

SI Appendix 2

Exploring the Model

The range of possible outcomes from the model is very large. The obvious question to ask is whether the outcomes reported in the article, the patterns, are representative of the processes in the fishery and, consequently, whether the model might be used to better understand its competitive dynamics. So far as we know there is no unambiguous way to answer this question. We approach the answer by a process of triangulation, i.e., a process in which the consistency of a large number of tests of the model combine to provide a certain degree of confidence even though no single test might be offered as conclusive proof of the model's validity.

We use several methods for gaining confidence in the patterns generated by the model. First, the patterns have to pass the straight-faced test with our own and consulting fishers' sense of the dynamics of the fishery. For example, in the model the spatial pattern individuals generate while fishing is generally, but not always, one in which a move to a new location is followed by one or several days' fishing in that location until it is fished down. At that time other locations appear more profitable and another move follows, generally to the location of one of those more profitable locations. To ourselves and to fishers, this movement is the typical way lobstering is done. It is not always true, but it is typical. These "anecdotal" tests of the model were used mostly to refine the design of the basic structure of the model. In other words, when initial formulations of the model produced patterns that contradicted experience, we reexamined and changed the design of the model.

Second, after we finished the initial design, we asked whether the patterns generated by the model replicated patterns detected in the large, fine-scale dataset from Maine Department of Marine Resources (DMR). The DMR data do not record the frequency with which fishers encounter one another, do not include the entire population of fishers in a particular area, and do not show the movement of a trap from one location to another. This lack of specific information limits our ability to directly test the patterns in the model; nevertheless, there are two consistent patterns that appear in both the model and the data from the fishery.

1. There is a pattern of remarkably efficient "population-level" allocation of traps by depth and/or area. In the model, fishing and changes in water temperature constantly alter the locations where lobsters are most catchable. Individuals and groups respond to these environmental changes by continually adjusting the location of their traps in order to maintain the highest possible catch rate. Even though individual search is often ineffective, the collective result is a spatial allocation of traps that is close to optimum. The same efficient spatial allocation is observed in the data from Maine DMR (see *SI Fig. 7*). In both the real fishery and the model fishery, fishers allocate their traps to different depths and/or areas of fishing in almost strict proportion to the availability of lobsters.

2. In the model, the “innovate-and-exploit” search pattern used by individuals generates a continuous nonequilibrium “churning” around the current average catch rate. Traps are moved when their catch is low; they are dropped in places where the fisher expects the catch to be higher, which lowers the catch of all the fishers in that neighborhood and shortly triggers attempts to move to other more productive locations. The same churning of the data appears in the DMR data (see *SI Fig. 4*). At this scale, the incentives driving competition prompt individual behavior that always disturbs an approaching equilibrium; but at a broader scale this same behavior generates very regular behavior.

Third, fishers begin the model with a random set of rules and begin learning from the circumstances they are dealt in this way, which creates a certain path dependence that alters the particular outcomes in each run of the model. Consequently, we run the model many times to ascertain whether the patterns we observe are stable in the face of this randomness. We find that the broad patterns that appear in the model are consistently stable but the particular numerical outcomes and even the location of territories vary from run to run depending on the different histories that develop from the initial conditions. The variation that does occur is reported as error bars in Fig. 1 in the article, *SI Fig. 3*, *SI Fig. 6*, and *SI Fig. 9*.

Fourth, there are two factors, especially, that tend to be responsible for the persistence of the patterns observed in the model. They are (i) changing patchiness, i.e., spatial and temporal variability in the biophysical environment and (ii) communications among fishers. We created two modified models in order to better understand the importance of patchiness and communication. The modified models let us examine fishers’ behaviors in a homogeneous environment and/or in an environment in which there is no communication among fishers.

