estandarizacion de datos de captura por unidad de esuerzo. El modelo permite que los animales tengan características individuales y que interaccionen espacialmente el uno con el otro. Una flota ejerce esfuerzo pesquero sobre los peces disponibles y cada embarcación tiene características individuales, incluyendo una propensión diferente hacia el riesgo, que determina el comportamiento de selectividad mas apropiado para para maximizar el rédito de la pesca. Consideramos varios escenarios para las simulaciones que sugieren que mientras la estandarizacion de CPUE puede proporcionar un estimado de abundancia apropriado cuando se aplica a datos de pesca industrial que apuntan una sola especie, los mismos estimadores no rinden seguramente tan bien cuando se aplican a datos derivados de pesquerias de pequegna escala. Las flotas que participan en esta pesca a menudo cambian las especies objetivo y redistibuyen el esfuerzo causando cambios en la selectividad de la flota que si son difíciles de incorporar en el proceso de standardización. En este articulo usamos este modelo para evaluar que tan robustos son estos estimadores.

PALABRAS CLAVES: modelo basado en agentes, CPUE, pesqueria de pequeña escala

INTRODUCTION

In order to understand and effectively regulate the impact of fishing on fish populations and their interactions with one another and their environment, it is necessary to not only study the population dynamics of the fish, but also the population dynamics of the fishermen themselves (Branch *et al.* 2006, Hilborn 1985, Hilborn and Walters 1992, Lane 1988). Like any other population, the fishermen that make up fishing fleets can range from being somewhat homogeneous, to heterogeneous and complex with dynamic interactions across space and time. The degree of heterogeneity within a given fishing fleet has important effects on the observations of catch and effort from that fishery, and the subsequent estimations and underlying assumptions that govern the calculation of a standardized catch per unit effort index and ultimately population status. Heterogeneity of fleet dynamics results in variable catchability across the fleet, something that is often assumed to be constant (Bishop 2006). Assuming catchabilty to be constant when in reality it is highly varied may lead to changes in catch per unit effort that are misinterpreted to be due to changes in abundance. Population models based on catch data that is inappropriately standardized are likely to provide spurious results that offer inappropriate management advise and threaten fishery sustainability, individual livelihood and elimination of communities and cultures (Bishop 2006). Despite this, however efforts continue to focus disproportionately on the biology, dynamics and ecology of fish, and result in some population assessment and management failures (Salas and Gaertner 2004).

Fisheries that tend to be more heterogeneous are the small-scale commercial multi-species, multi-gear fisheries that characterize Caribbean nations (Impact Assessment 2005, Polunin and Roberts 1996, Fiedler and Jarvis 1932, Hill 1969). These fisheries are unique in that unlike their large-scale counterparts, fishermen of smaller operations are more affected by changes in biological or economic conditions, which may alter the relative profitability of one species over another (Impact Assessment 2005). Due to their smaller size, the redistribution of fishing effort can be performed more frequently in an effort to maximize fisher revenue (Holland and Sutinen 1999). This adaptability leads to flexible selectivities for species and allows fishers to target a variety of animals (Salas *et al.* 2004, Cabrera and Defeo 2001). The inherent complexity of vessel switching behavior that occurs in small-scale fisheries makes it difficult to foresee how effort has historically been allocated among various target species and thus forecast potential effort allocation scenarios for management (Salas *et al.* 2004).

For small-scale commercial multi-species, multi-gear fisheries, it is necessary that catch per unit of effort indexes are standardized using a disaggregated, individual vessel-based approach due to the fact that individual vessels have dynamic catchability coefficients across time and space. In order to do this, we must first understand the processes and factors that cause redistribution of fishing effort, and the affect of these factors on the calculation of the catch per unit effort index. Most models that have been developed to study fisher behavior have focused on spatial dynamics (Opaluch and Bockstael 1984, Bene 1996, Cabrera and Defeo 1997), however few have been developed to evaluate fisher decision-making regarding species selection (Holland and Sutinen 1999, Pelletier and Ferraris 2000). Consequently, an agent-based, object-oriented model is constructed using Java programming language in order to investigate the effects of fleet heterogeneity and individual vessel revenue maximization on catch per unit of effort as a proxy for abundance.

