5-2001

Capturing Feedback in Complex Marine Ecosystems: Two Models

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CAPTURING FEEDBACK IN COMPLEX MARINE ECOSYSTEMS:
TWO MODELS

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A.B. Bowdoin College, 1997

A THESIS

Submitted in Partial Fulfillment of the

Requirements for the Degree of

Master of Science

(in Marine Policy)

The Graduate School

The University of Maine

May, 2001

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An Abstract of the Thesis Presented
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Marine systems are complex and highly variable. Feedback is required to learn in and manage these systems. Unfortunately, feedback in complex marine systems is difficult to capture and ambiguous.

Feedback is a function of system structure. Conventional fisheries management simplifies this structure by focusing on individual species. It assumes that variability in populations is due solely to changes in the adult population (i.e., that a stock-recruitment relationship exists) and all necessary feedback is available by simply observing the size of the adult population. Unfortunately, this approach does not consider the environment of the species and most marine stocks show poor functional stock-recruitment relationships.

Complex systems (hierarchy) theory suggests that this approach may not be the most appropriate way to simplify the system. Hierarchy theory simplifies the system on the basis of nearly decomposable subsystems, whose boundaries are defined by rates of interactions. It implies that feedback can be captured more readily within than between subsystems and that there is more pattern stability at the subsystem level than at the species level in the system.

This implies that feedback is best captured from subsystems, not from changes in the abundance of individual species.

Fishermen have traditionally dealt with variability by utilizing one of two harvesting strategies. With the Little Box approach, fishermen target a single species across multiple subsystems, averaging the variability. With the Big Box approach, fishermen target multiple species within a subsystem, relying on the relative stability of that subsystem. We hypothesize if less noise exists at the subsystem level than at the species level, then better feedback can be gained with a Big Box approach to management.

Two age-structured, multispecies, bioeconomic models were created to explore the two harvesting rights regimes described above in terms of how well they allow decision-makers to capture and respond to feedback. The Little Box model allocates rights to single species across subsystems. The Big Box model allocates rights to multiple species within a subsystem.

Results of the models illustrate significant advantages for sole ownership compared to open access. The baseline model assumes a sole owner with perfect abilities and high quality and timely information. Results show little difference between Big Box and Little Box management under these "perfect" conditions. The model was then run under various scenarios to reflect imperfect feedback conditions (e.g., measurement errors, delayed response times). Impairment of the sole owner's ability to respond to feedback and degradation of the quality of feedback resulted in advantages for the Big Box sole owner over the Little Box sole owner.

ACKNOWLEDGEMENTS

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1:

MANAGEMENT IMPLICATIONS OF COMPLEXITY IN MARINE SYSTEMS

Introduction

Complex systems are found everywhere – examples include social systems (e.g., formal organizations), biological systems (e.g., organisms), physical systems (e.g., matter), and symbolic systems (e.g., books composed of chapters, sentences, words, etc.) (Simon, 1962). There is a large body of literature devoted to the study of the organization and behavior of complex systems. This theory spans multiple disciplines including physics, mathematics, biological sciences, computer programming, economics, and the social sciences (Simon, 1962; Pattee, 1973; O'Neill et al, 1986; Waldrop, 1992). Researchers from these diverse disciplines have made progress towards understanding complex systems and recognize hierarchy theory as the tool most useful in understanding the organization and behavior of complex systems. This is because, as we will see, hierarchy "is one of the central structural schemes that the architect of complexity uses" (Simon, 1962).

Marine ecosystems are complex systems (e.g., Steele, 1974; Cushing, 1975; Laevastu, 1996; Levin, 1999) and some may even be chaotic (e.g., Wilson et. al., 1991). Similar to other complex systems, they are characterized by strong (often non-linear) interactions, complex feedback loops, time and space lags, discontinuities, thresholds and limits (Costanza et al., 1993; Holling, 1987). Complexity creates many difficulties for those seeking to manage marine resources (Ludwig et al, 1993; Dayton, 1998). Conventional fisheries management tries to simplify this complexity by focusing on individual species populations. Additionally, the conventional approach typically seeks to reduce fishing mortality by controlling fishing effort. Rules utilized by this approach usually focus solely on numerical controls (e.g., Wilson et al, 1994; Acheson and Wilson, 1996). Marine resource managers are now struggling to improve this approach in order to address the .complex nature of the environment (e.g., Sherman, 1991; OECD, 1997). In particular, there

is increasing interest in developing an ecosystem approach to management (e.g., Sherman, 1991; Apollonio, 1994; Larkin, 1996; Laevastu, 1996; NMFS, 1998; and Fogarty and Murawski, 1998; Wilson, 2001).

One significant source of difficulty resulting from the complex nature of the system lies in learning how to make meaningful management decisions (i.e., how to know if rules will result in sustainable resource use) (Wilson, 2001). The variability and complexity of interactions in the system make it impossible for us to predict the results of our actions. Unless we know how the system will respond to human intervention (or how our actions may influence the structure and function of the system) we cannot make informed decisions. Additionally, with this uncertainty, particularly regarding the future of the system, users have little or no incentive to adopt a conservation or stewardship ethic. This is because a user only has an incentive to restrain his/her activities today if they believe they will receive benefits from that restraint in the future. With the high levels of variability and complexity in the system, users cannot be assured that they will benefit from any conservation efforts that they make.

Holland (1998) describes the difficulties of learning in complex systems and offers insight into how pattern feedback can facilitate the learning process.[1] Holland (1998) uses the example of the checker board game to illustrate how, with feedback, we can learn how the system responds to outside influences such as exploitation and management. Holland explains how we unconsciously use feedback in our everyday lives to develop conceptual models that allow us to cope with the uncertain nature of the complex world around us. In creating these models, we focus on the important components and interactions in the system and ignore unnecessary details. With these models, we learn how to act and what we might expect will result from our actions.

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[1] Feedback can be defined simply as: "Influence on a system component mediated by changes induced by that component" (Levin, 1999, 233).

Ulanowicz (1997) similarly describes how with "propensities" we can find order in complex systems.[2] Propensities are the tendencies that certain circumstances might occur within a given context (Ulanowicz, 1997, 37) and are basically probabilities that are contingent upon circumstances and interfering events (Ulanowicz, 1997, 38). By paying attention to system propensities, it is possible to gain at least a qualitative understanding of the system.

However, as will be discussed, the nature of feedback (and propensities) in complex systems is imperfect, which has important implications for fisheries management. This chapter reviews complexity and hierarchy theory and attempts to apply these concepts to the study and management of marine systems. After reviewing the theory of complex systems and describing marine systems as complex, the implications of this complexity, particularly the problems posed by imperfect feedback, are explored.

What are Complex Adaptive Systems?

Simon (1962) defined a complex system as "one made up of a large number of parts that interact in a nonsimple way." Simon (1962) further explained that "complexity frequently takes the form of hierarchy and that hierarchic systems have some common properties that are independent of their specific content." O'Neill et al. (1986) extensively reviewed hierarchy theory as it is applicable to understanding the structure and function of ecosystems. Properties common to hierarchic complex systems, as described primarily by Simon (1962, 1996) and O'Neill et al (1986), are summarized in the following section.[3]

Nearly Decomposable Subsystems

Hierarchy theory finds that complex systems are composed of multiple subsystems that are described as nearly decomposable.[4] By nearly decomposable, it is meant that

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[2] Ulanowicz borrows the concept of propensities from Karl Popper.
[3] Many ideas of this section also resulted from of a seminar discussion on ecological approaches to fisheries management led by Dr. James Wilson at the University of Maine in the Spring 2000.
[4] Subsystems are simply the individual components that make up the system.

despite interactions between subsystems, boundaries can still be defined. At a given level in the hierarchy, subsystem boundaries are distinguished on the basis of rates – rates of interactions. Interactions are more frequent and intense within subsystems than between subsystems. Also, the subsystems themselves can be viewed as hierarchic in structure until some lowest subsystem level. The levels in the hierarchy are nearly decomposable because they can be isolated from each other according to the distinctly different rates at which they operate. Processes "higher" in the hierarchy exhibit slower rates than processes at the "bottom" of the hierarchy (O'Neill et al, 1986). Again, the subsystems (and components of subsystems) are considered nearly decomposable since they can be isolated from each other. Hierarchy theory allows us to simplify complex adaptive systems by focusing on the near redundancy that is inherent in their organization (Low et al, 2001).

An example of a complex system that is widely cited is a forest (e.g., O'Neill et al (1986; Pahl-Wostl, 1995). For simplicity, the system here is viewed as being composed of an assemblage of trees, which are composed of their individual parts (e.g., leaves). Individual tree leaves respond rapidly to momentary changes in light intensity. The leaves respond by either increasing or decreasing photosynthesis. However, the growth of a tree responds more slowly to these short-term changes. Additionally, the species composition of the forest changes even more slowly, on the time scale of decades or centuries. Therefore, processes occurring lower in the system (i.e., the reaction of the tree leaves to changes in light intensity) are rapid in comparison to the processes that occur higher in the system and do not have as large an impact on the system. The reactions that occur within a single leaf will not drastically alter the entire forest. The processes occurring higher in the hierarchy (e.g., tree growth) occur very slowly and have large impacts on the system. Despite the rapid processes that occur at the lower levels, the forest generally appears stable. This is because the processes occurring at the lower levels are averaged or smoothed as they "move" up the hierarchy. That is, the higher levels constrain the fast dynamics that occur at the lower levels. The processes occurring at that level result in emergent properties of the

tree that we see at a higher level (e.g., leaf color). When we view the forest from the scale of an individual tree, we can essentially ignore what happens at the level of the individual leaf (e.g., how the leaf responds to changes in light). It is not necessary for us to know exactly the processes that occur at the level of the individual leaf to know whether the tree is healthy. By losing the detail that occurs at the scale of the individual tree leaf, we simplify what is otherwise a very complex system.

The hierarchy can also be viewed as a series of constraints that act on the rates of processes in the system, which exist at multiple scales (O'Neill et al. 1986; Apollonio, 1994). A constraint is something that functions to slow down system dynamics, increase relative stability and predictability, and integrate system components (O'Neill et al, 1986). The higher constraints are characterized by slow dynamics and cover a broad spatial area. The lower constraints are characterized by fast dynamics and have only a limited impact on the system. In the example above, the growth rate of the tree limits the rapid dynamics of the processes occurring within an individual leaf. Therefore, the higher levels are considered to be constraining the lower levels. The processes occurring at the lower levels result in emergent properties, which are only viewed at the higher levels in the hierarchy. Process rates are averaged as the hierarchy is ascended, and thus, there is a loss of detail at the top of the hierarchy. In other words, the effects of events occurring at lower levels in the system are diminished by the time they make their way to the system level. The result is that the dynamics at the system level are generally more stable. Although the composition of components within a system may change, the system level is considered stable as it is characterized by familiar and recurrent patterns. Consequently, there is more qualitative predictability at the system level than at the subsystem level.