Here we report on a number of tests we conducted with the modified models in order to learn more about the five basic patterns that are generated by both forms of competition. *SI Tables 15* and *16* describe two variations on the structure of the model. One creates a homogeneous (i.e., nonpatchy) resource environment; the other creates an environment in which fishers are not able to communicate with one another, i.e., they are not able to learn about one another’s activities. The tables list the hypotheses about changes in the five patterns, note the results, and point to output (tables, graphs, etc.) pertinent to those results. With one exception, all five patterns noted in the article fail to appear when either patchiness or communication among fishers is removed. The exception is the pattern of individual search in a patchy environment, which still tends to follow a basic innovate-and-exploit pattern even if there is no communication among fishers.

SI Table 15. A uniform distribution of lobsters

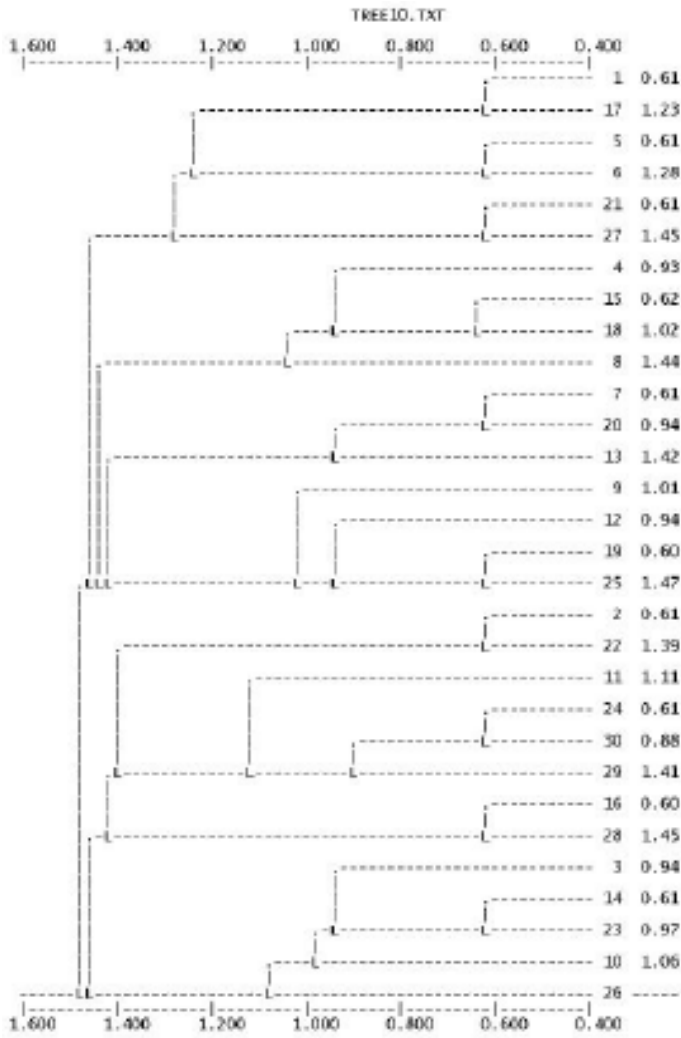
Model variation	Effect on patterns
<p>(1) A uniform environment but fishers are able to communicate:</p> <p>Lobsters are redistributed evenly at the end of each day. All other attributes of the model are retained, e.g., depth, temperature, and bottom type variations. Fishers keep track of how often they encounter other fishers, global catch rates are known, and so on. This model variation is applied only to scramble competition.</p>	<p>(1) There is no pattern to individual search. Fishers follow no discernible search pattern. On any day catch rates are identical for all traps at all locations (see <i>SI Movie 2</i>).</p>
	<p>(2) Groups form, but there are no advantages or disadvantages to being part of a group (see <i>SI Fig. 18</i>).</p>
	<p>(3) Fishers have no reason to develop strategies that lead them to one location rather than another; therefore, all decision rules are equivalent. Fishers use more than one rule but the feedbacks (catch rates) for all rules are identical. Consequently, rules tend to have equal weight and are not subject to a selection process. Each rule has an equal probability of being used (see <i>SI Fig. 19</i>).</p>
	<p>(4) The spatial allocation of fishers' traps is efficient. Catch rates every day for every trap are the same; consequently, no spatial allocation can be inefficient.</p>
	<p>(5) There are no groups of fishers roving over the entire map. Fishers do form groups based on their preferences for fishing with neighbors (see 2 above) and move over the entire map. But no advantage arises from this behavior because the catch per trap haul is always equal (see <i>SI Movie 5</i>).</p>