METHODS

Today, most computer programs are object-oriented including Windows, Mac OS, Word Processors and Spreadsheets. An object is an actively running instance of computer code, which has data (variables) and functionality (methods). Agent-Based Models (ABMs) turn this capacity into a means for scientific modeling where the agents are objects with specifically defined sets of rules or behaviors, according to which they interact with their surrounding environment and with one another. ABMs can be used in a variety of disciplines to model various complex systems and study the emergent properties that result from the underlying object interactions and behaviors. This modeling approach is well suited to studying complex fishery-fleet and fishery-ecosystem interactions because it does not rely as heavily on equilibrium and steady state assumptions. The approach does not replace equation-based modeling, but is complementary and can incorporate equation-based models to govern agent behaviors (McManus 2006).

A spatially explicit, agent-based, object-oriented model is constructed using Java programming language in order to investigate the effects of fleet heterogeneity and individual vessel revenue maximization on catch per unit of effort as a proxy for abundance. The Multi-Agent Simulator Of Neighborhoods (MASON) library is imported and used as the foundation for this custom Java simulation, providing functionality and visualization tools to fit object and simulation needs (Luke, et. al. 2004). Three different classes of agents exist in the simulation: vessel, herbivore and piscivore. Each agent class contains code defining that agent's potential characteristics and behaviors. At the start of each simulation, an array of each agent is produced generating populations of the herbivore, piscivore, and a fleet of vessels. Each individual object created has its own individual characteristics and behaviors (movement, fecundity, foraging, etc.) based on the coding within each agent class.

Piscivore and Herbivore Populations

The piscivore and herbivore classes relate as predator and prey respectively. Both classes contain the following biological parameters:

Carrying capacity

Abundance at time zero (initializing abundance at start of simulation)

Yield per mature recruit

Recruitment time (time interval at which new individuals recruit to the ecosystem and fishery)

Age of Maturity (time period between recruitment to the ecosystem and sexual maturity)

It is assumed that the recruit time is equal to the time at which animals are available for fishing exploitation. During spawning events, sexually mature animals are able to contribute their recruits to the population up to the population carrying capacity; recruitment ceases once the population reaches carrying capacity. The piscivore contains an additional hunger parameter, which governs when that animal hunts for an herbivore. The piscivore will consume the herbivore if it is hungry (has not recently eaten) and is

Table 1. Randomly assigned piscivore and herbivore selectivities for the heterogeneous fleet without increase in effort.

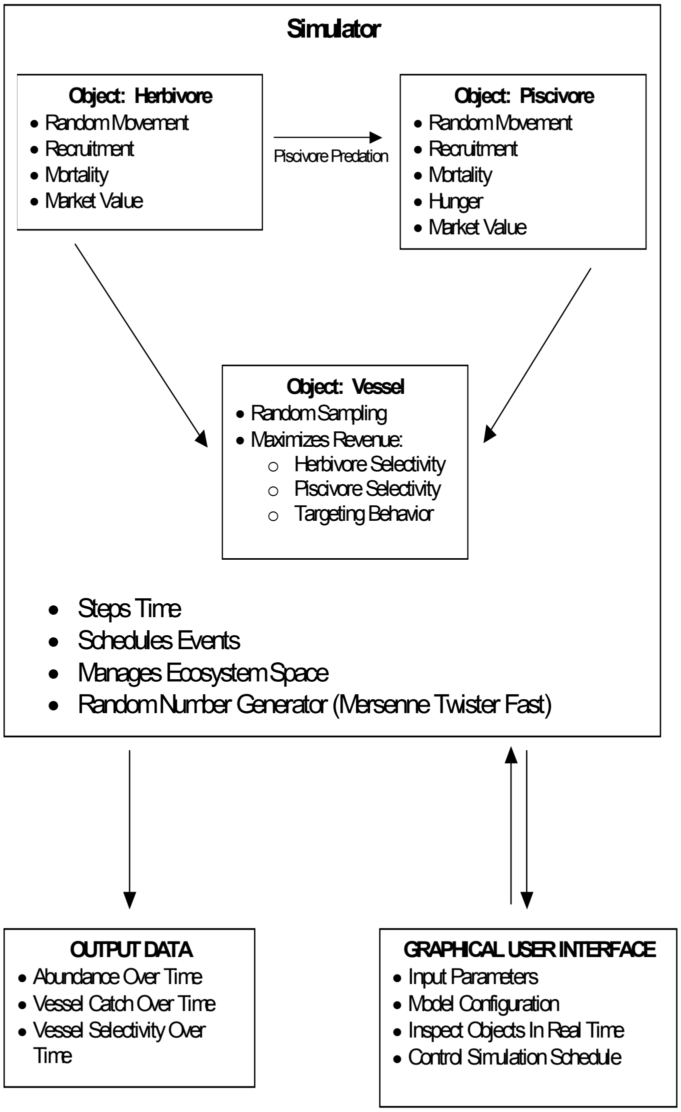
Vessel	Piscivore Selectivity	Herbivore Selectivity
0	0.29	0.71
1	0.45	0.55
2	0.53	0.47
3	0.39	0.61
4	0.92	0.08
5	0.91	0.09
6	0.75	0.25
7	0.08	0.92
8	0.85	0.15
9	0.02	0.98