Feedback Problems

Another important property of complex systems is imperfect feedback. There are essentially two causes of imperfect feedback. One source of imperfect feedback arises with

the connections that exist between subsystems, which make them *nearly decomposable* as opposed to *completely decomposable*. These connections create leaks through which feedback is lost.[5] If there were no leaks, all feedback could be captured locally. Strong, non-linear interactions between components present additional problems for those seeking feedback from complex systems. Therefore, even if feedback is captured, it will not be captured entirely and it will be ambiguous. Ambiguous feedback hinders our ability to understand the behavior of the system. Both feedback problems pose difficulties as we try to learn about and understand complex adaptive systems.

Marine Ecosystems as Complex Systems

It is well known that marine systems are complex. The following section attempts to provide a hypothetical hierarchical description of these complex ecosystems. Here marine systems are described as spatially organized hierarchies, where marine systems are composed of spatially discrete, but not completely independent subsystems layered in a hierarchy.[6]

At the level that is referred to as the *subsystem level* in the hierarchy there are patchily distributed resources, which are similarly repeated at other locations at the same scale. The distribution of these resources results from oceanographic processes (e.g., currents, gyres), as well as geological and bathymetric features in the system. Boundaries of the next higher level are defined by where the rate of interactions between subsystems declines. In other words, unique processes that occur at different rates distinguish each level in the hierarchy. As one moves from the system to subsystem level or from the top to the bottom of the hierarchy, process rates increase and dynamics become more variable.

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[5] However, feedback lost through these leaks is manifest at the next level in the system and theoretically could still be captured.

[6] The description below is only one of the many possible ways to organize the structure and behavior of marine systems using hierarchy theory. For example, one could also organize the system according to trophic levels.

One could imagine the hierarchy as extending down to infinitely small scales.[7] However, for conceptual purposes, the smallest subsystem considered here is the scale compatible with what ecologists think of as ecosystems (i.e., self-organized ecological systems), but with migration occurring between areas. These ecosystems are composed of interacting abiotic and biotic elements (*sensu* Whittiker, 1972). Such ecosystems may be described in terms of energy flow, trophic levels, species interactions, functional groups, redundancy, stability, resilience, and assembly rules (e.g., Holling, 1973; Paine, 1980; Walker, 1992; Weiher and Keddy, 1995; Larkin, 1996; Naeem, 1998; Steneck, 2001).

In many ways, the subsystems described here are compatible with the spatially distributed patches that comprise metapopulations.[8] Metapopulation theory has a long history, but has only recently begun to make its way into the population biology and conservation literature (Hanksi and Simberloff, 1997). The term *metapopulation*, first introduced by Richard Levins in 1969, was used to describe a set of spatially discrete groups of individuals (Wells and Richmond, 1995). Weins (1997) summarizes the basic tenets of metapopulation theory below.

> [A] metapopulation is spatially subdivided into a series of local (patch) populations. The classical view emphasizes a balance between extinctions and recolonizations that facilitates long-term persistence of the metapopulation...The dynamics of local populations are density-dependent within patches but asynchronous among patches, and migration (dispersal) among patches links them together.

However, unlike traditional metapopulation theory, this paper is principally concerned with the problem of obtaining feedback from disturbance (i.e., the harvesting of) multi-species assemblages. The patches (i.e., subsystems), therefore, are viewed as comprising metacommunities.[9] Metacommunities can be defined as "a set of local communities in different locations, coupled by dispersal of one or more of their constituent

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[7] For example, another level below the subsystem level is the population (or functional group) level, which is composed of individuals. Individuals are also made up of subsystems (e.g., organs). As is clear, one could infinitely continue to dissect the system.

[8] Metapopulations can be defined as "a set of local populations coupled by dispersal" (Hanski, 1990).

members" (Holt, 1997,150). A patch is defined as "a continuous area of space with all necessary resources for the persistence of a local population and separated by unsuitable habitat from other patches" (Hanski and Simberloff, 1997).

System Dynamics

As noted, the subsystems (i.e., ecosystems) can be viewed as self-organized communities (or metacommunities) composed of species and their habitats (e.g., substrate). Dynamics within a subsystem are highly variable and unpredictable. However, the interactions between species and between species and their environments result in emergent properties of the subsystem such as stability and resilience.

For instance, two important interactions that occur within a subsystem are predation and competition (e.g., for food and/or space). In a food or energy limited system, a population will either increase or decrease depending on predator and/or competitor abundance and food availability.[10] That is, when a species' competitors and/or predators decline, one would expect its population to increase to take up the newly available energy (or food/space) that now exists (e.g., release from predation or competitive release).[11] As noted by Levin (1999, 169), "Though individual species may fluctuate more when they are mixed with other species, the total biomass of all species may be expected to fluctuate less because some species will be at their peaks while others are at their lows. Individual species take up the slack for each other, owing in part to independent statistical fluctuation, and no doubt in part to reduced competitive pressures." In other words, although the species composition of in the subsystem is likely to change, the subsystem system as a whole will continue to be relatively stable and show typically recognizable patterns.

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[9] Metacommunities do not go extinct, but merely change in species composition.
[10] Ignoring such things as environmental influences, fishing, etc.
[11] We refer to the replacement in the system of one population by another as *compensation*. By replacement, we do not mean that the species is absent from the system, but its influence in the system (in terms of energy consumption) has declined. The compensating species is viewed as simply taking up the newly available energy (or space) in the system.

Although each subsystem may contain the same or a similar assemblage of species, the species in many ways can be considered local to the subsystem to which they belong.[12] The species in each subsystem are less influenced by conditions existing at other subsystems, but are similarly influenced by events occurring at a larger scale in the system (e.g., large-scale phenomenon such as climate change). For example, if a disturbance occurs at one subsystem, fish of the same species residing in another subsystem may not be affected at all, except through effects emanating from the larger system. These properties are consistent with metapopulation (or metacommunity) theory.

The species found within a subsystem fulfill various functions in the subsystem and typically occupy overlapping niches. It is convenient to organize the species within a subsystem according to functional grouping (Steneck and Dethier, 1994; Steneck, 2001). Redundancy within functional groups may be a prerequisite for stable subsystem dynamics (Stone, 1995; Naeem, 1997; Peterson et al., 1998; Steneck, 2001; Jackson et. al, 2001). For example, if a species in one functional group is removed from the system, another species in that same functional group can move in and take its place. This suggests that conservation should try to maintain the integrity of functional group diversity within an ecosystem.

Hypothetical Hierarchy for the Gulf of Maine

This section attempts to describe the Gulf of Maine region as a hierarchically organized complex system.

At the top of the hierarchy, there are large marine ecosystems. Sherman and Alexander (1986) describe large marine ecosystems as being characterized by distinct hydrographic regimes, submarine topography, productivity, and trophically dependent

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[12] One exception to this, however, is migration, which represents one leak through which feedback is lost. The migrating species represent links (or flows) between subsystems.

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populations. These systems are generally greater than 200,000 km. An example of a large

marine ecosystem provided by Sherman (1991) is the U.S. Northeast Continental Shelf. [13]

Sissenwine (1986) describes this large ecosystem as being composed of two

systems - the Gulf of Maine and Georges Bank.[14] However, the boundary between these

systems is not perfect. The Georges Bank system is connected to the Gulf of Maine and

other regions via water movement, larval drift, and fish migration. Water circulation patterns

in the Gulf of Maine and on Georges Bank involve seasonally variable gyres (Baukus,

1987; Townsend, 1989; Sissenwine, 1984). The gyre in the Gulf of Maine is cyclonic

(counterclockwise), while the gyre operating on Georges Bank is anticyclonic (clockwise).

The gyre in the Gulf of Maine breaks down in the fall and winter and water is allowed to

drift onto Georges Bank. This movement of water from the Gulf of Maine onto Georges

Bank represents a linkage between these two systems. Similarly, the western side of the

gyre on Georges Bank breaks down and water is allowed to drift to the Mid-Atlantic area.

Therefore, although these are not closed systems, the Gulf of Maine and Georges Bank can

be considered two components of a single large system (e.g., Fogarty and Murawski, 1998.)

It is possible to consider these two systems as being composed of subsystems (or

metacommunities). One can imagine these subsystems as being nearly decomposable and

patchily distributed. However, it is difficult to envision exact boundaries of subsystems

within the Gulf of Maine or within Georges Bank. One problem is that the scientific

agenda established for managing fisheries has not been focused on this scale of the system

(Wilson, 2001). Consequently, much of the oceanographic work that has been done in this

region has occurred at a larger scale than the "subsystem" level.[15] However, it is still

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[13] Two other examples of large marine ecosystems given by Sherman (1991) are the Gulf of Mexico and the North Sea.

[14] However, considering the biogeographic and oceanographic characteristics of the Northeast Continental Shelf, this description is somewhat misleading. Georges Bank is clearly separated from the shelf by the Great South Channel.

[15] Despite the difficulty involved in trying to identify the most appropriate boundaries of these subsystems, there is evidence that processes occurring at this local scale are important and management should not ignore this level of the system (Ames, 1996; Hunt von Herbing, et al, 1997).

possible to envision subsystems within these areas. For example, in the Gulf of Maine these subsystems could be as small as or smaller than Penobscot Bay or as large or larger than the Bay of Fundy. More work will need to be done before suitable boundaries of these ecosystems can be described.[16]

Ideally, the boundaries should be designed to allow scientists and managers the ability to capture the most appropriate feedback from the system (Wilson, 2001). It is possible that sufficient feedback may be gained by focusing management at the scale of what here is described above as a system.[17] In addition, it is likely that future boundaries established for management purposes will ultimately be determined on the basis of both ecological and social criteria. For example, if the U.S. chooses to manage Georges Bank as a separate system from the Gulf of Maine, it will in reality only be managing part of the bank since the Northeast Peak belongs to Canada.

As noted above, the subsystems (i.e., ecosystems) within these systems (i.e., Georges Bank and the Gulf of Maine) can be viewed as metacommunities composed of species and their habitats (e.g., substrate).[18] Each subsystem is likely to contain the same or a similar assemblage of species. However, the species in many ways can be considered local to the subsystem to which they belong. The dynamics that occur within a subsystem (e.g., recruitment in individual populations) are highly variable and unpredictable. However, the interactions between species and between species and their environments should result in emergent properties of the subsystem (such as pattern stability[19]).

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[16] Since there are really no absolute boundaries in the ocean and the concept of boundaries is mainly dependent on how the system is viewed and/or the scientific questions being asked, it is in reality impossible to define exact boundaries in the ocean.

[17] That is, sufficient feedback may be captured by managing the Gulf of Maine and Georges Bank separately. Even if in actuality more feedback could be gained by focusing lower in the system, it is a good place to begin a transition towards an ecosystem approach to management.

[18] However, there is conflicting evidence that makes it difficult for us to know whether these populations are discrete or metapopulations.

<u>Does the Gulf of Maine Really fit the Description of a CAS?</u>

The Gulf of Maine region, unlike the generic complex marine system described previously is characterized by little diversity (including low functional diversity) (Anonymous, 2000). There are also few species left in this system that interact strongly (Anonymous, 2000).[20] This suggests that the system is less stable and predictable than systems with high diversity and functional redundancy. This does not mean, however, that the theory described here cannot be applied to this region.

