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Practical Implications of Chaos in Fisheries

Ecologically Adapted Management

James A. Wilson
University of Maine

Peter Kleban
University of Maine

ABSTRACT This paper discusses the practical implications for fisheries management if fish populations behave chaotically. The paper argues that the principal effect of chaos is manifested in terms of information and measurement problems. In particular, recruitment based policies are likely to require unattainable measurement accuracy and lead to unpredictable outcomes. This raises questions about how sustainability can be maintained in chaotic fisheries. The paper suggests that management based on the relatively stable ecological relationships in fishery systems may be the most practical way to manage chaotic fisheries. It also hypothesizes that successful cases of traditional (community) resource management are likely to be based on qualitative ecological approaches rather than the direct quantitative manipulation (e.g., quotas) of exploited populations.

In a recent article and comment Estellie Smith (1991) and Chris Finlayson (1991) discuss the implications of chaos theory for fisheries management. Both Smith and Finlayson describe chaos theory as a competing paradigm for the conventional 'linear paradigms'[1] of fisheries management. With only minor quibbles we agree with their perspective of the problem and would simply like to add to their discussion a few points concerning the practical implications of chaos in fisheries.

To begin, what we mean by a chaotic fishery is one in which the time path of abundance of individual species has no equilibrium tendency but varies unpredictably within certain limits. This contrasts with standard theory (including its stochastic versions) that assumes population abundance tends towards some predictable equilibrium value.[2] As we point out below, there is a great difference between the two theories regarding the kinds of useful knowledge about fisheries that we can realistically acquire and, as a consequence, the kinds of practical management controls that can be exercised over fishery populations. In a very basic way, the presence of chaos transforms the management problem into a question of what we can hope to learn, the conditions under which that learning can take place and what we can hope to control. Our major conclusion is that the best hope for successful management of chaotic fisheries lies with 'ecologically adapted' management, i.e., policies that rely upon the relatively stable ecological interactions in the system.

If a theory of chaotic fisheries is (or were to become) a competing scientific approach to fisheries, there is an important question about how scientists and practitioners might choose between theories of chaotic and equilibrium (i.e., standard, or conventional) fisheries. A naive view of the scientific problem might lead one to assume that some decisive test could be developed that would clearly show that one or the other theory was correct. Realistically, this is not a possibility, because the ocean environment creates extreme measurement problems that preclude unambiguous testing. To validate a theory of chaotic fisheries, for example, would require long and extremely accurate time series that recorded many aspects (e.g., annual year class strengths) of the populations of the relevant species and biosystem. The same is true of standard theory.[3] A stalwart defender of either theory could simply, and correctly, claim that an unambiguous proof of the 'other' and invalidation of his or her favorite theory was not available.

Over the long term, what is likely to decide the matter is, first, the intuitive, qualitative assessment of scientifically inadequate evidence by practitioners in the discipline and, second, the equally subjective assessment by those same practitioners with regard to the eventual success of the research and policy program implied by each paradigm (Kuhn 1962). The former consideration does not place chaos theory at any particular disadvantage. All but the most uneducated practitioners are aware of the strong variability and difficult prediction problems associated with marine ecosystems. Most are willing to toy with the ideas of chaos once they understand its deterministic nature.

Where chaos theory fails to be intuitively compelling (or to hold its own with standard theory) is with regard to its implications for future research and policy. Standard theory presents an impressive array of policy alternatives. Almost all are derived from the commonsense notion that 'less fishing effort means more spawners' and 'more spawners means more recruits.' Even if one is aware that there is, at best, only scanty evidence to support this idea (Hall 1988) or even if one is blissfully unaware of *any* theories about the fishery, the power of this anthropocentric view[4] of the fishery is compelling. When it is elaborated with sophisticated mathematical and economic models that promise the ability to manipulate the environment in a win-win fashion, it is hard to reject. Everyone gains. Fishermen have more fish, higher incomes and stability. Consumers consume more fish at lower prices and the environment is restored to a state of abundance. All that needs to be done is to engineer a social contract that enforces the admirable attributes of individual restraint. In short, when it comes to the question of 'what to do' standard theory presents an extremely strong, intuitive case.