SI Table 16. No communication

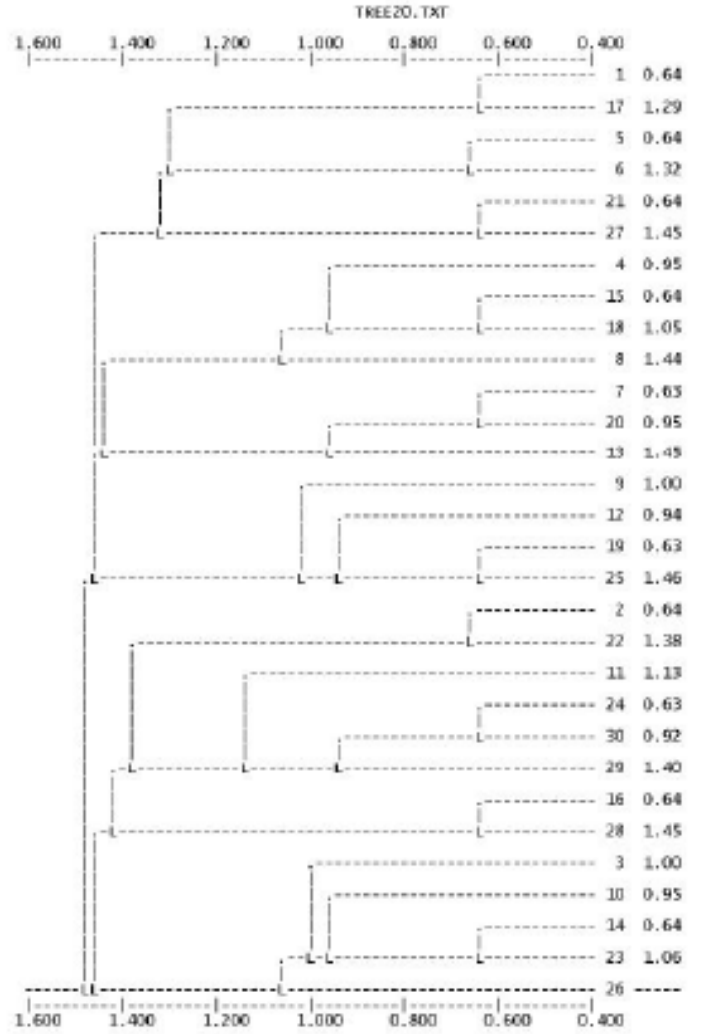
Model variation	Effect on patterns
<p>(2) Fishers cannot communicate but the resource is patchy.</p> <p>Fishers do not know the global catch rate, do not acquire knowledge of other fishers' activities and cannot imitate. Movement in individual search is triggered by a catch rate below the individual's recent average. Applies only to scramble competition.</p>	<p>(1) The pattern of individual search does not change, except that fishers' choices of location are not a function of other fishers' activities. Fishers follow a typical innovate-and-exploit search pattern. Fishers acquire knowledge of the resource through their own search but, because fishers cannot communicate with one another, learning occurs at a much slower rate than with imitation (see <i>SI Fig. 3</i>, <i>SI Table 4</i>, and <i>SI Movie 4</i>).</p>
	<p>(2) No groups form. The lack of communication also erases any advantage that might accrue to being a member of a group (see <i>a–e</i> in <i>SI Fig. 5</i>).</p>
	<p>(3) Fishers evolve decision rules strictly on the basis of their own activities. Consequently, the pattern for the group as a whole does not reflect as good a “fit” to the local environment as occurs with communication. Fleet profits are consistently less than 5% of what occurs with communication (see <i>SI Fig. 3</i>) and no groups form (see <i>a–e</i> in <i>SI Fig. 5</i>).</p>
	<p>(4) The spatial allocation of fishers' traps is efficient. Fishers learn to allocate nearly as effectively without communication (see <i>SI Fig. 20</i>).</p>
	<p>(5) Groups of roving bandits do not form. Fishers move over the entire map but not in groups.</p>