In fact, the Gulf of Maine region may exemplify what happens when the hierarchic structure of complex marine systems is degraded. Prior to the advent of otter trawling and the commercialization of fishing, there was an abundance of cod, "haddock", and other predatory finfish in the system. These predators dominated the system despite hook and line fishing for at least 5,000 years (Steneck, 1997). However, beginning in the early part of the 20th century, with the advent of the otter trawl and the commercialization of fisheries, exploitation of these top predators intensified. Today, these species are now considered to be ecologically extinct from the region (Steneck, 1997, Steneck, 2001, Jackson et al, 2001). The system is now largely dominated by commercially less important species (e.g., sculpins, dogfish, skates) and several invertebrate species (e.g., lobster, crabs, urchins) have also increased in abundance (Steneck, 1997). Harvesting methods (e.g., trawling) have also contributed to the alteration of the system by reducing the structural complexity of habitats (Watling and Norse1998; Fogarty and Murawski, 1998). Despite management efforts to reduce harvesting pressures (e.g., groundfish closures), the once abundant predatory groundfish populations remain noticeably reduced in the system (Ames, 1997; Murawski et. al, 2000).

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[19] Here stability does not mean individual populations at or near equilibrium, but refers to the tendency of the system to vary within a range and to show typically recognizable patterns.

[20] This could suggest that compensation between species may not occur, and so the total system biomass may be variable instead of remaining relatively stable. However, even if species do not interact strongly, they do interact in the sense that they compete for available energy, which is limited.

According to the systems perspective described above, it appears that, as a result of harvesting activities, important constraints in the system (e.g., trophic structure, habitat, spatial distributions) have been removed and the system is more variable than it might be otherwise. That is, the hierarchic organization has been compromised and this complex system may no longer be as stable as it may have once been. Wilson (2001) suggests that maintaining the integrity of the "long time step variables" (e.g., habitat, climate, stock structure, spatial distributions) increases the likelihood of observing similar configurations in the system, which makes the system more stable than it might be otherwise. It is possible that if we restore these system variables, then the system may begin to resemble a more typical complex system (i.e., one characterized by stable patterns) similar to the one that existed prior to extensive exploitation by humans.

In summary, marine systems, such as the Gulf of Maine region, can be described as hierarchically organized complex systems with properties common to other complex systems. Processes that occur at the top of the hierarchy are slower, but impact a large spatial area. Processes occurring at the bottom are fast and only influence a small spatial area. Also, the subsystems and the species comprising the subsystems are constrained by processes occurring at higher levels (e.g., at the system level). The system is not greatly influenced by what happens at the subsystem level. Also, rates are averaged as the hierarchy is ascended, so the system level is more stable and predictable than the subsystem level. Similarly, events occurring at the subsystem level are more stable and predictable than what happens within the subsystem. For example, although the biomass of individual species may be highly variable, the average biomass of the subsystem remains relatively stable (e.g., May et. al, 1979; Laevastu and Hayes, 1981, Murawski and Idoine, 1992; Fogarty and Murawski, 1998; Levin, 1999).

Management Difficulties Posed by Imperfect Feedback

Describing marine systems in terms of hierarchy theory has several implications for managing fisheries. For successful management systems to evolve, we need to learn what does and does not work. In order to for us to learn in complex systems, it is essential that we have feedback from the system (Holland, 1998; Ulanowicz, 1997, Wilson, 2001). Otherwise, we have no idea what rules work best. Furthermore, we have no way of learning how to make existing rules more meaningful. Unfortunately, the highly variable nature of the system makes it very difficult for us to capture, understand, and respond to feedback in the system.

Capturing Feedback

Feedback from the system is difficult to capture. Some feedback will inevitably be lost between the flows that connect the subsystems. For example, some feedback will be lost from an area because of larval drift and migration. In addition, given our human (imperfect) measurement abilities, we are likely to miss some of the feedback that results from our actions. As we try to capture feedback from the system, we need to have some idea what it is that we need to measure and how to measure it. If we do not measure the "right" things, then we may miss some important feedback. Then at some point we must analyze and interpret the data and observations that we have made, which then must be communicated to decision-makers. These processes take time. By the time the feedback is analyzed and in the hands of the decision-makers (i.e., captured), it is likely that the system has changed.

Ambiguous Feedback

Another problem exists – ambiguous feedback, which results from the non-linear nature of the system. Ambiguity poses a more serious problem for resource managers because even if feedback can be captured, we may not know what the feedback means or

how to respond to it. Additionally, even when a rule appears to work well, it cannot be assured that the rule will continue to have similarly favorable outcomes in the future. There is simply always going to be a lot of uncertainty regarding the results of our actions (Wilson, 2001). Given this, it goes without saying that we should try to adopt the most precautionary and conservative policies – assuming that we know what they are.

In addition, as suggested earlier, the uncertainty created by ambiguous feedback makes it difficult for users to develop conservation incentives. For example, a user only has an incentive to restrain his/her activities today if they believe they will receive some benefits of that restraint in the future. With the kind of uncertainty that exits in marine systems, users cannot be assured that they will benefit for any conservation efforts that they make. Similarly, the flows responsible for imperfect feedback discourage users from adopting stewardship roles. This is because the boundaries of the resource (subsystems) are permeable, and users are less likely to capture all of the benefits provided by their conservation efforts. Institutions can be designed to create assurances for users that encourage them to conserve the resource despite the uncertainties that discourage them (Wilson, 2001). In addition, Wilson suggests that assigning broad rights will likely create an environment where users have incentives to invest in the future, and thus adopt conservation practices.

Responding to Feedback

Assuming that feedback can be captured and understood, decision-makers must also be able to respond to the feedback. For example, feedback from the system may indicate that one species is doing poorly and that users need to remove effort from that fishery and switch either to a new location or to another fishery. It may be difficult for the user to adjust if they need to switch fisheries. For example, it may be necessary for the user to re-rig their vessel with another gear type in order to target a different species, which may be costly in terms of both time and money. Switching fisheries may be prevented because of certain

license requirements. Legal boundaries may prevent the user from fishing for the same species in a different area. Or, small vessels may not be equipped to travel long distances to other fishing locations.

Additionally, if fishing experience indicates a need for a new rule, coming to an agreement will likely take some time and negotiation. If a new rule is agreed upon, it must be implemented which may involve long legal processes (e.g., through legislatures). Then users must be informed and change their strategies to conform to the new rule. Local level institutions are more likely to be capable of responding to changes in feedback than are regional institutions because local level institutions are generally smaller and more adaptable.

Another problem in responding to feedback involves how to interpret it. Analytical errors can hinder our ability to respond appropriately to feedback. When interpreting feedback, decision-makers use some form of model to determine what the feedback means and what should be done. If, for example, feedback is analyzed with an imperfect model (or with a flawed understanding of the system) the response may actually result in harm to the resource. Additionally, we may know what kind of response is appropriate, but we may not know how much response is adequate. For example, we may receive feedback that tells us that there is an abundance of a particular species and we determine that the appropriate response is to switch effort towards that species. In other words, it is possible for us to over and under respond to feedback and we may never be able to know exactly how much effort is appropriate.

In general, the problems we face in trying to respond to feedback are due to the highly variable and complex nature of the system. When everything is changing rapidly, it is difficult for us to know how to respond appropriately and quickly enough. If we hope to sustain fishery resources, it is important that we organize the structure of fishing rights so that we can maximize our abilities to capture and react appropriately to feedback from the subsystems.

The Organization of Fishing

Traditionally, fishermen have adjusted to the variability in the system by utilizing one of two fishing strategies. One strategy is for a vessel to target a single species across multiple ecosystems. With the second strategy, fishermen target multiple species in a relatively small geographic area. Considering these two strategies, there are two licensing options available for managers. The first approach, based on conventional single species economic theory, is to allocate rights to single species across systems (i.e., the Little Box approach to management). The second is to allocate rights to multiple species within a well-defined area (i.e., the Big Box approach to management). These two ways to organize fishing can be easily described in the context of hierarchy theory.

If there were no flows at all, when subsystems are perfectly decomposable, all feedback can be captured within the subsystem. In this case, it makes sense to apply rules at this scale. Still, if we assume linkages between subsystems are only minimal, more feedback can be captured locally within the subsystem level than between subsystems. This is because the intensity of interactions is greater within than between subsystems. Further, even when flows are more than minimal, feedback loops are generally tighter at the local or subsystem level than at the regional or system level and feedback is quicker at the local level than the regional level (Levin, 1999).

This strongly implies that we may not get enough feedback when rules are focused solely on individual species at the system (regional) level, such as with the conventional, Little Box approach. The problem with focusing on individual species is that dynamics at this scale are too variable and unpredictable, which makes feedback "noisy". The problem with focusing solely at the regional level is that feedback is dissipated as it makes it way up from the subsystem level to the system level, and consequently our ability to understand it is diminished. Since more feedback can be captured at the subsystem level, the implication is that we need to find an alternative to the large scale single species approach to management,

17

where harvesting rights are assigned to individual species and those species are managed independently.

With this in mind, an attractive alternative approach is to adopt what users refer to as a Big Box approach to management, where harvesting rights are allocated to multiple species within a defined management area (which should correspond roughly with subsystem boundaries). This approach is explored in the next chapter using an age structured, multi-species bioeconomic model. Additionally, hierarchy theory suggests we design institutions to parallel the multi-scale hierarchical structure of the marine system (Wilson, 2001; Wilson, 1996). Each level in such a "parallel management structure" would aim to capture feedback at a specific scale in the system. A "parallel management structure" would be complimentary to a Big Box approach to management. In addition to allowing us to capture the most feedback possible (i.e., from all scales in the system), this approach would also enable us to capture the feedback that is lost through leaks between levels (e.g., through migration).

Summary Chapter 1

The complex nature of the marine environment has made it very difficult for us to manage the world's fisheries. We have to simplify the system, but hierarchy theory suggests that the single species approach of conventional fisheries theory and practice may be the wrong way. The result has been a nearly universal failure to protect the marine environment and its resources. For successful management systems to evolve, we need to learn what kinds of rules will result in sustainable resource use. This requires that we receive feedback from the system. Complexity and hierarchy theory suggest that more feedback can be captured by paying attention to subsystems rather than single species. This is because there is generally more stability and predictability at the subsystem level than at the species level in the system. Additionally, the interactions that occur within the subsystem are tighter and quicker than the interactions that occur across subsystems. By

managing the system at the species level, it is unlikely that we can capture the kind of feedback that we need. Therefore, in order to capture the most feedback from the system, we need to move away from the purely large scale, single species approach to fisheries management. New institutions are needed if we are to incorporate the complex behavior of the system into fisheries management policies. These institutions need to parallel the multi-scale hierarchical structure of marine ecosystems and provide incentives for users to invest in an uncertain future. Unfortunately, feedback in highly variable complex systems is imperfect and ambiguous. New alternatives need to be explored as we learn how to capture, understand, and respond to feedback from the system.