Chaos theory, at present, offers little in the way of ideas about 'what to do' about either research or policy. For scientists and managers concerned with the state of our knowledge and our ability to successfully manage fisheries this is a major problem. If one were to accept the idea that fisheries populations are chaotic, there is no obvious implication for how we should begin to alter our day-to-day management of such fisheries and, perhaps more important, there is no apparent research agenda that suggests how we might eventually find solutions to our management problems. For many, probably most, practitioners the idea that fisheries populations are unpredictable seems to deny the possibility of *ever* achieving a practical management approach. In fact, the immediate negative implications of chaos theory are so strong that many practitioners of our acquaintance tend to view the theory simply as a very sophisticated way to argue for no management whatsoever. We do not agree with these conclusions; but without an obvious and articulated direction for a practical research and policy program, we can empathize with this perspective.

What we'd like to explore here (briefly and speculatively) is the research and policy program we believe implicit in chaos theory. May (1978) has shown that under certain (usually thought to be unrealistic) parameter values the conventional single-species models used for fisheries populations can exhibit chaotic properties. It is much more likely, however, that the chaos in ocean ecosystems (if it exists) arises from the complex and non-linear, compensating interactions at the system (multi-species) level (Wilson et al. 1990); in short, it is most likely a property of the entire ecosystem and not one which arises from the independent behavior of individual populations. Under these circumstances, the conventional straightforward cause and effect thought to operate on individual populations (e.g., 'more spawners means more recruits'), can be expected to be replaced by much more involved trains of causation that depend upon the interactions with the other species and components of the ecosystem. Consequently, traditional species-specific policies such as quotas or effort reductions *may or may not* lead to an increase in a depleted population and *may or may not* have significant effects on the remainder of the system. What will determine the magnitude and direction of change in an individual population or the effects on the remainder of the system is the condition of the overall ecosystem at that point in time and the nature of the interactions among the species and other components of that system.

For example, Georges Bank is currently dominated by highly predatory dogfish and skates – about 75% of the fish biomass (Status 1991). Given this state of the ecosystem, it is conceivable that a quota on cod, say, might produce more cod eggs, larvae and juveniles, but that those juveniles might become food for the dogfish and skates and never recruit to the fishery. Numerous other ecological configurations might lead to similar quota-confounding outcomes. Under still other, probably numerous ecological circumstances, a quota on cod might have the desired effect. The point is that in the absence of knowledge of the relevant ecological interactions, traditional policies (such as quotas or other forms of effort management) applied to a chaotic system will lead to unpredictable results and an inconsistent and frustrating management experience – one in which cumulative learning by doing is not possible.

Consequently, the need to successfully manage a chaotic fishery means that we must focus our efforts elsewhere. In fact, and this is our main point, we contend that the appropriate scientific and policy research agenda implied for a chaotic fishery must concentrate on understanding (1) the nature of the ecosystem interactions[5] (where fishing and fishermen are treated as part of the system) and (2) the extent or conditions under which it is possible to control, manipulate or influence those interactions. In the rest of this article, we make an initial attempt to further define this agenda. Our argument is developed by reference to the quantitative attributes of our simulator of multispecies chaotic fisheries and its real world equivalents (Wilson et al. 1991).

The quantitative attributes of this kind of model fall into two categories: (1) the constant parameters and interactions of the model and (2) the values that each of the variables assume during each (simulated) year during the running of the model. Their real world equivalents are (1) the relatively stable ecological, technological and social rules that determine the interactions among species, fishermen and other components of the system and (2) the highly variable (chaotic) values reflecting the abundance of a species, number of fishermen and so on, at a point in time. This latter set of attributes is, of course, the one in which the peculiar characteristics of a chaotic system are manifested. In most real fisheries this chaos is most clearly present in the recruitment, or sustainability, of each population. It is important to note, however, that within real world fisheries and our chaotic simulator there are relatively stable or predictable aspects. For example, once a year class (of any particular species) is established its numbers tend to decay at a reasonably predictable (or measurable) rate determined by natural and fishing mortality. In most real world fisheries, this predictability is the basis for yield per recruit management. Another relatively stable characteristic of our simulator and most fishery system is the overall biomass; among other things a relatively stable biomass implies compensation among species – as one species declines for one reason or another, other species grow in compensation. These stable or predictable aspects of the system are potential sources of control and management; unfortunately, they have little direct bearing on the sustainability of individual species.