spatially located in the same grid space as the herbivore. If an herbivore is not found or none are available, the piscivore will ultimately perish of starvation. Consequently, herbivore abundance at any given time is a function of piscivore predation activity, while piscivore abundance and carrying capacity at any given time is limited by herbivore abundance at that time.

Vessel Fleet

The vessel class creates a fleet of boats with individual characteristics and various scenarios that examine the application of fishing effort to the two populations. Vessels have the opportunity to catch either an herbivore or a piscivore that is located in the same location of the vessel or located within the Moore neighborhood (square neighborhood around the vessel) out to one grid space of that vessel at any given time (nine potential locations around the vessel where a fish could be caught). A market value is assigned to the herbivore and piscivore, which each boat uses to estimate revenue for a given time period. Each vessel is assigned a risk parameter from zero to one at the beginning of the simulation, which determines the risk a vessel is willing to take to maximize its revenue. Based on risk and earned revenue for a recent time period, vessels will switch effort allocation from one species to another in order to try and maximize their revenue. The user also has the option to allow vessels to respond to seasonal trends in abundance, which appear in the catch, and can consider these seasonal trends either in conjunction with or apart from maximizing individual revenue.

Figure 1. Schematic diagram of program stratification and interactions.



Ecosystem Simulator and User Interface

The virtual ecosystem in which the agents exist is a 100 by 100 cell grid in toroidal space where interactions are permitted to occur based on spatial proximity of one agent to another. Time is recorded in steps, where each program step, the objects (every vessel, herbivore and piscivore) perform the actions coded in their class according to the parameters specified. When translated to real time, roughly 7,500 steps equate to one calendar year, with about 20.5 steps occurring per day. The simulator is independent from the user interface and is charged with initializing the program at start time, scheduling events, stepping the code (time), filing the output, and maintaining geographic space (the grid). The user interface controls the input parameters, allows the user to control the schedule in real time, graphically displays the interactions, and allows the user to query the agents in real time to see their characteristics.

Scenarios Examined

Various model simulations are explored to examine how fleet heterogeneity affects the estimation of catch per unit of effort. A disaggregated, individual vessel-based analysis of catch per unit of effort is conducted on the simulated data in order to make apparent the variance due to fleet heterogeneity.

Scenario A: homogeneous fleet and heterogeneous fleet exert constant effort on the herbivore and piscivore across time.

Scenario B: homogeneous fleet and heterogeneous fleet exert increasing effort on the herbivore and piscivore across time from the point of virgin stock, to stock depletion of the piscivore. This situation makes it possible to examine catch per unit of effort for various levels of average abundance.

Scenario C: fleet begins homogeneous and across time, decides to become specialized according to their propensity to take risks and their own individual boat's past revenue (imperfect information). Based on their catch history, individual vessels can alter their selectivity for or against one species or another to maximize revenue.