CHAPTER 2:

EXPLORING IMPERFECT FEEDBACK UNDER TWO HARVESTING MANAGEMENT REGIMES USING TWO AGE-STRUCTURED, MULTISPECIES BIOECONOMIC MODELS

Introduction

As described in Chapter 1, marine ecosystems are highly variable, non-linear systems characterized by complexity (e.g., Levin, 1999). This complexity creates many problems for those seeking to manage marine resources (Ludwig et al, 1993; Dayton, 1998). Possibly the most important difficulty arises from the numerous levels of uncertainty and predictability that exist in fisheries, both political and biological. This uncertainty (1) makes it nearly impossible for decision-makers to learn how to make meaningful management decisions (i.e., how to know if rules will result in sustainable resource use) and (2) can create barriers against the development of conservation or stewardship ethics (Wilson, 2001). In order to learn and minimize uncertainty in complex marine systems, we must rely on feedback from the system (Holland, 1998; Ulanowicz, 1999; Wilson, 2001). Unfortunately, feedback in highly variable, non-linear complex systems can be imperfect and ambiguous. Furthermore, even if feedback can be captured and is understood, managers and users must be able to respond in a way that furthers their objectives. Thus, understanding feedback in marine systems is essential if we are to create sustainable management systems.

Two Perspectives for Dealing with System Variability

In complex marine systems, successful fishermen must know how and be able to adapt to changes in the system (i.e., system variability). In order to deal with the variability that exists in the system fishermen have generally utilized one of two fishing strategies. One strategy is for a vessel to target a single species across multiple ecosystems. With the second strategy, fishermen target multiple species in a relatively small geographic area.

A notable example of the first strategy is the U.S. redfish fishery that existed until the 1980s (Ames, pers. communication). These large vessels traveled from the Gulf of Maine as far as Labrador, targeting local stocks of redfish. These vessels were able to react to the variability of redfish in any particular area by always moving to areas of greater abundance. That is, they relied on the stability in the average redfish biomass across systems (in one area redfish biomass may be low, in another area redfish biomass may be high – so the average is relatively stable). The Soviet fleets pursued a similar strategy on a much larger scale. Because small boats cannot travel long distances, this strategy is more suitable for large vessels. Additionally, this strategy is more economically feasible for large vessels because they do not have to switch between multiple gear types. The forgone fishing cost when the boat is in the yard is especially costly to large vessels, which is why they prefer to target a single species or species complex.

An example of the second strategy is the traditional Maine inshore multi-species fishing operation. These small vessels typically would target lobster in the spring and early summer, groundfish in the summer, shrimp and scallop in the winter (Acheson, 1988). In fact, inshore, small boat fishermen everywhere are known for switching from fishery to fishery (or from species to species) as needed. Switching between fisheries allows them to take advantage of market trends and changes in species abundance (Acheson, 1988). In other words, this strategy deals with system variability by relying on the stability that arises within the system. That is, although individual species populations may change from year to year, there is always something in the system for these fishermen to harvest. These small boats are generally not able to move across multiple subsystems to chase individual species. Only large vessels are capable of this migration. Additionally, switching between multiple gear types is less costly for small boat operators because it can be done quicker. Therefore, small boat fishermen generally prefer switching from fishery to fishery (or species to species).

These two short-term strategies for dealing with system variability represent two licensing options for managers and suggest two ways that we may be able to capture and respond to feedback in the system. One approach is to allocate harvesting rights to a single species throughout its range. This approach, known as the Little Box approach, is most suitable for large vessels that are able to fish across multiple ecosystems. The second option, known as the Big Box approach, is to allocate rights to multiple species within a defined management area. This approach is more suitable for small vessels that must remain in a relatively small geographic area. The recent trend in fisheries management, which relies on conventional single species fisheries economics, has been towards the Little Box approach to management.

Conventional, Single-Species, Little Box Perspective

The conventional perspective, which implies Little Box management, attempts to capture feedback from the marine environment by focusing on individual species in isolation. Because species-specific rights are allocated to users across systems and subsystems and rules typically cover the entire range of a particular stock, local conditions and processes (e.g., habitat, local stock structure, fish behavior) are essentially ignored.

The conventional perspective conceives the problem in a way that assumes that we simply need to estimate the current size of the adult population in order to get sufficient feedback from the system. This perspective assumes a simple balance between the growth of the population (e.g., births and growth) and mortality (including fishing mortality).[21] This model (e.g., the Schaeffer model, Ricker model, and Beverton/Holt model) finds that recruitment to the population is governed by the adult size of the population (e.g., spawning stock biomass) and that the population will grow until it reaches its maximum size, which assumes that there is an attainable equilibrium determined by a carrying capacity (Fig 1).

The variability that occurs in the population is considered to be due to changes in the adult population and environmental "noise". Along these lines, the theory suggests that we can get feedback by monitoring changes in the adult population (i.e., recruitment). It assumes we can learn from this feedback and, by changing mortality due to fishing, can exercise control over the population. Basically we can either increase or decrease fishing effort (which will either increase or decrease the size of the population) and will know how the population will respond (i.e., in terms of future recruitment).

Figure 1: Theoretical Stock-Recruitment Relationship

Recruitment

Spawning Stock Biomass
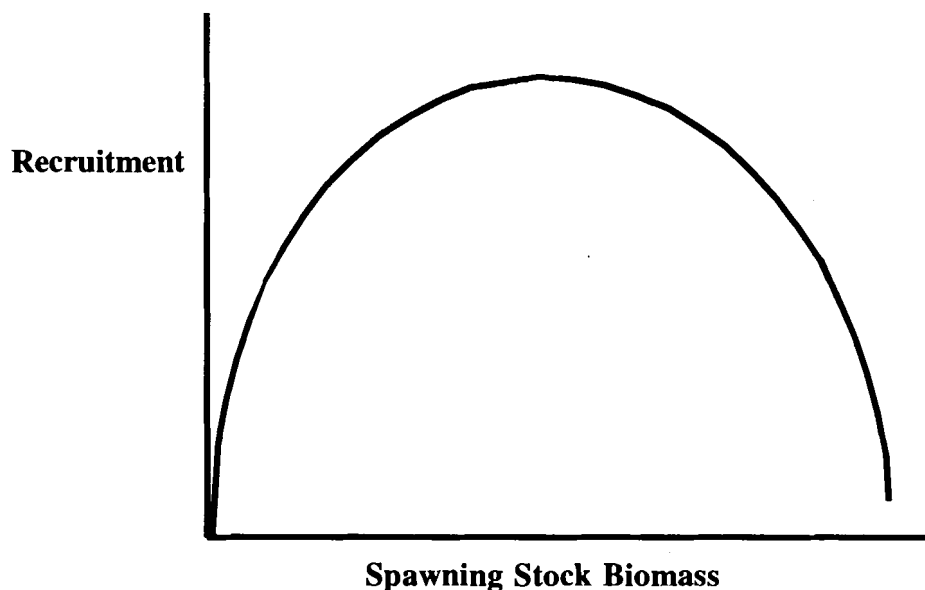
Fisheries economics recognizes the need for some sort of resource control or property rights. In the absence of property rights, a situation referred to as open access, feedback and learning do not take place. Consequently, profits are not maximized and the resource is overexploited, a situation known as "the Tragedy of the Commons" (Hardin, 1968). This is due to the lack of individual incentives that encourage users to conserve the resource. With no property rights, under open access fishing, users cannot be assured that they will benefit in the future for any conservation efforts that they make today. With little

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[21] Anderson (1986) provides a complete description of the conventional economic theory of fisheries

stake in the future of the resource, there is little incentive to learn, and so users to do not pay attention to feedback in the system. Consequently, fisheries management seeks to create a sole owner, which through exclusion, will bear all of the costs and enjoy all of the benefits of the future condition of the resource. Loosely defined, the sole owner can take the form of a collective body such as the government, a corporation, a co-op, or a community. A sole owner is a theoretical construct that represents a single decision maker who is given all rights to the resource. The sole owner bears all of the costs and enjoys all of the benefits of conservation, and thus, has an incentive to learn how to harvest the resource in the most sustainable manner in its efforts to maximize profits. Thus, the sole owner will be more likely to pay attention to feedback in the system.

Based on the ecological assumptions described above (i.e., stock-recruitment relationships), conventional economic theory utilizes effort-yield curves to describe the amount of fish that the sole owner can take and still allow the stock to sustain its population level. While biologists describe the largest amount that can be taken that will achieve sustainability as the population's maximum sustainable yield (MSY), economists refer to the greatest value fish that can be taken as the maximum economic yield (MEY). MEY is the amount that a theoretical sole owner would remove from the system in order to maximize profits and occurs at a population level higher and catch level lower than MSY. With one decision-maker controlling the amount of effort in the fishery (i.e., the sole owner), the feedback problem is greatly simplified. Theoretically, the sole-owner should know exactly how much effort it is using and can more quickly change its effort levels according to changes in stock size.

There are many important assumptions underlying this perspective that may over simplify feedback problem in marine systems. First of all, this theory assumes that we can capture perfect, or at least very good, feedback from the system by simply looking at changes in the size of the adult population relative to fishing. It assumes that we know what

management.

24

the feedback means (i.e., that it is not ambiguous). With this theory, we know that in a population of X size, recruitment will be Y. Thirdly, it assumes that we can respond appropriately to the feedback by simply changing levels of fishing effort. This perspective requires that we know what impact we are having on the system (i.e., what our effort levels are and what they mean) and requires that we can accurately estimate population sizes.

In reality, however, marine systems are complex and feedback is difficult to capture, ambiguous, and difficult to respond to. Although examples do exist where fish populations have recovered after the cessation of fishing (e.g., the recovery of fish stocks during world wars), there have also been instances where the result was not as the conventional, single-species theory would have predicted. Mike Sinclair, a scientist at the Department of Fisheries and Oceans in Canada, recently described the concern over unexpected increases in young cod death rates that have occurred since a moratorium was imposed on the species in the early 1990s.[22] Considering the single species models and a 10-year suspension of harvesting activities, one would expect that the cod resource would have recovered by now. However, this has not been the case. Another notable example occurred in New England. When spawning area closures were implemented to protect the groundfish resource on Georges Bank in 1994, the expectation was that the groundfish stocks would recover with the removal of fishing pressures. However, 5 years after these areas were closed to fishing, the result was not the recovery of the groundfish populations, but a booming scallop population (Murawski et. al, 2000). A third example is illustrated by the loss of the inshore cod and haddock stocks in the Gulf of Maine (Ames, 1997). Although, harvesting pressures were removed on the inshore stocks in the 1960s, the stocks have not since recovered. These examples illustrate the complicated causality in complex marine systems and the high probability that simply changing levels of fishing effort cannot achieve sustainability.

This raises an important question: If the source of variability in fish populations is not due solely to changes in the size of the adult populations, then does the conventional

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[22] Auld, A. December 22, 2000. *Bangor Daily News.* A7.

single-species approach oversimplify the feedback problem? Put another way, if stock-recruitment relationships do not exist, can we get sufficient feedback from the system by looking solely at individual species across systems (i.e., using a Little Box approach to management)? Or, is it necessary to take some form of non-species specific approach to management?

