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A METHODOLOGY FOR SIMULATING THE U.S. RECREATIONAL FISHERY FOR BILLFISH

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ABSTRACT

A simulation model of the process for recreational tournament fishing for billfish is developed using the northeastern Gulf of Mexico as the study area. The objective is to explore the relationship between catch-rate and abundance. Starting with an initial fish population, both the boat and fish move throughout a spatial grid as the fishing day progresses. The simulation first determines if a fish is within proximity of a boat and, if so, if the fish was subsequently raised to the bait. It then determines if a raised fish was hooked. Data are tabulated on the number of fish hooked by all boats fishing during a tournament day per 100 hours of effort. The catch-rate is classically used for indexing abundance.

1 INTRODUCTION

A general problem associated with the study of marine fish stocks is that information necessary to assess the status of the stocks often must be obtained by indirect methods. In the case of billfish, problems are further exacerbated because catches are generally rare events. Nevertheless, billfish catch and effort data are available from tournaments. Conceptually, the ratio catch/effort can be used as a means of estimating abundance trends. Hence, these data might be used for estimating changes in the population if a reliable index of abundance could be derived from them.

A simulation model of the fishing process is developed in order to explore relationships between catch-rate and abundance. The approach taken is to simulate boat movement through a defined spatial grid while the simulated population of billfish move within that study area. It is assumed that if a fish is at the same location as a boat, it is figuratively within the sphere of influence of that boat. A stochastic procedure is defined that determines when a fish is raised to the bait (given its proximity to the boat), and then if it is hooked (given it was raised). The stochastic movement of the fish is defined in response to a non-random bottom topography which in turn relates to hypothesized habitat preference. The degree of bias in directional movement related to habitat preference is regulated by the magnitude of the concentration parameter of the Circular-Normal (von Mises) distribution. Following each time step, the boat and fish are moved and the proximity/raised/hookup logic is repeated.

Only the methodology employed in the development of the *BiLL*fish *SIM*ulation Model *BLLSIM* is presented. Details of the results generated by the model, under various scenarios and movement patterns, are described in Farber (1990). A detailed explanation of the fish-moving algorithm is found in Farber (In review, *MOVEFISH*: A spatial algorithm for simulating movement of billfishes. MS submitted to *Natural Resource Modeling*).

2 A BRIEF DESCRIPTION OF THE RECREATIONAL FISHERY

The word "billfish" is a general term that is accepted internationally by fishermen and scientists to include all those fish with the upper jaw prolonged into a sword or bill (Mather 1976). Among the most common species in the Atlantic and adjoining waters are the white marlin and the blue marlin. Recreational (synonymous with "sport") fishing for marlins is normally conducted with heavy-tackle rod and reel equipment with dead or artificial baits (lures) being trolled at speeds ranging from 3 to 15 knots

(Beardsley and Conser 1981). Once a billfish is hooked, the boat operator usually maneuvers the boat in order to reduce the work required of the angler to fight the fish. If the fish is not lost during the fight, and the angler is sufficiently skilled and/or lucky to bring the fish to the boat, the fish is either released, tagged and released, or brought on board and kept.

Most of the recreational fishing effort for billfishes along the U.S. Atlantic coast, Gulf of Mexico, and in the Caribbean Sea is concentrated either around key ports, fishing centers, or at billfish tournaments. Here, "tournaments" are organized competitive fishing events where participants are targeting their efforts specifically towards catching billfish. These tournaments are usually of a relatively short specified time duration, e.g., eight or ten hours per day for three to five days. They often are regulated by a board of directors who establish rules of entry and conduct. These rules normally follow guidelines established, and annually published, by the International Game Fish Association (IGFA 1990).

The abundance of marlins may be indexed as a function of catch-rate. The catch-rate is the species specific catch-per-unit-effort. For this study of the recreational fishery, "catch" is considered to be synonymous with "hooked". Therefore, the catch-rate is actually a hooked-rate, commonly referred to as hooked-per-unit-effort, HPUE; i.e., the ratio of the number of white marlin or blue marlin hooked to the number of hours trolled. Ideally, the effort should be standardized to the number of lines fished per hour; however, this information is not collected. Typically, four lines are trolled irrespective of the number of fishermen on the boat. The use of the unit "day" for the effort would be inappropriate due to the non-uniformity of a fishing day among vessels with respect to the number of hours trolling baits. Therefore, number of hours trolled is the most useful statistic available for tournament fishing effort. For scaling purposes, the actual unit for effort used in calculations is 100-hours trolling. In summary, HPUE represents the number of fish (by species) hooked per 100-hours of trolling effort.