SI Fig. 18. Persistent groups form with a homogeneous biophysical environment

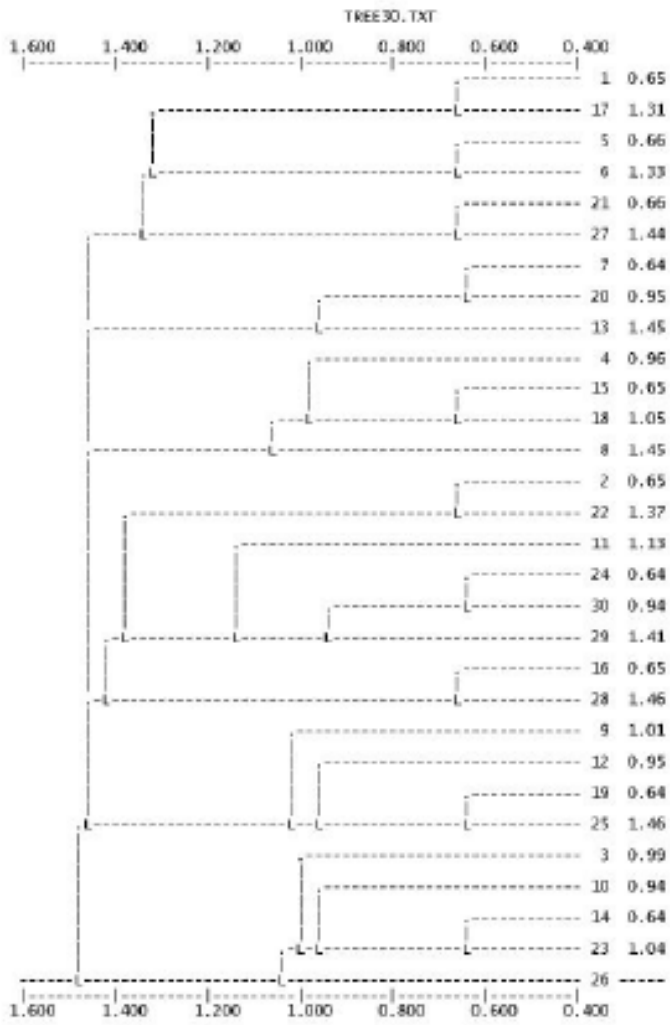
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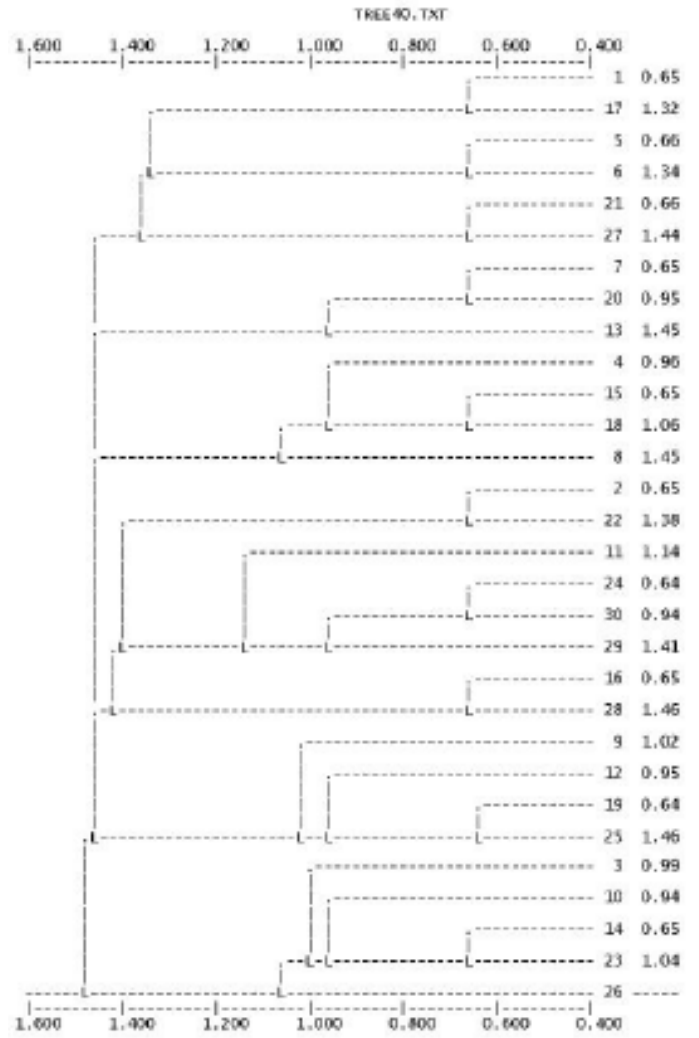