An Ecosystem Perspective

An alternative view, which implies a Big Box management approach, considers the system as being composed of patchily distributed subsystems and as having both spatial and temporal heterogeneity. This perspective assumes a hierarchically organized complex system, as described by Simon (1962) and O'Neill et al. (1986).[23] This view recognizes the importance of the interactions that occur between species and between species and their environments. Furthermore, this view assumes a non-equilibrium based, dynamic system characterized by high levels of variability and non-linearity.

Nevertheless, there is an important form of stability found in these systems. Multiple subsystems create redundancy, which provide resilience for the system and for the species that occupy the system (Simon, 1962; Levin, 1999). This redundancy makes marine systems relatively resilient to perturbations (disturbances).[24] For example, if one area experiences a disturbance (e.g., from a storm) that results in zero settlement of one species, then it is possible that individuals of that same species from an adjacent area will be able to re-colonize that area (Holling, 1973). This is consistent with metapopulation theory (e.g., Hanski and Gilpin, 1997). In addition, another type of redundancy, resulting from species diversity within functional groups, may also result in subsystem stability (e.g., Peterson et al, 1998; Jackson et al, 2001). With the loss of one species there is likely another within that functional group in that subsystem that performs the same, or nearly the same, function (allowing the system or subsystem as a whole to function as always (e.g., Steneck, 2001).

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[23] See also Chapter 1.

Additionally, interactions among the components (i.e., species) of the subsystem provide stability through post-settlement (pre-recruitment) regulation. The most significant of these interactions occur during species early life stages.[25]

Compensation among species is another strong attribute of these systems. The fact that systems are food or energy limited suggests that when the population of one species increases, another species' population must decline since energy will not exist to completely support it. This is due to niche overlap. That is, with the removal of even one individual, there is "room" in the system for another. Similarly, when one species is reduced or removed, another may be able to take its place. How a species reacts to changes in the system is a function of their intrinsic characteristics (e.g., fast growing and short lived or slow growing and long lived). We use the word *compensation* to refer to the growth of a population as a result of the decline in another. The result of compensation is that although individual species populations are highly variable, there is relative stability of biomass at the system level (e.g., Laevastu and Hayes, 1981, Levin, 1999).

There are several notable examples that illustrate compensation in the Gulf of Maine region. It has been suggested that compensation, resulting from community predation, may explain the recent growth in the abundance of elasmobranchs (e.g., dogfish and skates) on Georges Bank that has occurred since the depletion of the groundfish populations (Fogarty and Murawski, 1998). Diet overlap could explain why the elasmobranchs were able to increase after the decline in the groundfish populations (i.e., due to a release from competition). Similarly, another example often noted is when sand lance populations increased dramatically with the decline in herring and mackerel populations in the 1960s (Sissenwine, 1984). Populations of herring and mackerel were subsequently able to recover to historical levels, perhaps since these species feed on post-larval and juvenile sand lance. In coastal regions of the Gulf of Maine, the once abundant large finfish predator species

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[24] This does not mean, however, that the system will rebound back to a single equilibrium condition.
[25] One example of such an interaction that occurs at early life stages is predation – or the tendency of big fish to eat little fish (Sissenwine (1984).

(e.g., cod, haddock) are now considered to be ecologically extinct. Consequently, the region is now largely dominated by commercially less important species (e.g., sculpins, dogfish, skates) and several invertebrate species (e.g., lobster, crabs, urchins) have also increased in abundance (Steneck, 1997).

This perspective attempts to simplify the complexity (and variability) in the system by focusing on the stability that arises within the system. That is, this approach assumes that the variability of populations is due to what is happening within the system (e.g., with interactions between species and their environment), and so does not assume a stock-recruitment relationship. Although the various components of the system (e.g., species) fluctuate unpredictably, they do so within a general range and the system as a whole is generally stable. This approach assumes that most of the feedback from our actions will be contained within the system, and so we should look towards the system level as we try to capture and respond to feedback. Additionally, it assumes that we can capture more feedback by looking at the system level where dynamics are more stable compared to the dynamics that occur at the species dimension (where "noise" makes it difficult to perceive feedback).

Summary and Hypothesis

Thus, there are essentially two different perspectives on how to deal with complexity in marine systems. One view, the conventional approach, tries to simplify the system by focusing on the individual species populations. A second approach attempts to simplify the system by focusing on hierarchical structure and the stability that exists at the system level. Each perspective on how to deal with complexity suggests the need for a different approach to fisheries management. The first approach implies harvesting rights to species across systems (the conventional single species approach, or the "Little Box" approach). The

second approach implies rights to multiple species within a system (the "Big Box" approach).[26]

It is hypothesized that if there is more stability at the system level (and that variability in species populations is due to constraints imposed on the species by system factors) compared to the variability and "noise" in the species dimension, then the Big Box approach to harvesting will allow for better use of feedback in the system (i.e., that more feedback can be captured and harvesters can respond better to that feedback without having to deal with as much "noise") compared to the Little Box approach to harvesting. This hypothesis will be explored using two age-structured, multi-species bioeconomic models. In particular, the models are used to explore the conditions under which appropriate feedback can be captured (and responded to) in highly variable complex marine systems.

Two Bioeconomic Models of A Complex Marine System

Modeling is a useful tool that allows us to think through what we think we know about the system and helps us realize what we do not know. Hannon and Ruth (1997) describe the "art of modeling" as an extension of our thinking and as a learning tool.

> Throughout our life we have learned to develop models in our minds of the processes that we face everyday. We do solve an amazing class of dynamic problems, such as hitting baseballs and driving cars, by acquiring through trial and error the skills that are necessary to put the various components of a dynamic system together in our mind, draw the necessary conclusions, and react accordingly. However, the more complex the system, the less we are able to sufficiently grasp in our mind its workings and to prepare our actions. We simply cannot hold the many aspects of a dynamic process in mind at once. We need to be able to capture our knowledge, possibly that of others, in a consistent and transparent way so that we can better understand, and act in, a changing world.

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[26] *Sensu* Wilson, Brennan, Acheson (1997).

Given the complex nature of the marine system, modeling should be viewed as an important tool with which to explore the way we conceptualize the system. Further, modeling can yield insight into how our actions will influence system dynamics.

In order to explore the dynamics of a multispecies fishery and the implications of the two management approaches previously described, two age-structured, multiple species models were created using the graphical programming language STELLA 6.0.[27]

These models were designed for the purpose of exploring the ideas previously presented. These models were not designed to be predictive and do not exactly replicate what happens in the real world (e.g., the Gulf of Maine). That was not the intention. The intention was to create tractable models that qualitatively depict the dynamics of a basic complex marine system. The purpose was to use the models to explore and extend logically our conception of complex marine systems.

Description of the Models

Both models are complex and function similarly to ones used by Wilson et al. (1991) and Wilson et al. (1999). One model simulates the conventional single species approach to management (or the Little Box model) and the other replicates a multispecies system approach to management (or the Big Box model). Each model consists of two biological sectors, representing two geographically proximate multispecies systems, and an economic sector that governs harvesting activities.[28]

Overview of the System

Both models view the system as complex and dynamic. The two systems are considered local but may be connected by larval drift or migration.[29]

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[27] The models were created through a joint effort between Dr. J.A.Wilson, D.F. Gilbert, and the author.
[28] The biological sector was adapted from the FORTRAN Model used by Wilson et. al 1991.
[29] No larval drift or migration was included for the purposes of this thesis.

Two ecological characteristics of the model are important to specify. They are (1) the differentiation of the species and (2) a system biomass constraint. The species were intentionally differentiated to account for the diversity of species that exist in real world systems. Despite this differentiation, the species still occupy overlapping niches. The system biomass constraint is included to represent the system's energy budget, or carrying capacity.[30] The system is tight and energy efficient. It is assumed that primary production is efficiently converted to fish production and the system is considered to be food limited.

Two important properties emerge as a result of these characteristics. These properties are believed typical of multiple species systems. The first property is relative dynamic stability of the overall biomass of the system with highly variable, unpredictable component populations (e.g., Simon, 1969; May et. al, 1979; Laevastu and Hayes, 1981, Sissenwine 1984; O'Neill, 1986; Murawski and Idoine, 1992; Fogarty and Murawski, 1998). The second property is compensation (due here to density-dependent non-species specific negative feedback at the larval and post-larval stage of the species life) (e.g., Sissenwine, 1984; May et. al, 1979; Mayo et. al, 1992; Levin, 1999).

The Systems

Each biological sector is similar and contains five age-structured populations. These species represent one functional group (or trophic level). These populations have been labeled, for convenience only, "herring", "cod", "haddock", "redfish", and "sand lance". These species should not be confused with the species found in any real world ecosystem. The species were loosely modeled after several species found in the Gulf of Maine/Georges Bank region.[31] However, it was necessary to slightly alter some aspects of the species life history characteristics in order to differentiate them. Differentiation of the species was necessary to represent the diversity of species that exists in real world ecosystems. Additionally, without differentiation, the model will either not keep each

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[30] For the purposes of this paper, the subsystems in each model are given identical carrying capacities.
[31] Weight at age data were taken from Ruth and Lindholm (1996), Holland (2000), and Northeast Fisheries Science Center (1998).

species extant or depicts the species in synchronous periodicity. Both of these behaviors do not realistically reflect real world population dynamics. The species are differentiated on the basis of weight-at-age attributes, age of maturity, fecudity, natural mortality, and age of recruitment to the fishery. Species longevity is reflected in the natural morality rate, which means that species with a higher natural morality rate are shorter-lived species. All species were given natural mortality rates from 18% to 25%. Each species enters the fishery at the same age that it becomes sexually mature. Additionally, at age 0 and age 1 the mortality of each species is differentially influenced by density dependent constraints resulting from the system carrying capacity (stated in terms of the biomass of all species).

As noted, the species were differentiated to appropriately represent the diversity found in real world systems. The principle underlying the differentiation used here is that species differ in fundamental ways and those differences can be thought of as lying on a continua from "r-selected" to "K-selected" life history strategies. Although this concept does not account for all aspects of species life history strategies, "it is a useful paradigm of the reality of qualitatively different kinds of strategies" (Apollonio, 1994). Species exhibiting "r-selected" strategies are characterized as opportunistic while "K-selected" species are described as equilibrium or competitor efficient species. Although the species are differentiated, it is assumed that there is significant niche overlap.

The Species

"Sand lance" and "herring" can be considered to lie towards the "r-selected" end of the spectrum. These two are the most short-lived of all the species in the model. "Sand lance" represents a "bloom" species that is capable of quickly taking advantage of unused energy (e.g., food) in the system. "Sand lance" becomes mature at age 2. This species is not harvested and represents the untouched biomass that is present in most marine ecosystems. Because it is not harvested and is the most fecund of all the species in the system, "sand lance" can dominate the system when everything else is heavily fished. This

allows overfishing with relative biomass stability. "Herring" is also a light, fast growing, and relatively fecund species. "Herring" reaches sexual maturity at age three.

"Cod" and "haddock" could be thought as lying somewhere in the middle of the continua. "Cod" grows fast and large and is very fecund. It has an intermediate life span, compared to the other species. "Haddock" has a shorter life span (higher natural mortality rate) and is less fecund than "cod". Both species reach sexual maturity at age 4.