3 DESCRIPTION OF STUDY AREA AND MODEL PARAMETERS

The fishing area modeled in *BLLSIM* is the northeastern Gulf of Mexico, from 30°10′N to 28°30′N latitude, and 88°30′W to 85°10′W longitude (Figure 1); an area roughly 100 nm x 200 nm, south of the Florida/Alabama border. Each 10′ latitude x 10′ longitude (i.e., 10′ x 10′) area in the study area is segmented into a 4 x 4 grid, with each of the 16 subareas being defined as the smallest spatial increment for this study, referred to as a pixel. (These pixels are depicted in area {i=2, j=6}, Figure 1.) Hence, each pixel is an area 2.5 minutes of latitude by 2.5 minutes of longitude (i.e., 2.5′ x 2.5′), or equivalently, approximately a 2.5 nm x 2.5 nm square (Figure 2). Any attributes typical of, or assigned to, any 10′ x 10′ is passed-on to each 2.5′ x 2.5′ pixel within that area.

A typical month of tournament fishing was chosen in order to establish parameter values for *BLLSIM*. The data values used to represent a typical month, using white marlin as the example, are:

- Total boat-hours fished in typical month = 2,899
- Total number of boat-days fished in tournaments that month = 289
- Number of tournament-days that month = 7
- Number of boats = 289/7 = 41
- Number of minutes fished per fishing day = (2,899 hr/7 day) = 24,848.57
- Number of minutes fished per boat per fishing day = (24,848.57/41) = 606.06
- Number of white marlin raised over total study area during month = 246
- Number of white marlin hooked over total study area during month = 190

Also input to the simulation are two arrays of data from the typical month representing the number of white marlin raised and hooked in each 10′ x 10′ square. Therefore, using these data to initialize the appropriate simulation parameters, each of the 7 tournament-days consists of 41 simulated boats fishing 606.06 min (≈ 10 hrs).

4 SIMULATION METHODOLOGY

The FORTRAN stochastic simulation model is executed on a 386/20 Mhz PC with math co-processor. Actual elapsed time for the simulations varied from approximately 8 hrs to 29 hrs, depending on the fish population abundance simulated. The simulation models the fishing process typical of tournament billfish fishing. The model is a discrete-event simulation using a next-event time advance approach (Law and Kelton 1982). The model accounts for both the distribution of vessels and the behavior of the fish. Logic is defined for both vessel and fish movement within the specified spatial grid. Trolling speed for the vessel is set at 10 kt for the fishing day. The time advance at each step is the amount of time necessary to move a designated distance within the spatial grid