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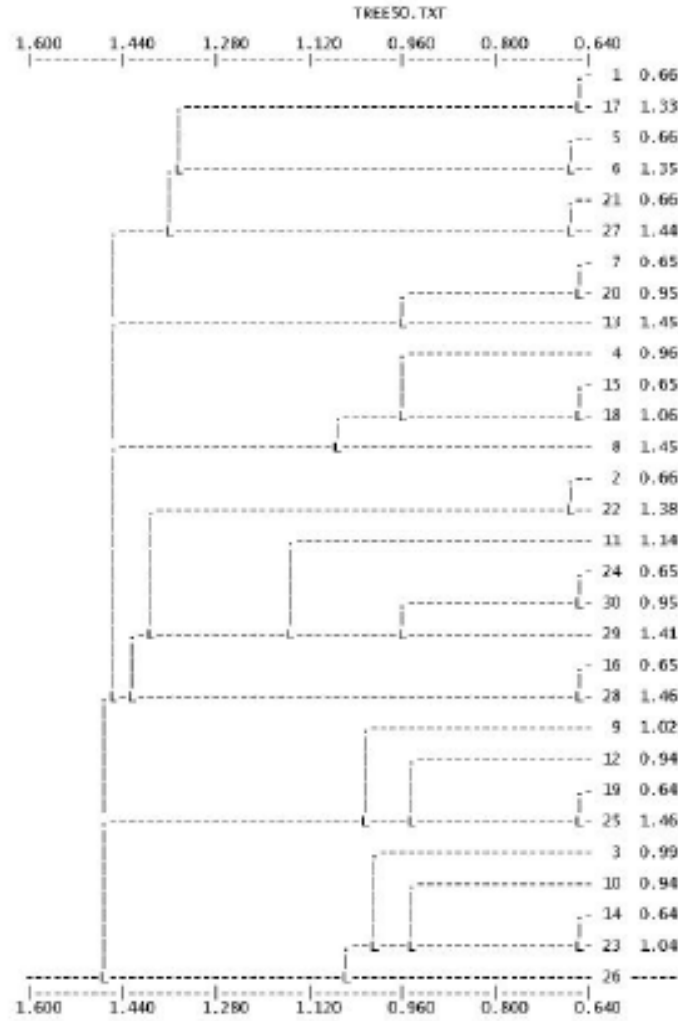
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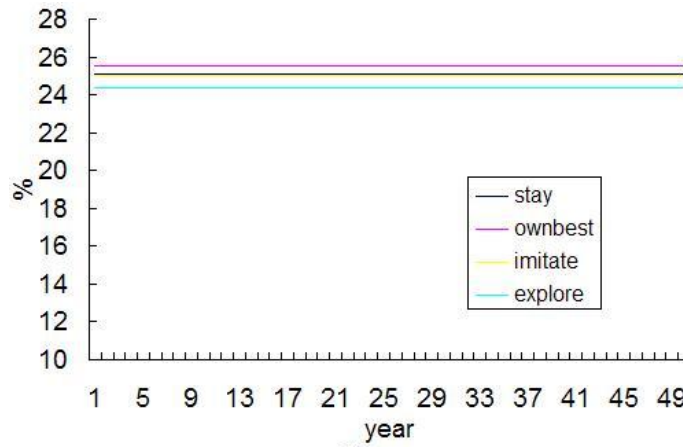