Scenario D: fleet begins homogeneous and uses both

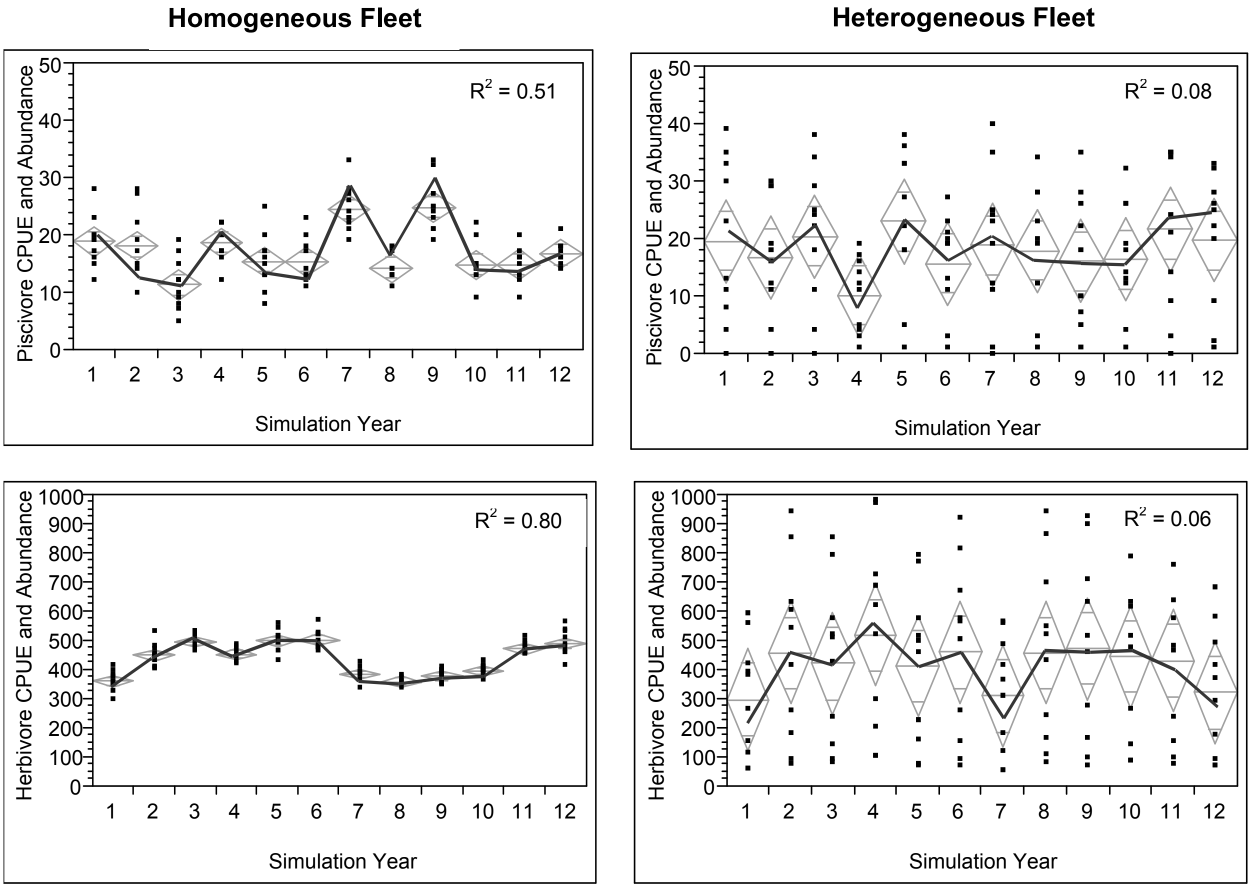


Figure 2. Individual vessel-based observations of CPUE (points) for a homogeneous and heterogeneous fleet, and average abundance (line) for the herbivore and piscivore populations across simulation years.

their own individual boat's past revenue, as well as seasonal abundance fluctuation observations acquired from their knowledge of the fishing fleet as a whole (their fellow fishers) to determine effort allocation (perfect information) (Figure 1)

RESULTS

Scenario A:

In the simplest situation, a homogeneous fleet with constant effort and a heterogeneous fleet with constant effort are simulated and exert effort on the herbivore and piscivore across time. During model initialization, vessels in the homogeneous fleet are uniformly assigned and maintain throughout the simulation a 0.5 selectivity for both the herbivore and piscivore. Vessels in the heterogeneous fleet are randomly assigned selectivity for each the herbivore and piscivore during model initialization (Table 1).

Analysis of CPUE for each of these situations across time reveals that there are statistically significant differences in catch per unit of effort from one vessel to another when the fleet is heterogeneous. Differences that appear in catch per unit of effort for vessels within the homogeneous fleet are due to the spatially explicit nature of the model. The difference between the variance of the homogeneous fleet and heterogeneous fleet represents the variance that results from having a fleet that is heterogeneous (Figure 2).