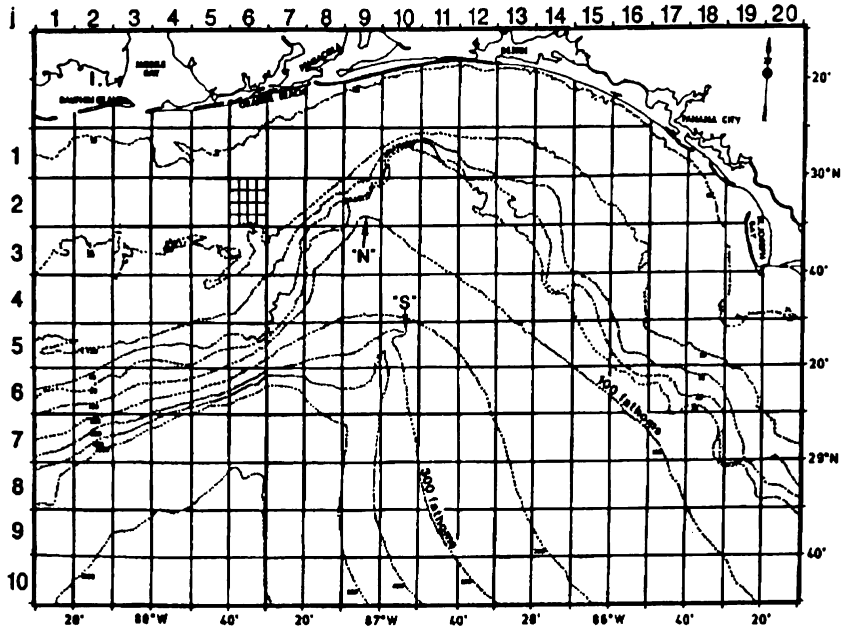

Figure 1: Fishing Area Modeled in *BLLSIM*

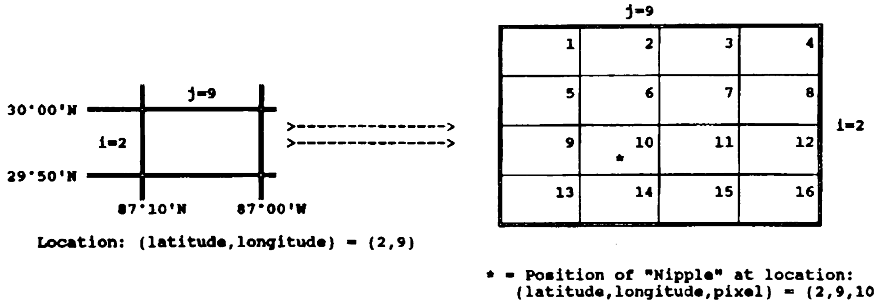

Figure 2: Enlargement Of Area {2,9}, Segmented Into 16 Pixels

at 10 kt, which is dependent on the location and direction of the vessel.

For each simulation, the parameters set include the initial abundance of marlin, the number of boats that will fish during one tournament-day, and the number of tournament-days fished during a month. The data are aggregated over the total number of fish hooked by all boats fishing during one tournament-day and the total time fished that day by all boats. This establishes the basic HPUE unit, in number of fish per 100-hours trolling effort, for one tournament-day. This is repeated for all tournament-days that month. Replications are made in order to calculate overall means and variances based on a month. In subsequent simulations, the initial abundance is varied and the HPUE statistics are compiled.

BLLSIM was developed in modules. A block diagram showing the relationship between the main program and the modules is presented in Figure 3, with the detail of the logic flow presented in Figure 4. The MAIN program declares variables and calls subroutines (modules). The first module called is INPUT, where all non-varying data and simulation parameters are established. Counters are initialized, and re-initialized when necessary, in the BEGIN module. All storage arrays and initial values of variables that change during the simulation are maintained in module INIT. Also, one of three declared

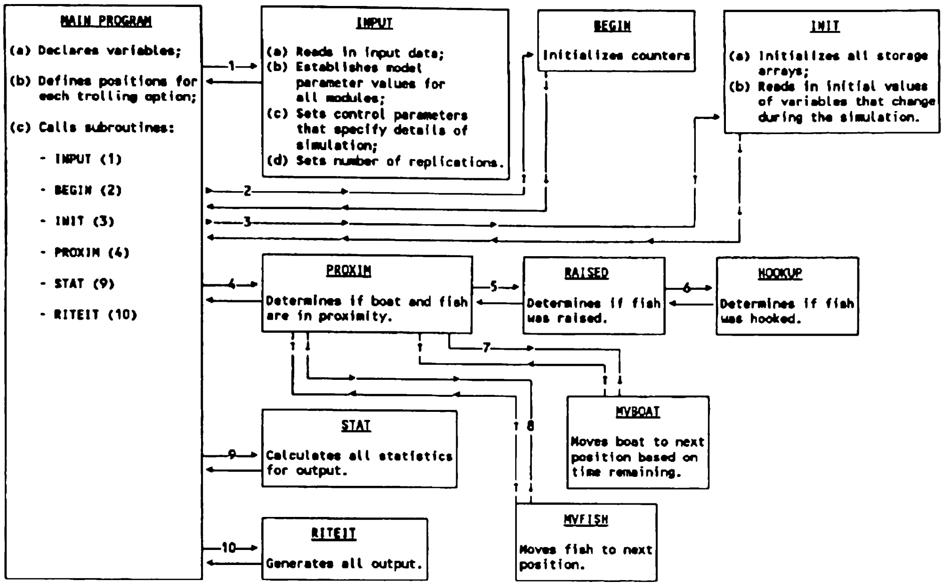

Figure 3: Block Diagram Of The Main Program And Modules For The Billfish Simulation Model *BLLSIM*

trolling options based on historical fishing patterns in the study region is chosen in INIT via the generation of a random number, Y_t, distributed U(0,1). If $Y_t<0.33$, then option 1 is chosen; option 3 is chosen if $Y_t\geq 0.67$; otherwise option 2 is chosen. The actual {i,j,k} positions for each option are declared in MAIN.