"Redfish" is characteristic of a "K-selected" species. It is a long-lived (experiences relatively low natural mortality) and slow growing species. This species reaches maturity later than the other species (age 7) and is assumed to invest more energy into ensuring the survival of its young. Therefore, it produces comparatively fewer eggs that are less susceptible pre-recruitment mortality.

Changes in the population size of each species are determined by species specific density-dependent egg survival rates, natural mortality, and fishing induced mortality. A density-dependent mortality rate controls the number of eggs that survive to age 1 and is a function of the total size of the species population. Due to the high levels of interactions between these species, the populations are very sensitive to changes in the number of births and natural mortality rates. Additionally, the species in the system are also constrained by a system carrying capacity. The carrying capacity represents the total biomass that the system can maintain. As the total biomass of the system nears the carrying capacity, the individual species experience additional mortality on age 0 and age 1 classes. Survival of age 1 fish is also influenced by an additional density-independent mortality that serves to further differentiate the species and allow for compensation. This mortality is randomly generated but extends over a wide-range (producing greater variability) for "sand lance" and "herring" and less variability for "redfish".

The Economic Sectors

The economic sectors of the two models differ substantially. In both models, four of the five species in the system are harvested and decisions are made on the basis of

profitability. In the first model, the Little Box model, fishing rights are allocated on a single species basis. Fishing occurs across the two systems and each boat is restricted to a single species. In this model, current profits per boat are compared between systems and a proportion of the vessels will migrate towards the most profitable system. In the second model, the Big Box model, fishing rights are allocated within one system and vessels are allowed to switch between species. In this model, individual vessels compare the relative profitability between fishing for the currently targeted species and the profitability of fishing for each of the other species, and move to the species where profitability is greater. Two ownership regimes are modeled, open access and sole ownership.[32]

The sole owner is an analytical construct used in resource economics. It implicitly assumes away all the problems of organization, internal transactions costs, monitoring problems, accountability, and most of all, individual incentives within an organization. The sole owner rule assumes a single decision-maker that "owns" all of the boats. It has access to all relevant information (e.g., biomass levels) with which it determines how to best allocate effort each year. With the profit maximizing sole owner, decisions regarding whether to add or subtract vessels are based on the results of a search process that compares the owner's past decisions to add or subtract boats, with the results of those decisions (i.e., whether they were profitable or not).

The model assumes that harvesters do not have problems finding alternative forms of employment and that no regulatory barriers exist to impede entry. It is assumed that boats can be bought or leased and are immediately able to enter the fishery. The model also assumes that capital is perfectly fungible. Thus, there are no delays in entry and exit. Similarly, it is assumed that there is no cost associated with switching fisheries (e.g., with switching gear types).

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[32] Under open access there are no barriers to entry and exit (e.g., in the form of a license requirement). Entry occurs when average profits are positive and exit occurs when average profits are negative. When no profits occur, no entry or exit occurs. Since open access assumes there are no barriers to entry and exit (e.g., restricting vessels to a fishery), open access is run only with the Big Box model.

In a simple non-age-structured single species model, the system provides immediate feedback to the sole owner, implying a rapid ability to learn. In this model, feedback is delayed because the action of the sole owner needs a chance to work its way through the system. It may be a few years before the sole owner knows what kind of impact its decision has had on the system.[33] Additionally, in this model, intervening events can generate "noise" in the feedback that the sole owner uses to make it decisions. In the Big Box for example, while the sole owner sees an abundance of "cod" and begins to direct effort to that species, there may be a bloom in "herring" that causes the system constraint to be exceeded, which consequently induces a high level of mortality on young "cod" (age 0 and 1), which is not seen by the sole owner for a few years. The increase in "herring" may signal to the sole owner that profits are high and the sole owner may add more boats to the system. When the sole owner "realizes" what happened to the "cod" population, it may not be able to move effort out of that fishery quickly enough.

In order to differentiate population signals from the system noise, resulting from the variability of the populations, the sole owner bases its decisions on a 5-year trend. However, in one of the early versions of the model this noise led to the sole owner finding a local sub-optimum instead of finding the profit maximizing solution. Therefore, the sole owner was given a "memory" of past circumstances that lead to high profits. The sole owner "remembers" the ratio of biomass to boats that existed at times of high profits and adds and subtracts boats in order to move towards those profitable circumstances. This gives the sole owner a more "global" perspective that avoids local optima. Additionally, the sole owner considers alternative sources of income that could be gained outside of fishing. It does this by comparing the average profits per boat with an arbitrarily set "floor" which represents the income that could be generated by a unit of effort outside of fishing. When the average profits per boat fall below the "floor" the sole owner removes a portion of its boats from the fishery.

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[33] Due to the delays and noise, the sole owner cannot find the profit maximizing solutions by looking for

As noted earlier, switching in both models is done on the basis of profitability. In the Little Box model, the sole owner looks at the relative profitability between harvesting the species in one system versus harvesting that same species in the other system, and boats will migrate towards the more profitable system. For example, the profitability of fishing for "herring" one system vs. fishing for "herring" in the other system is compared, and the sole owner will move a portion of the boats to the most profitable system. In the Big Box model, the relative profitability of each species is compared and the sole owner reallocates effort to increase profitability. This does not, however, mean that the sole owner will move all of its effort to the most profitable fishery. This is prevented by limiting the amount of effort that can be relocated during a given year (i.e., the switch rate).

Profitability is calculated as total revenue generated minus the total costs. Revenue is simply the total catch (pounds harvested) multiplied by the price per pound. Prices for all species were held constant, as it was assumed that the fishery was operating in the context of a world market. Catch is a function of the number of boats, the available harvestable biomass, and the vessel's efficiency. Total costs are a function of the number of boats and the operation costs per vessel. In order to more easily interpret model results, prices, operational costs, and harvesting efficiencies were kept constant and the same for all four harvested species. This effectively eliminates noise that would otherwise be generated by variations in these economic variables. Also, it creates a direct link between profits and species or system biomass. Hence, monitoring changes in species or system profits is equivalent to monitoring species or system biomass.

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the 1s/2nd derivatives, as can be done with analytical single species models.

CHAPTER 3:

RESULTS OF THE MODELS

Restatement of the Hypothesis

The models were created with the intention of simulating a hierarchically organized complex marine system composed of two subsystems, each constrained by a local carrying capacity. Specifically, the models were created with the intention of exploring how feedback can enable learning in complex marine ecosystems. Feedback can be defined as "influence on a system component mediated by changes induced by that component" (Levin, 1999). The process of learning involves first observing changes in the system and then trying to discern the results of those changes (i.e., feedback). However, the complex nature of the system makes capturing and understanding feedback difficult.

Complexity and hierarchy theory suggest that because subsystems are more stable than the individual populations that comprise them, better feedback can be gained by looking at changes in the average biomass in the system (i.e., at the subsystem level) than by observing changes in individual populations. The stability of the average biomass (i.e., the subsystem level) is due to constraints imposed by a system carrying capacity (e.g., energy limitation). Within these subsystems, compensation between species occurs due to competition among functionally similar species for available space. The result is that although the composition of species within the subsystem can change rapidly, the average sum biomass of the species is relatively stable.

Given this stability, feedback is less "noisy" at the subsystem level compared to the species level. This means that feedback will be easier to observe and less ambiguous at the subsystem level. In other words, at the species level in the system where dynamics are highly variable (more "noisy"), it is more difficult to capture, understand, and adapt to feedback. This suggests that more learning and adaptation can take place if rights are

allocated to harvest multiple species within a subsystem than if rights are allocated to harvest individual species across subsystems. Therefore, it is hypothesized that the Big Box model will produce more favorable results than the Little Box model.

Evaluating the Model

Due to the complexity of the models, testing the hypothesis requires breaking up the feedback problem into multiple components and looking for patterns in the results of the models. The feedback problem can be divided into three components. The first problem is capturing the feedback. The second problem requires an understanding of that feedback (e.g., distinguishing signals from noises). And the third problem is being able to respond to feedback.

The initial design of the model minimized all three components of the feedback problem. The sole owner under the baseline model is assumed to have perfect information about the biological and economic status of the resources, but not causality. Additionally, the sole owner knows how to and is able to adapt to that information immediately (e.g., there are no decision lags, no barriers to entry and exit, no costs associated with moving its fleet around, etc.). Starting with these "perfect" conditions, the model is then altered to better explore the feedback problem. This is done in a variety of ways but essentially involves (1) impairing the quality of feedback received by the sole owner and (2) hindering the sole owner's ability to adapt to changes in the system. The purpose was to observe how well the sole owner is able to respond to feedback in a variety of conditions with the hope of seeing patterns in the observed results.

Given the complexity of the feedback problem and the models used, no single indicator in the model quantifies how much feedback is captured and used by the sole owner. Feedback use is reflected in how the resource is exploited. One can assume that the better the quality of feedback and the better individuals are able to adapt to feedback (and changes in the system), the more efficiently the resources are harvested. This means that use

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of the resources becomes more economically and ecologically sustainable. It is assumed that profits signal to the users what is happening with the biological status of the resource. This is because profits are a linear function of the amount of harvestable biomass available. With little or no (or poor) feedback getting to the sole owner, one would assume that harvesting of resources would be done less efficiently.

Again, due to the complexity of the models and the nature of the feedback problem, both economic and biological indicators were relied on to assess the harvesting efficiency of the two models. Looking at multiple indicators provides a better opportunity to see patterns in the observed results.

Wealth, or accumulated profits, is viewed as the most important indicator used to evaluate the two models. Since profits are indirectly a function of the harvestable biomass available, wealth is also an indicator of the health of the resource. The purpose of the other indicators was to aid in our interpretation of the observations that we see in wealth (i.e., to check for noises). The other indicators reported were catch (biomass harvested), spawning stock biomass (mature biomass), system biomass (ages 2 and up)[34], and fleet size.

Running the models

The model reports annually the results of the year's harvesting activity. The species composition of the biomass in the subsystem changes each year due to the harvest and changes in the system constraint. The result is that catch is different each year for each species, and consequently so is wealth. Looking at one year will not provide much feedback about a given simulation. Therefore, in order to evaluate the model it was necessary to generate an average over multiple years. The model was run for 500 years and averages were then calculated for the last 400 years of each 500-year run. The first 100 years of each run were ignored to allow the model to adjust to initial conditions. Each time the model is run (i.e., a 500-yr run) the random component on age 1 mortality results in a different 400-year average. It was therefore also necessary to generate another average (of multiple

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[34] System biomass (ages 2 and up) reflects the population surviving post-settlement mortality.

runs). Therefore, under each simulation, the models were run 50 times for 500-year intervals. The 400-year averages (ignoring the first 100 years) were then averaged for the 50 runs. Averages for all simulations are summarized in the Appendices.

Consistency Tests

Before the models were used to explore the hypothesis, they were tested for reliability. A number of tests were done to make sure that the dynamics observed in the model conformed to expectations. These tests include dynamics of the populations in the absence of harvesting, the response of the species to exploitation, and the implications of the kind of harvesting regime on the status of the resource. A final test was done to make sure that the only difference between the two models is the kind of property rights regime constraining the sole owner. As shown below, the models respond as expected.