Due to the large abundance of the herbivore, and the resulting ability of the fishing fleet to capture more individuals, when compared to the piscivore, a more precise estimate of CPUE is obtained for the herbivore. Despite this, however, even for the herbivore in the heterogeneous fleet, the variance overwhelms the ability to obtain a good estimate of CPUE.

Scenario B:

For the homogeneous and heterogeneous fleets, fishing effort can be imposed on a simulated virgin herbivore and piscivore stock starting at low effort levels, and linearly increasing across time until the piscivore abundance is depleted. This situation enables us to analyze CPUE at various levels of abundance in order to determine whether CPUE is a good estimator of abundance. Individual-based analysis of the results indicates that catch is a better measure of abundance for the homogeneous fleet compared with

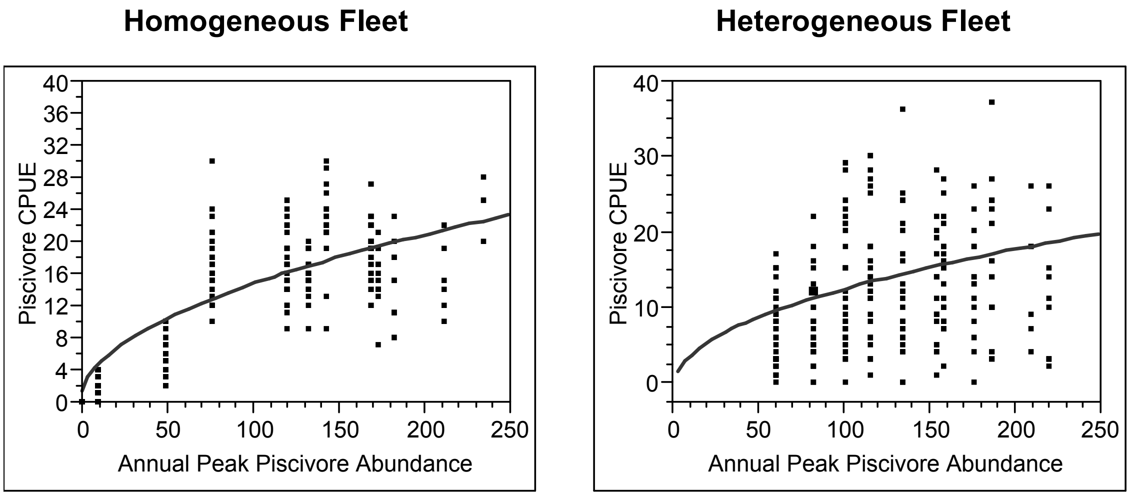


Figure 3. Individual vessel-based observations of piscivore CPUE for a growing fleet that is increasing fishing pressure on the stock over time starting at zero effort until stock exploitation.

the heterogeneous fleet. The annual peak abundance represents the abundance of the species for that particular year once all of the animals have been recruited that year (Figure 3).

Scenario C:

In reality, fleets become heterogeneous because fishermen decide how to allocate their fishing effort based on which targeting approach or gear configuration provides them with the maximum economic return. Over some period of time, fishermen will examine their earnings and decide to stay where they are or to "switch" from one gear to another or from one targeting approach to another in order to maximize their revenue. A scenario is modeled where fishermen all start off with equal propensity to capture one species over another (homogeneous) and through evaluation of their earnings each year, choose over time to become specialized in capturing one species over another (Figure 4).

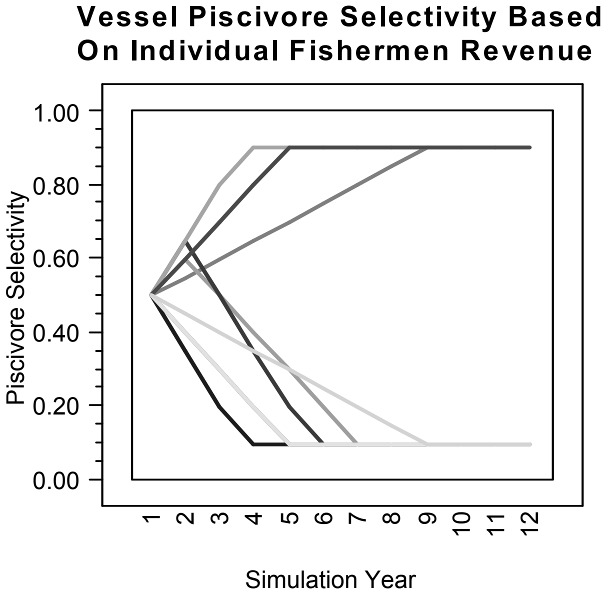


Figure 4. Individual vessel effort redistribution over time according to revenue earned in the previous time period.