The logic for determining if the boat and a fish are within proximity of each other is defined by the module PROXIM. If they are in proximity then the RAISED module determines if the billfish is raised to the bait. If the fish was raised, the HOOKUP module determines whether a billfish is hooked. If so, this becomes part of the count for the numerator of a boat-day HPUE (i.e., number of fish hooked). Boats are moved via module MVBOAT based on the trolling option chosen, the amount of time remaining in the fishing day, and a possible effect of a neighboring boat hooking a billfish (detailed below). Fish are moved in the MVFISH module based on various scenarios of possible conditions of relative environmental quality. Both MVBOAT and MVFISH are called from within module PROXIM.

All simulation statistics are compiled, and arithmetic calculations carried out, in the STAT module, which is called by MAIN. This is done at the end of each tournament-day. When all tournament-days are completed for a given replication of the simulation, control returns to MAIN, which in turn calls the BEGIN module. When all replications are completed, module RITEIT generates output files. All statistics that are tabulated and calculated in STAT are printed via RITEIT.

As each boat-day is simulated, the number of fish hooked and the trolling time (in minutes) for that boat are recorded. At the end of a boat-day, the total number of fish, the total time trolling, and the ratio (i.e., HPUE) are tabulated. A frequency histogram of the number of fish hooked during each boat-day is then produced. This is repeated for each boat-day until the completion of a simulated tournament-day. Basic statistics (mean, variance, standard deviation and coefficient of variation) are calculated for that tournament-day, over the individual boat-day HPUE's. This is repeated for each tournament-day until the completion of a month of tournament fishing (i.e., 7 days) which marks the completion of one replication of the simulation. Again, basic statistics are calculated for that replication of a month of fishing, over the individual tournament-day HPUE's. The next replication is begun, and the process repeated. At the completion of all replications, basic statistics (including the standard error of the mean HPUE) are calculated over the replicated mean monthly HPUE's.