e



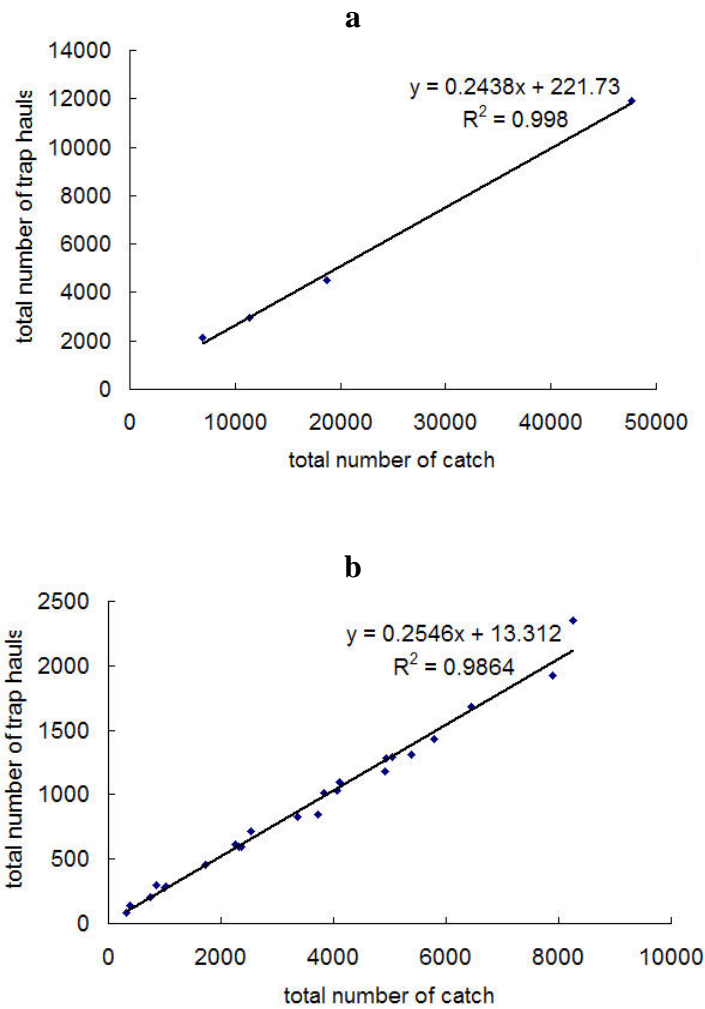
In a homogeneous environment, fishers imitate one another and persistent groups form. These associations begin with initial random encounters and persist only because fishers do not know that other fishers (not in their group) are doing just as well. There is no selection mechanism at work; any fishing strategy works as well as any other. There is no cost to being a member of a group, and there is no benefit.

SI Fig. 19. Choice of strategies in a homogeneous environment



When lobsters are evenly distributed across the map, fishers choose each of the four strategies with near equal probability in the first year and maintain those proportions over the remainder of the run. No decision rule evolves to be stronger than any other. Each rule is the equivalent of a random choice.

SI Fig. 20. The spatial allocation of traps with no communications, by depth and by area



When individuals search without communications with other fishers in a relatively stable environment they tend to allocate their traps efficiently to different depths and areas. Compared with a situation in which they are able to communicate, the difference is attributable to the speed with which individuals learn (see *SI Fig. 3*). Graph *a* in *SI Fig. 20* shows the allocation of trap hauls by depth in year 50 of a model run. Graph *b* shows the allocation by area for the same year.