The increase in a fisherman's skills and knowledge, and the accompanying shift in effort toward capturing one particular species over another enables fishers to enjoy increased revenue returns for that species and serves as a positive feedback mechanism to continue this behavior. Individual vessel-based disaggregated analysis of CPUE for a fleet under this scenario reveals a clustered or patterned trend, where vessels may be able to be grouped for analysis based on their gear or targeting behavior (Figure 5).

Scenario D:

Fishermen, however don't exist in a vacuum and therefore don't make decisions solely based on their own individual revenue. Generally, decision-making is based both on what they themselves take out of the water and what they observe from their fellow fishermen within that particular fishery or fleet. When modeled, considering the catch of the entire fleet helped fishermen to observe more of the global population dynamics that are occurring temporally within their environment. Using this information in conjunction with the analysis of their own individual catch results in a simulation where fishermen combine these two information sources to make gear and targeting decisions (Figure 6).

Individual vessel-based analysis of CPUE for this scenario results in the grouping of vessels with similar characteristics similar to that which was seen in Figure 5, however this is a little less pronounced due to the inclusion of the additional seasonal abundance trend. It was anticipated that this scenario would generate selectivities and therefore

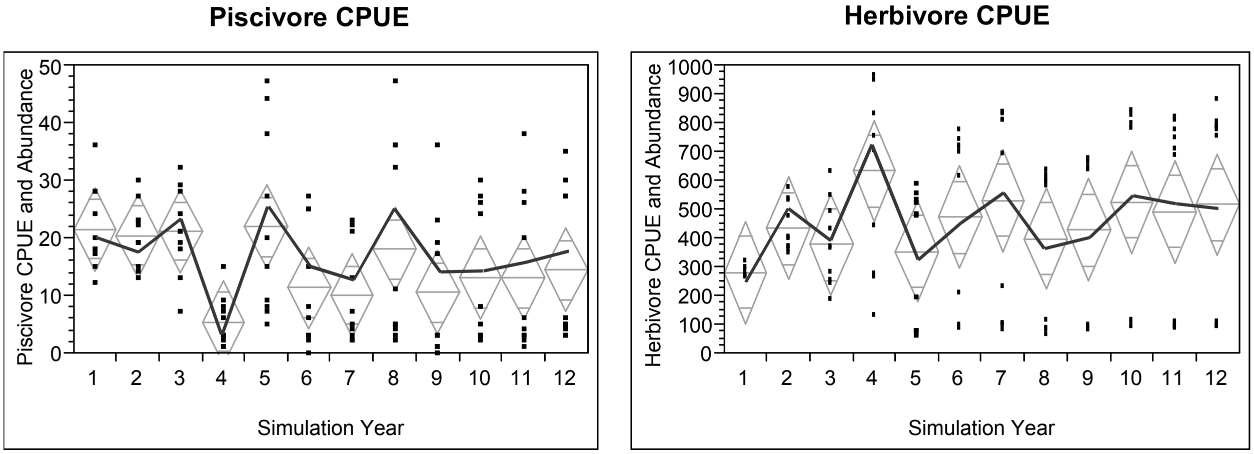


Figure 5. Individual vessel-based observations of CPUE (points) and average abundance (line) for the fleet undergoing effort redistribution described in Figure 4 above.

results that are more characteristic of a completely heterogeneous fishery (such as Figure 2), however the model is over sensitive to individual vessel revenue maximization and adjustments must be made in order to obtain more realistic results (FIigure 7).