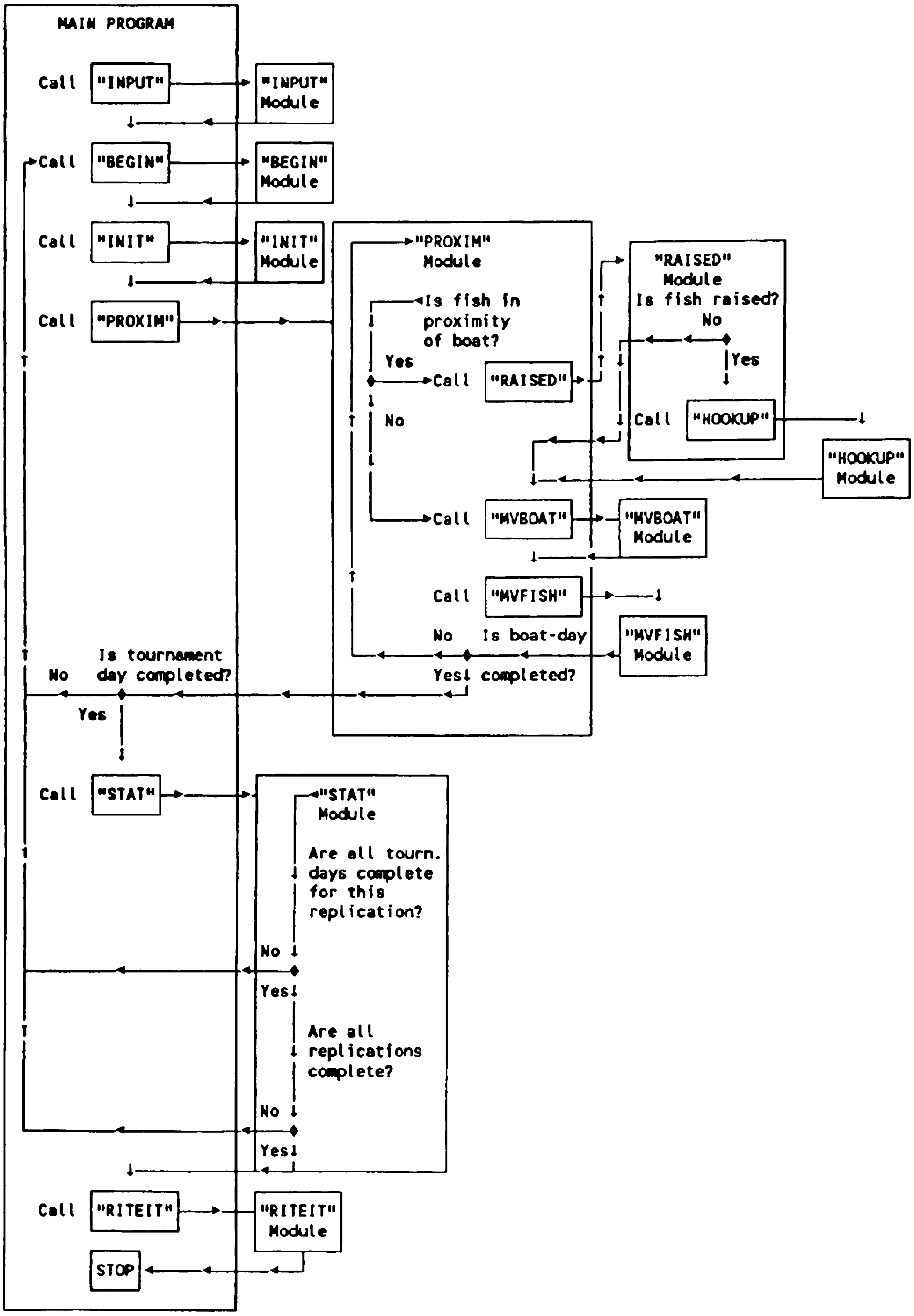

Figure 4: Logic Flow For The Billfish Simulation Model *BLLSIM*

(Though beyond the scope of this paper, the mean monthly HPUE from each replication can be used for deriving a functional relationship between abundance and HPUE by nonlinear regression techniques [Farber 1990]).

5 VESSEL MOVEMENT

Three possible trolling strategies are defined for the boats based on actual techniques followed historically by vessels participating in these tournaments. Each option defines the exact pixels through which the boat passes with one exception explained in the following paragraph. All vessels begin trolling at the northern location of the 100-fathom curve, commonly designated as the "Nipple", (N). The options are: (1) trolling approximately southeast along the 100-fathom curve; (2) trolling southwest along the 100-fathom curve; (3) trolling south-southeast into deeper water towards the "Spur", (S), the northeastern protrusion of the 300-fathom curve, and then, time permitting, west-southwest along the 300-fathom curve (see Figure 1). The mechanics for determining the next {i,j,k} location for the boat are specified in module MVBOAT. As noted earlier, the determination is made depending upon the amount of allotted fishing time expired. If more than one-half of the allotted time remains, then the vessel continues trolling outbound; if less than one-half of the time remains, the vessel starts trolling inbound, retracing its course; and if no time remains the boat-day terminates.

The exception to this deterministic movement is when a neighboring boat in the same pixel hooks a billfish. It is reasonable that this information should not be ignored and that the vessel captain would likely act differently knowing that a billfish was caught within the same pixel/time strata. Specifically, the captain is assumed to react to this information by changing the immediate vessel movement during the following time step rather than continuing on the fixed course that was initially chosen based on historical fishing patterns but void of any feedback from the current day's fishing. The ability of the captain to detect this occurrence is facilitated by the setting of an "on/off" flag logically coded whenever a fish is hooked. The assumption is that the hooking and fighting of a fish has caused a short-term disturbance to the immediate environment. The captain uses this information, does not fish in the current pixel, and moves his vessel to one of the eight surrounding pixels during the next time step (Figure 5). MVBOAT simulates this strategy by first generating a random variable from a U(0,1) distribution. Based on the value generated there is a one-eighth probability assigned for movement to each of the eight surrounding pixels. The vessel then moves to the appropriate neighboring pixel, retaining a memory of the pixel from which it is moving. At that point the simulation continues with the MVFISH routine and a determination is made as to whether the vessel and a fish are now within proximity of each other. When the simulation returns to MVBOAT, the vessel moves back to the previous pixel and fishes there, this time ignoring the logical "on" flag. This strategy is reflective of the tendency of a captain to fish in the general vicinity of another successful boat. The simulation continues as before with the calling of the subroutine MVFISH. This stochastic excursion is repeated whenever a boat is in the same pixel/time strata as a boat that had hooked a billfish.