One of the fundamental characteristics of a chaotic system is that future outcomes of the chaotic variables are very sensitive to the particular values of each variable at an earlier point in time. This is called 'sensitivity to initial conditions.' Very slight changes in initial conditions rapidly lead to very different outcomes. In principle, because chaotic systems are deterministic, it is possible to predict the future value of variables; but as a practical matter, an extraordinary and unattainable degree of measurement accuracy of all elements of the system is required. This is the source of practical unpredictability in chaotic systems.[6]

If real world fisheries are indeed chaotic, then the problem of sensitivity to initial conditions strongly suggests that conventional management approaches, such as quotas[7], that attempt to directly manipulate recruitment to individual populations are unworkable. As a practical matter (and consistent with the predictions of a theory of chaotic fisheries), the difficulties of recruitment-oriented quotas are generally recognized and rarely attempted (Sissenwine and Sheperd 1987). Instead managers tend to seize upon the relative predictability of year-class decay for the purpose of yield per recruit management. Yield per recruit management attempts (through the annual quotas or other forms of effort control) to maximize the yield in weight (or value) obtainable from any given (single-species) year class. Managers recognize that the single-minded pursuit of yield per recruit policies can have unintended consequences for recruitment of that particular species and tend to modify those policies in ways that they hope will minimize adverse effects or, perhaps, help recruitment. Chaos theory, or for that matter any theory that addresses the problem from a system perspective, strongly suggests that yield per recruit management also will lead to unintended consequences (either beneficial or costly) elsewhere in the system. These consequences might be compensating growth, mortality or recruitment distributed among the many species in the system or, as in the example of dogfish and skates on George's Bank, they may possibly concentrate in one sector of the system. Furthermore, in a chaotic system the difficult measurement problems, the complex interactions and the continuous nature of the intervention (e.g., changing annual quotas), make it unlikely that all except the most exaggerated of these unintended consequences will be traceable to their cause.

Consequently, when management pursues species-specific recruitment or yield per recruit policies in a chaotic environment, it implicitly takes upon itself a very large, costly and basically impossible measurement burden. More importantly, the practical absence of this kind of extremely precise quantitative knowledge of the system means that the outcomes of such policies cannot be evaluated. From the perspective of learning by doing, management that proceeds on a conventional course in a chaotic environment will experience success at times, failure at other times, a strong tendency to create unintended and unrecognized outcomes and, always, an inability to understand the reasons for either success or failure. In short, the measurement and knowledge requirements of a chaotic environment strongly suggest that conventional management approaches will not be able to accumulate the kind of useful knowledge that leads to improved management performance.