DISCUSSION

Obtaining a valid standardization of catch and effort data from the commercial or recreational fishery is important in order to obtain comparable rates because standardized CPUE often serves as a critical input to stock assessment. In small-scale fisheries, where multiple species and multiple gears are available to fishermen, CPUE observa-

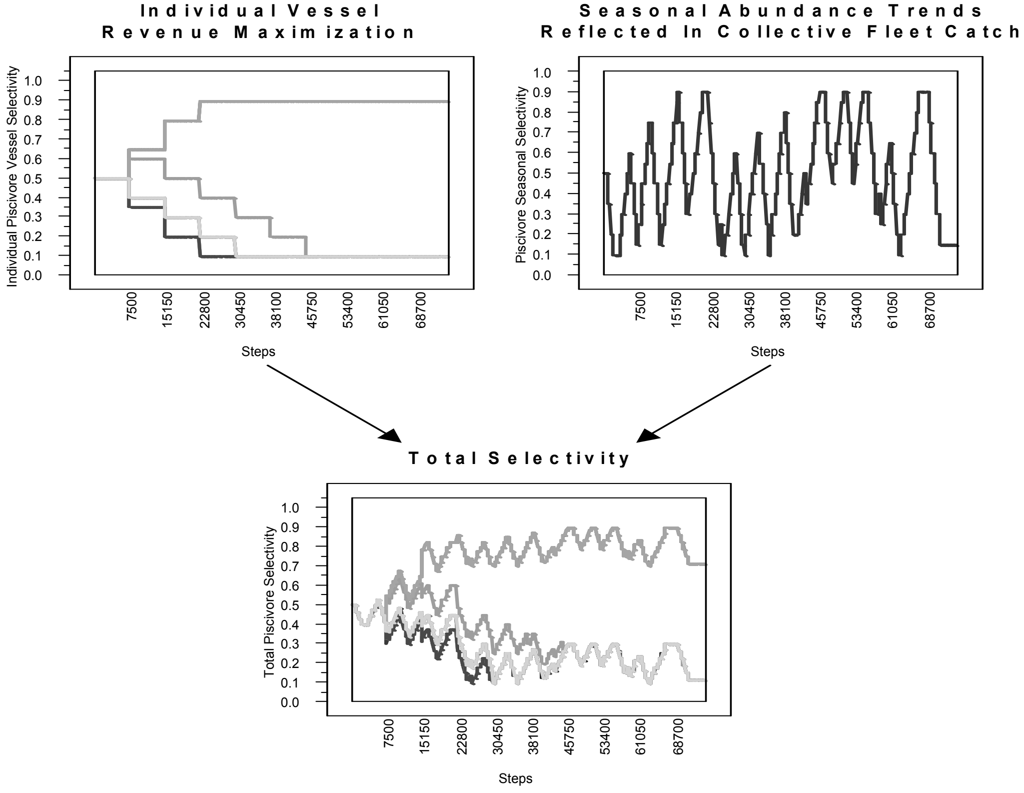


Figure 6. Effort redistribution for a simulated fishery in which fishermen use their own revenue and their broader knowledge of biomass seasonal trends reflected in catch. Steps are measured in the x-axis in order to illustrate the selectivity variability present within years; one calendar year equals approximately 7,500 steps.