System Dynamics Under No Harvesting

With no harvesting, the species are variable and exhibit compensation. However the overall biomass of the system is stable (Fig 2). The system can be considered energy efficient, as the total biomass of the system is stable and the individual populations act as if they are food or energy limited. When no fishing occurs, "cod" and "redfish" dominate the system. This makes sense because these are the most long-lived of the species in the models (with the lowest natural mortality rates). These results represent what we might expect in an unfished system.

Figure 2: System Biomass (ages 2 and up) under No Harvesting
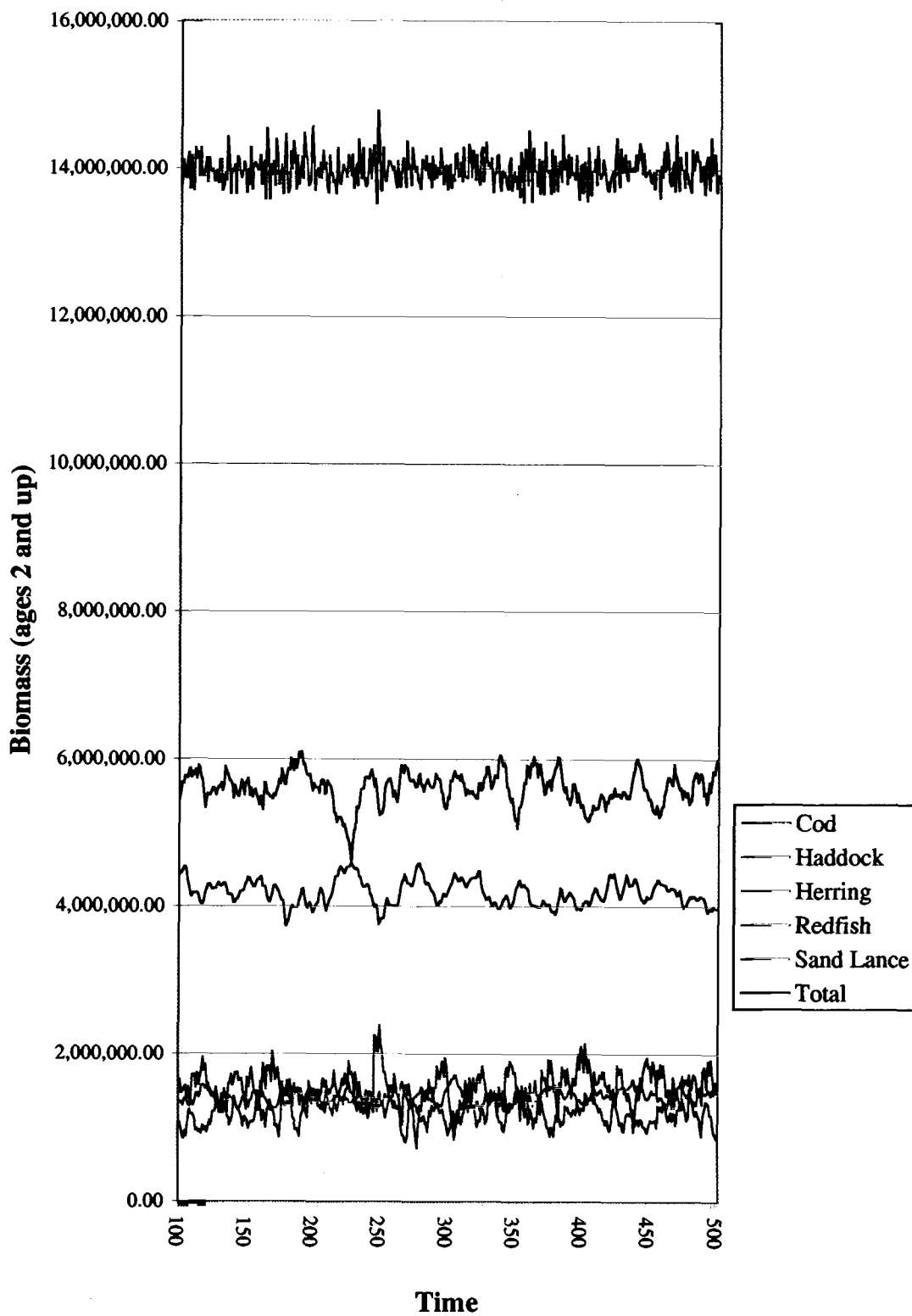
System Dynamics Under Two Ownership Regimes

Two ownership regimes typically described in economics are modeled; open access and sole ownership.[35] According to economic theory, because no property rights exist under open access uncoordinated entry takes place fishery until profits are zero. The result is overcapitalization in the fishery (too many boats) and, given sufficient demand, the "inevitable" overexploitation of resources. Under sole ownership, property rights are assigned to a single, profit-maximizing decision-maker who has an incentive to invest in the future of the fishery. According to economic theory, the sole owner is able to maximize profits and sustainable use of the resources occurs.

When the model is run, first under open access and then with a sole owner, it responds as expected from economic theory. The biomass of the individual species is reduced and the populations are substantially more variable than was observed under no harvesting (Fig 3). The biomass at the system level remains more stable than the biomass at the species level. The system biomass is also more variable compared to the system in the unfished state (Fig 2,3). Compensation between species can also be seen under harvesting conditions. Under open access fishing conditions, "sand lance" (the unfished species) clearly dominates the system, while the remaining species are now at similar biomass levels (Fig 3). However, "cod" slightly dominates among the fished species.

Under sole ownership, "sand lance" no longer dominates the system and all species are at similar biomass levels (Fig 4). Since under open access "sand lance" dominates the system and under sole ownership "sand lance" does not dominate the system, the model conforms to traditional economic theory. Traditional theory says that in the absence of property rights (open access) resources are overexploited. The theory further suggests property rights (sole ownership) provide incentives that lead to sustainable use of resources. The dominance of "sand lance" in open access suggests that the resources have

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[35] Open access is only modeled with the Big Box model because the Little Box model assumes that there is some barrier (i.e., license restriction) limiting a vessel to fishing a single species. Open access assumes no barriers to entry and exit.

Figure 3: System Biomass (ages 2 and up) under Open Access Fishing
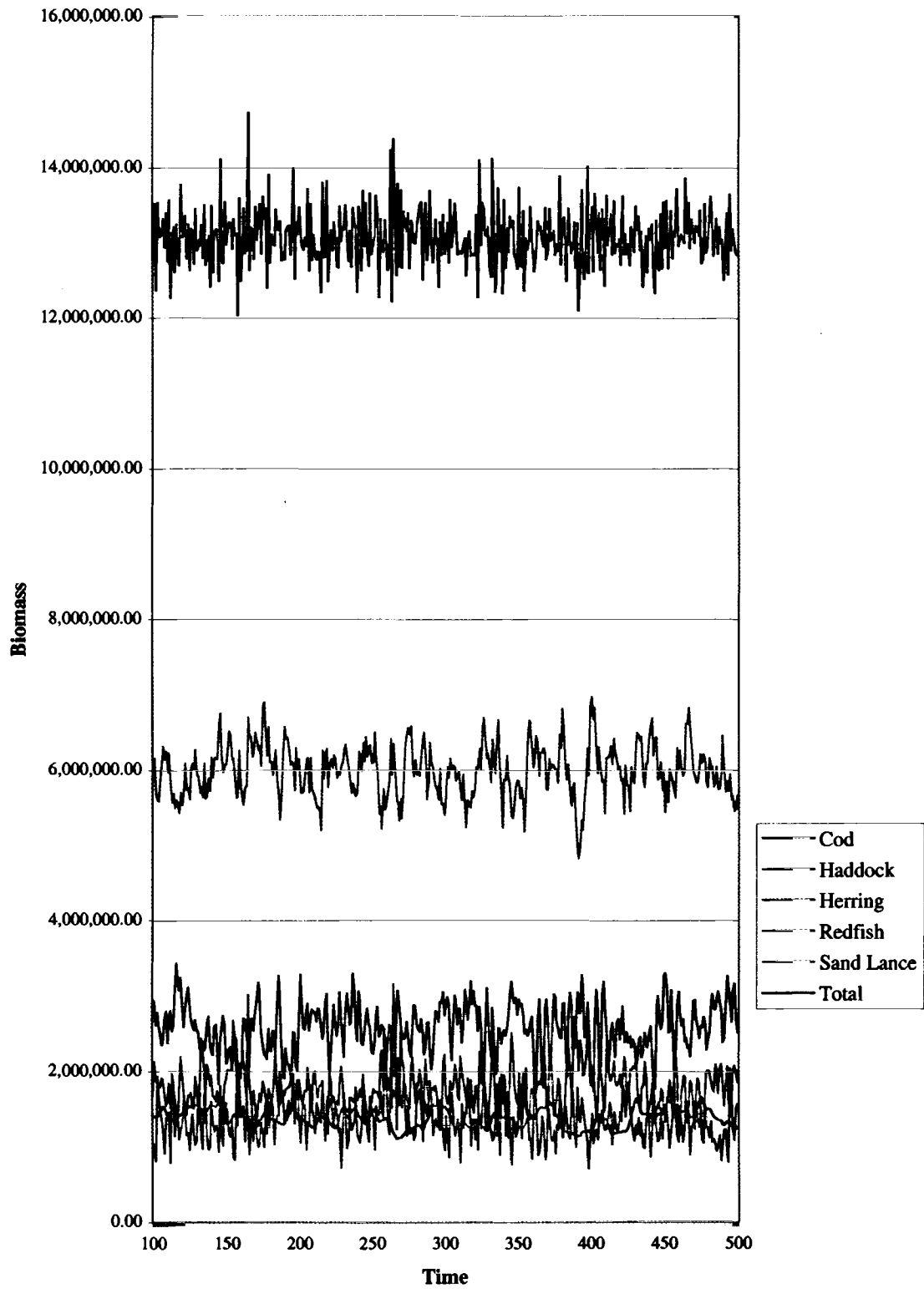
Figure 4: System Biomass (ages 2 and up) under Sole Ownership
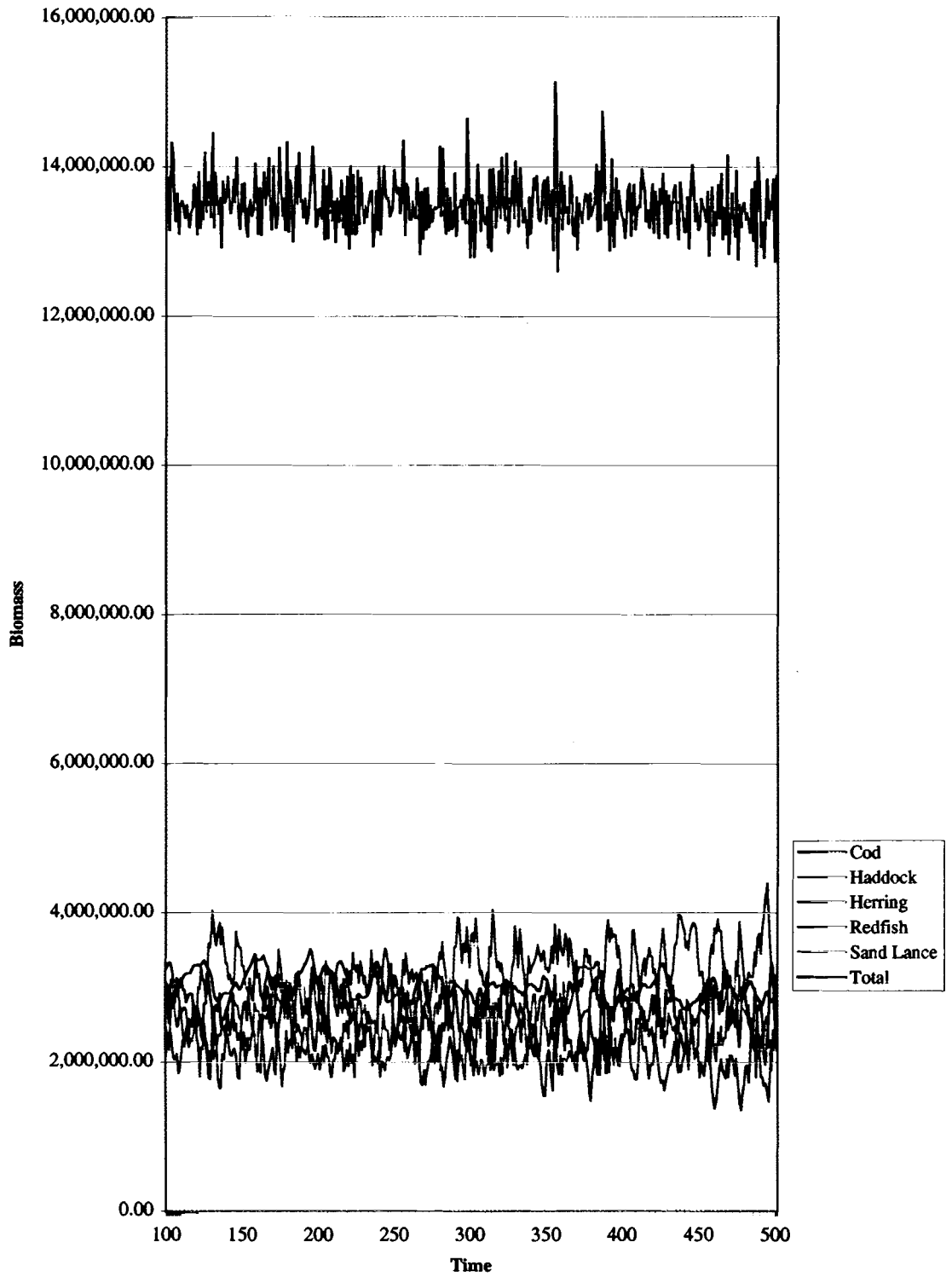
been overexploited, otherwise there would not be so much "room" for "sand lance" to dominate. Therefore, the dynamics of the species under the two property rights regimes provide confidence in the models.