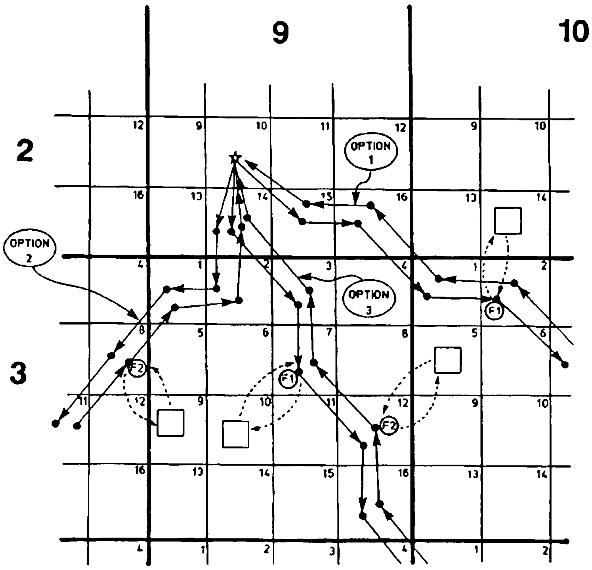

Figure 5: Diagram Representing The Initial Five Outbound, And Last Few Inbound, Vessel Moves Under Each Trolling Option

6 FISH MOVEMENT

Before *BLLSIM* is executed, a specified abundance of fish is dispersed over the study area. This is accomplished via a stochastic algorithm, *MOVEFISH*. The algorithm initially distributes the population randomly within the study area, with each fish given an {i,j,k} position and a random direction vector necessary to begin the simulated movement. At each time step, each fish is moved from its current pixel to one of the 8 surrounding pixels (Figure 6) based on a strategy having a probabilistic preference for movement towards areas of higher environmental quality. Alternative strategies for moving the fish can be specified and evaluated according to criteria that define environmental quality, which in turn is related to habitat preference. Following some suitable number of time steps the fish population is stochastically distributed with preferential directional movement towards areas of higher environmental quality. The position and final direction of movement for each fish becomes part of the initial conditions for beginning *BLLSIM.* The general logic of the mechanics for fish movement in the *MOVEFISH* algorithm is incorporated into the MVFISH module of *BLLSIM.* Thus, as the simulation progresses, the fish continue to move according to the same moving algorithm.

MOVEFISH is a spatial algorithm in which each fish moves in a probabilistic, but non-random manner so that they tend to aggregate in higher than average densities. The basic approach is to use the von Mises distribution, also known as the Circular-Normal distribution (Batschelet, 1981). The methodology is that of Kleiber and Edwards (1989) which they applied to simulating the movements of purse seine vessels and dolphin schools over a specified area in the eastern tropical Pacific Ocean (Edwards and Kleiber 1990). The application of *MOVEFISH* in conjunction with *BLLSIM*, under several hypothesized scenarios, is detailed in Farber (1990).

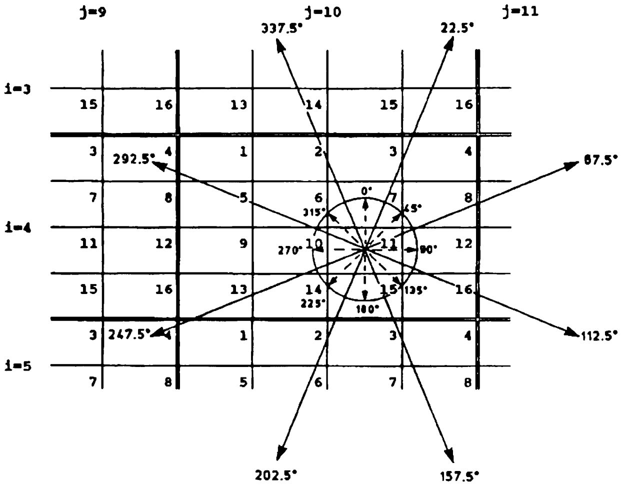

Figure 6: Graphical Presentation Demonstrating The Fish-Moving Logic Incorporated In The *MOVEFISH* Algorithm

7 INTERACTION OF VESSEL AND FISH MOVEMENT

The simulation starts with one vessel at the beginning location (the "Nipple", {2,9,10}) and all fish having a position {i,j,k} and a direction vector output from *MOVEFISH.* If any fish and the vessel are at the same position they are considered to be within proximity of each other, a pre-condition to a fish being raised to the bait. In order to determine if this has occurred, module PROXIM compares the current boat location with that of every fish. If any fish is found to be in the same pixel as the boat, the module RAISED is called (Figure 4); otherwise the remaining trolling time is calculated and PROXIM calls module MVBOAT, which is responsible for moving the boat to the next location depending upon the amount of trolling time remaining in the fishing day. If a fish is raised, the logic flows from RAISED to module HOOKUP. Another function performed by PROXIM is that of calling the MVFISH module which is responsible for moving the fish.