The alternative in a chaotic regime is to turn to long-term, ecologically adapted policies based on knowledge of the ecological relationships of the system. The kind of knowledge required for this approach is (relatively) stable over time, does not have to be completely renewed annually, and requires comparatively modest and attainable investments in knowledge of the system parameters. More importantly, policies based on changes in system parameters or interactions (where fishing is considered part of the system) are not subject to the information and measurement problems created by sensitivity to initial conditions. Consequently, to the extent that knowledge of ecological relationships is available such policies can be expected to yield predictable results. *But* because of the sensitivity to initial conditions problem, this predictability cannot be characterized in terms of quantitatively accurate statements about future states of the system. Instead, predictability comes in the form of qualitative changes in the long-term relationships of the variables in the system. For example, a (permanent) change in the age of maturity or the egg production of a given species can be expected to alter that species' relationship to others in the system in a qualitatively predictable way. Along the same lines, a change in the parameters governing who is preying upon whom or when will lead to certain qualitative expectations with regard to consequences. Similarly, an increase in mesh size in a partially exploited system (i.e., one in which some but not all species are fished) might be expected to generate changes in the long-term relative abundance of exploited and unexploited species and may also be expected to have effects on the relative abundance of the exploited species depending vulnerability to the new mesh size (Wilson et al. 1991). Even if the available knowledge of ecological relationships is imperfect, our modeling experience suggests such polices will have consistent, long-term impacts. If this is correct it suggests we have the ability to detect gross effects on the system and, equally, the ability to evaluate the success or failure of policies. Although this may be a slow process, it holds out the possibility of learning through experience; in contrast, management interventions (i.e., quotas, etc.) designed to affect the value of the chaotic variables in the system do not appear to provide the opportunity for even the slow accumulation of knowledge through experience.

We turn now to the question of what we mean by ecologically adapted[8] policies. The idea can be stated in terms of the evolutionary development of the system. The life strategies of each species in the system can be viewed as the successful, competitive adaptation to the other components of the ecosystem. Fishing can create mortality and other effects on the system that defeat the evolutionary strategies of each species or fishing can operate in a way that is roughly consistent with the operation of the system itself. This suggests that it is not out of place to think of fishing as the introduction of a new predator in the system and fishing management as the problem of defining the capabilities of that predator in such a way that the predatory activity is sustainable. For example, the ability of nets to completely decimate spawning aggregations may very thoroughly defeat otherwise effective anti-predation strategies of prey fish with long term destructive effects upon predator fishermen. A rule prohibiting fishing on spawning aggregations would define away that predatory capability. Gear that was selective by size or species would also move toward defining the predatory capabilities of fishermen. Even licensing rules can have this kind of effect. For example, when fishermen switch from species to species in response to changes in relative abundance, their behavior is consistent with the normal behavior of predators and tends to create feedback that results in larger populations and catches of all exploited species (compared with situations in which fishermen are licensed by species and switching does not occur) (Wilson et al. 1991). Conversely, in an ecologically adapted policy, the definition of the predatory capabilities of fishermen strongly influences the population of fishermen. As conditions in the fishery change, the population of fishermen/predators will change in response. In short, the choice of gear types and the conditions under which they are employed presents another way of defining the parameters of human predation so that it is adapted to the ecology of the system.

Consequently, compared with the conventional approach to fisheries management, a theory of a chaotic fishery suggests (1) that with regard to individual species, the emphasis of management should be on *how* effort is applied (i.e., the characteristics of inputs) rather than on *how much* effort is applied (i.e., the quantity of outputs), (2) that the question of how much effort should be applied is only appropriate to the entire system, and (3) that gross changes in the species mix of the system may be addressable. The principal reasons for these conclusions mainly derive, of course, from the limited nature of the usable knowledge and measurements that we can hope to obtain in a chaotic environment. With regard to individual species this limitation on our capabilities suggests that we may be able to learn, even if slowly, about a set of rules and technology of capture that is consistent with the ecological requirements of the fishery[9] but that our practical ability to fine tune, or even roughly tune, each species population individually through controls on outputs is severely limited, and probably not even possible.

Finally, we would like to address the question of why all this might be of interest to marine anthropologists. Our basic argument is that the practical management of chaotic fisheries rests upon information and knowledge about the relatively stable ecological parameters of the fishery. This is the kind of knowledge that fishermen can be expected to acquire through observation and experience. Consequently, we are likely to find that a theory of chaotic fisheries is consistent, not only with the perspective of fishermen as Estellie Smith points out, but also with the kinds of institutions and management techniques fishermen are likely to devise for the governance of fisheries. Management based on this kind of knowledge may be not only the most effective way to conserve our fisheries resources, as argued here, but it is also likely to be a management approach that is credible. Credibility, of course, is a necessary requirement for effective governance of fisheries (unless we want to rely upon police state methods). Therefore, if the governance of traditional fishing communities is actually aimed at the conservation of their resources and if such communities actually do perceive these resources as a chaotic system, then we should find (1) that fishing communities do have the knowledge necessary to develop the appropriate rules, (2) that those rules are based on knowledge of the relatively stable ecological parameters of the system and (3) that the effectiveness of these management regimes – their ability to restrain individual behavior for a collective end – is strongly dependent on the credibility provided by the correspondence of the rule structure and available knowledge of the fishery.