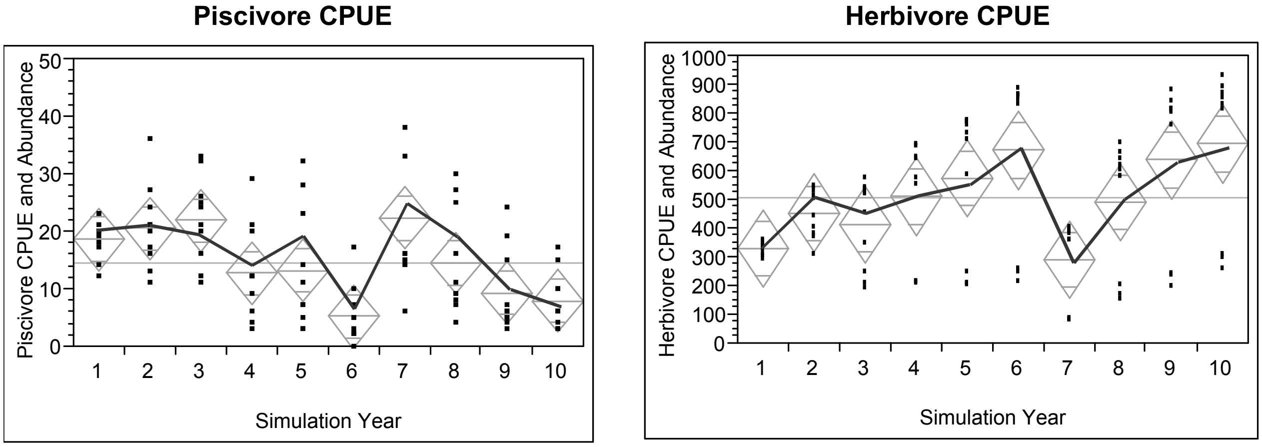


Figure 7. Individual vessel-based observations of CPUE (points) and average abundance (line) for a simulated fishery in which fishermen use their own revenue and their broader knowledge of biomass seasonal trends reflected in catch to adjust their selectivities as illustrated in Figure 6 above.

tions must be standardized for vessel classes that are homogeneous in catching power across time and area (Bishop 2006). The simulation of a homogeneous and heterogeneous fleet with constant effort (such as in Figure 2) reveals that when a fleet is heterogeneous and vessels have different catching power across time and space, CPUE contains added variance. Since the fleet is heterogeneous and vessels have different catching power, "vessel" cannot be used as a standardization factor because it violates the assumption that the classes being standardized for are homogeneous and introduces the risk of bias due to confounding (Bishop 2006). One alternative to this standardization problem could be to use a disaggregated, individual vessel-based analysis, and construct an estimation model, rather than a predictive model in order to focus on minimizing the bias of parameter estimates (rather than maximizing the variance explained as done by a predictive model, such as a generalized linear model). A statistical model that is designed for estimation but enables incorporation of external information could be appropriate (Bishop 2006).

Species specialization occurs when fishers within a multi-species fishery become knowledgeable about catching one particular species and redistribute their effort to that species. The desire to become species specialized could be due to a variety of factors including economics (desire to maximize revenue by concentrating effort on a high valued species), socio-anthropological (ability to capture one species over another offers higher societal status), or skill based (such as a trait that must be learned or passed on through family) (Bene and Tewfik 2001). When species specialization occurs, then disaggregating individual vessel catch for analysis may reveal that the data is categorical and homogeneous classes can be extracted from the overall heterogeneity of the fleet by grouping certain vessels or fishers with similar characteristics (such as illustrated in Figure 5). Assuming the effects of each vessel grouping are consistent across time and space, a CPUE index could be estimated for each data aggregation. If the effects of each vessel grouping are not consistent across time or space, then the fleet must be assumed to be completely heterogeneous as discussed above (Bishop 2006).

CONCLUSION

An agent-based, object-oriented model can be used to simulate the interactions that occur between two species in a predator-prey relationship and a fleet of fishing vessels within an ecosystem. Due to their small scale, these fisheries are able to easily redistribute fishing effort and switch effort among the multiple species present in their environment causing heterogeneity within the fleet. Simulation runs show the expected increase in catch rate variance due to the heterogeneity of a fishing fleet. In addition, simulation shows that the relationship between average abundance and catch per unit effort becomes less evident with high heterogeneity. Ultimately, the simulation results help us to understand the consequences of fleet heterogeneity, switching behavior, and the high variance within catch per unit effort that results from spatial realism.

Future work will focus on adding additional scenarios to the model to investigate the effects of fisher decision making on catch. More complexity will be added to the fish species by allowing the introduction of a size distribution and exploring different recruitment patterns. Additional species will be added to create more interactions, and spatial stratification of the grid will take place to simulate habitat structure. Ultimately, the model will be parameterized to fit various case studies in the Caribbean in order to simulate and ultimately better understand the population dynamics that occur within and between both fishermen and fish in small-scale commercial fisheries.

ACKNOWLEDGEMENTS

I am grateful to John McManus and Felimon Gayanilo at the National Center for Coral Reef Research (NCORE) for their instruction and assistance with java programming. This project was funded through the Cooperative Institute for Marine and Atmospheric Studies, a partnership between the National Oceanic and Atmospheric Administration and the University of Miami. Participation and presentation of this work at the 59th Annual Gulf and Caribbean Fisheries Institute meeting was funded by the Gulf and Caribbean Fisheries Institute Outstanding Student Presentation Award fund.

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