No data are available to estimate the conditional probability of a fish being raised, x_r=Pr(raised | proximity). It is reasonable to assume that some small percentage of the billfish in proximity of a boat will be raised, and that some percentage of these raised fish will then be hooked. In order to parameterize the variable x_r, the simulation was run using several values for x_r (=0.05, 0.10, and 0.20) over a range of initial abundance values. In general, when the average HPUE from empirical data is approximately equal to the mean HPUE from the simulation, then the distribution of HPUE and the percentage of zero occurrences of fish being hooked should be similar between observed and simulated data. This is a necessary (but not sufficient) condition for validating the selection of this parameter value.

For example, assume the average HPUE for a boat-day for white marlin in a particular month was 7.00 fish/100-hours trolling, based on all boats fishing that month. Further, say that the results of the simulation for $x_r=0.10$ yielded a mean boat-day HPUE $\approx$7.00 fish/100-hours trolling with an abundance of 1,000 fish. Then for the simulation with a population of 1,000, the percentage of zero white marlin hooked per boat-day, over all replications, should be approximately equal to the historical data if $x_r=0.10$ was a reasonable estimate. On the other hand, if the percentage of zeros from the simulation was higher than from the historical data, a lower value of x_r would be appropriate, and vice-versa. Based on this methodology, it was determined that $x_r=\Pr(\text{raised}\,|\,\text{proximity})=0.05$ was a reasonable estimate for the conditional probability of a fish being raised. A random number, Y_r, distributed U(0,1), is then generated. If $0 \le Y_r \le 0.05$, then a fish is raised at that time at location {i,j,k}, and the simulation proceeds to evaluate the conditional probability of a fish being hooked (given it was raised). Otherwise, the boat is moved to the next location.

To determine the conditional probability of a fish being hooked given it was raised, the ratio of the number of fish hooked in each 10' x 10' square, relative to the total number raised, for a given month, was tabulated. The distribution of these random proportions are modeled by the β-distribution (Christensen 1984), which contains two shape parameters (α_1 and α_2). These parameters are estimated from historical data. The β-distribution was used to fit these proportions (from each 10′ x 10′ square within the study area, from the typical month), resulting in $\alpha_1=2.70$ and $\alpha_2=0.30$. The mean of this distribution is ($\alpha_1/(\alpha_1+\alpha_2)=$) 0.90. Based on these results, the conditional probability $x_h=\Pr(\text{hooked}\,|\,\text{raised})=0.90$ is implemented in the HOOKUP module. A random number, Y_h, distributed U(0,1), is then generated. If $x_h<Y_h\le 1$ the raised fish was not hooked, otherwise $0\le Y_h\le x_h$ and that fish was hooked in that pixel at that time.

Fighting time for a hooked fish is a random variable. It is chosen based on the distribution of recorded historical fighting times which for white marlin were approximately distributed N(14.0,25.0). A N(0,1) random number generator is incorporated into the HOOKUP module in order to generate stochastic fighting times when needed. A minimum fighting time of 2.0 minutes is incorporated in the HOOKUP logic. In either event, the boat is moved to the next location.

The vessel then moves according to the randomly chosen initial trolling pattern, and all fish are moved following the technique used prior to beginning the simulation, with the proximity-raised-hooked logic being repeated. In the next-event time advance, the appropriate amount of time for moving to the next pixel is deducted, as is fighting time if a fish was hooked. Inbound trolling begins after one-half of the fishing day has passed. A boat-day ends when the allotted trolling time for a fishing day has elapsed. The process is then repeated for the specified number of boats fishing during a tournament day.

It is important to visualize this simulated fishing procedure as being equivalent to simultaneous fishing by all the boats participating during a tournament-day. The simulation of one vessel at a time is to simplify the bookkeeping within the simulation. Hence the tendency of a boat to fish in the area of another successful boat is simulated via the stochastic element previously noted.

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