In summary, this paper argues that (1) the knowledge and measurement problems present in a chaotic system limit our ability to learn about and effectively intervene in such systems, especially with respect to short-term specific interventions; (2) that usable knowledge is likely to be restricted to information about the relatively stable ecological characteristics of the system, and (3) that there is a set of management tools appropriate to the management of a chaotic fishery – ecologically adapted policies. These policies *do not* attempt to fine tune the fishery on a year to year basis and, consequently, are not dependent upon timely, expensive and realistically unattainable measurement and knowledge of the current state of the fishery. Instead they derive from a working knowledge of the basic ecological interactions in the system; they are, in effect, the technology and rules that govern fishermen's interaction with the system and, consequently, can themselves be viewed as an extension of the ecological parameters of the fishery. Such policies are long term in nature and are designed to affect the *relative* position of species within the system. And, more importantly from a practical perspective, the information required for the use of these tools is the relatively modest, or at least attainable, knowledge of the nature of the ecological interactions of the system.

Acknowledgments

We would like to thank Mike Fogarty, Ross Shotten, Spencer Apollonio, Ted Ames, Keith Casey, Sue Hanna, Noel Roy, Ralph Townsend and Robin Alden for their helpful discussions and criticisms. Needless to say, they should not be held responsible for the ideas expressed in this article.

Notes

1. The usual models of fisheries populations are non-linear but have the property of being well behaved; that is, changes in variables have predictable outcomes. It is also true that a number of biologists have known about the potential instability of populations for a long period of time. In their classic work Beverton and Holt (1957), for example, develop phase diagrams that indicate a chaotic region. It is fair to say, however, that the sophistication of many biologists does not carry over into day to day management.

2. Both Smith (1991) and Finlayson (1991) provide numerous references for the reader interested in the literature on chaos theory.

3. Charles Hall (1988) reviews the evidence put forth for standard theory and concludes that there are no instances in the literature in which standard fisheries recruitment curves are validated by available evidence. A similar review of the same evidence, undoubtedly, would have to conclude that chaos theory was not validated either.

4. We call it anthropocentric because it is an idea that is appropriate to a K type species that gives birth to few young and expends a great deal of energy assuring their survival. Fish, with some exceptions, do not follow a similar reproductive strategy.

5. A number of other authors have come to a similar conclusion, not from the perspective of chaos theory, but primarily on the basis of the poor practical experience with the application of standard theoretical approaches. See for example, Peterson (1990), May et al. (1978), Kerr and Ryder(1989), and Apollonio(1988).

6. To give some idea of the magnitude of the problem, a computer program of a chaotic system will produce the same results in two consecutive runs with identical initial conditions only if all calculations are carried out without rounding errors to the 9th or 10th decimal point. In contrast we are probably able to measure fish populations at a point in time only with errors of 30-50%.

7. By conventional management approaches we mean, in particular, approaches that target the value of single-species variables (populations, age classes, etc.) in the system in an attempt to maximize sustained yield, yield per recruit or economic yield.

8. All species may not be desirable for the market but there may, nevertheless, be appropriate allocations of alterations in total effort to compensate.

9. We might suggest, for example, that the Maine lobster fishery, whose continued robust behavior is a puzzle for standard theory, is an instance of a set of rules of capture that, intentionally or not, is consistent with the ecological regime of the fishery. The principal rules include a minimum size of capture, fishing restricted to traps and prohibitions on the landing of 'egged out' females. With minor exceptions, the rules governing this fishery were proposed to the State Legislature by fishermen's associations.

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