Open Access vs. Sole Ownership

Further exploration of open access and sole ownership provided additional confidence in the model. As expected, open access management reduced harvested stocks to low levels and captured zero profits. With results consistent with theory, decision-making by a sole owner (under Big Box fishing), was economically and biologically superior to open access management (Table1). The amount of wealth generated in the open access regime was significantly less compared with the wealth generated under the sole owner in the Big Box model (Table 1).[36] Average mature biomass was significantly less under open access (Table 1). Average biomass (ages 2 and up) was also significantly less in open access (Fig 3d). However, "sand lance" biomass (ages 2 and up) dominated the open access system (Table 1). This makes sense because "sand lance" represents the untouched biomass in the system and is able to take up the space made available when the other species are fished. Average catch and fleet size in open access were greater than that seen under sole ownership (Table 1). In general, the result of open access is a depleted system largely dominated by the unharvested species ("sand lance").

In addition, the model responded as expected to changes in prices and operating costs under open access and sole ownership. For example, under open access, increased prices led to decreased biomass and consequently decreased wealth. Under sole ownership, the model resulted in a slightly greater harvest, increased wealth, and a slight decrease in biomass. Decreasing operating costs generated the same results as increased prices.

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[36] The wealth that does occur in open access is due to a delayed response to population blooms. When a bloom occurs, the resource is exploited by the boats in the fishery at the time of the bloom (resulting in profits being generated). Eventually "everyone else" responds, raising costs and ultimately driving profits to zero.

Table 1: Sole Ownership vs. Open Access

	Sole Owner			Open Access		
	Average	Stdev	N	Average	Stdev	N
Wealth	14,892,498	218,261	50	119,502	43,224	100
C Wealth	7,190,082	141,639	50	737,904	40,482	100
Ha Wealth	3,819,098	166,913	50	347,318	23,800	100
He Wealth	2,844,946	161,190	50	857,739	102,465	100
R Wealth	1,038,373	78,898	50	0	0	100
Catch	2,327,787	82,249	50	2,705,801	22,575	100
C Catch	1,034,233	14,751	50	1,089,846	13,957	100
Ha Catch	603,832	36,758	50	744,856	12,451	100
He Catch	472,912	36,011	50	870,958	24,132	100
R Catch	216,811	4,128	50	141	161	100
Mature Bio	9,227,880	91,335	50	9,387,708	30,352	100
C Mat Bio	1,786,390	95,732	50	1,089,846	13,957	100
Ha Mat Bio	1,474,734	54,901	50	744,856	12,451	100
He Mat Bio	1,361,465	43,611	50	870,958	24,132	100
R Mat Bio	1,045,789	64,293	50	282	337	100
Sl Mat Bio	3,559,502	173,492	50	6,681,766	47,664	100
Fleet Size	1,048	87	50	3,767	36	100
C Fleet	394	26	50	1,332	15	100
Ha Fleet	277	27	50	987	12	100
He Fleet	236	26	50	1,095	21	100
R Fleet	141	9	50	352	13	100
System Bio	13,427,987	34,676	50	12,986,070	16,232	100
C Bio	3,213,549	74,632	50	2,694,464	34,753	100
Ha Bio	2,652,404	32,800	50	2,002,674	33,168	100
He Bio	1,822,274	27,471	50	1,606,312	44,336	100
R Bio	2,180,259	95,249	50	854	1,007	100
Sl Bio	3,559,502	173,492	50	6,681,766	47,664	100

Averages are for the last 400-years of N runs

These results are consistent with economic theory and provide confidence in the model. The results find that sole ownership is superior to open access, which is consistent with the theory of open access, also known as the "tragedy of the commons" (Hardin, 1968). This theory says that under open access resources are overexploited and profits are not maximized, both of which were observed in the model.

Given the advantages of sole ownership, the remainder of the thesis explores the conditions under which sole ownership can capture and respond most appropriately to feedback in the system. Specifically, the question explored is whether we should look for feedback at the system level (e.g., using the Big Box approach) or the species level (e.g., using the Little Box approach).

Big Box vs. Little Box Under Identical Harvesting Pressures

One final test was done to make sure that there were no differences in the biological sectors of the two models (i.e., that each model responded the same to identical conditions). When all fisheries (i.e., species) in the Big Box and Little Box models experienced the same harvesting pressures under sole ownership, the results of the models were statistically equivalent (Table 2). Harvesting pressures were kept the same by preventing switching and entry and exit. These results were expected and confirm that the biological sectors and general fishery characteristics are identical between models. Therefore, as different harvesting scenarios (with entry/exit and switching) are explored, any differences between models must be due to differences in the two harvesting regimes (i.e., Big Box vs. Little Box management).

Baseline Conditions of Sole Ownership: Big Box vs. Little Box

Results of Baseline

Under baseline conditions, the two models differ only slightly (Table 3). Although average total wealth (accumulated profits) is slightly higher in the Big Box (Table 3), the standard deviations of the means overlap. However, the Little Box actually does better in the "cod" fishery (Table 3). Similarly, average mature biomass is slightly greater in the Little Box – with more mature biomass in the "cod", "redfish", and "herring" populations in that model (Table 3). The Big Box model resulted in a higher average mature biomass in the "haddock" and "sand lance" populations compared to the Little Box model (Table 3).

Similarly, system biomass (ages 2+) is also only slightly greater in the Little Box compared to the Big Box (Table 3). System biomass in the "cod", "redfish", and herring" populations were greater in the Little Box, while "haddock" and "sand lance" were greater in the Big Box model (Table 3). Average catch is slightly higher in the Big Box, in all fisheries besides "redfish" (Table 3). The number of boats in the Big Box model is also slightly higher compared to the Little Box model (Table 3).

Table 2: Big Box vs. Little Box under Identical Harvesting Effort

	Big Box			Little Box		
	Average	Stdev	N	Average	Stdev	N
Wealth	15,077,082	86,178	50	15,104,358	110,813	50
C Wealth	7,133,770	104,381	50	7,186,867	113,704	50
Ha Wealth	4,300,887	110,504	50	4,284,761	97,513	50
He Wealth	2,874,350	51,430	50	2,876,781	64,059	50
R Wealth	768,075	51,960	50	755,949	54,220	50
Catch	2,307,708	8,618	50	2,310,436	11,081	50
C Catch	1,033,377	10,438	50	1,038,687	11,370	50
Ha Catch	630,089	11,050	50	628,476	9,751	50
He Catch	447,435	5,143	50	447,678	6,406	50
R Catch	196,807	5,196	50	195,595	5,422	50
Mature Bio	9,291,024	21,775	50	9,291,724	19,785	50
C Mat Bio	1,722,295	17,397	50	1,731,145	18,951	50
Ha Mat Bio	1,680,237	29,468	50	1,675,936	26,003	50
He Mat Bio	1,491,450	17,143	50	1,492,260	21,353	50
R Mat Bio	874,700	23,093	50	869,311	24,098	50
Sl Mat Bio	3,522,343	34,677	50	3,523,072	35,670	50
Fleet Size	1,000	0	50	1,000	0	50
C Fleet	400	0	50	400	0	50
Ha Fleet	250	0	50	250	0	50
He Fleet	200	0	50	200	0	50
R Fleet	150	0	50	150	0	50
System Bio	13,432,321	8,755	50	13,431,360	7,764	50
C Bio	3,150,920	31,544	50	3,167,219	34,974	50
Ha Bio	2,938,819	51,376	50	2,931,102	45,326	50
He Bio	1,947,609	22,270	50	1,948,651	27,925	50
R Bio	1,872,630	49,571	50	1,861,316	51,616	50
Sl Bio	3,522,343	34,677	50	3,523,072	35,670	50

Averages are for the last 400-years of N runs

Table 3: Big Box vs. Little Box under Baseline Conditions

	Big Box			Little Box		
	Average	Stdev	N	Average	Stdev	N
Wealth	14,892,498	218,261	50	14,721,389	234,792	50
C Wealth	7,190,082	141,639	50	9,101,447	197,731	50
Ha Wealth	3,819,098	166,913	50	3,033,790	192,550	50
He Wealth	2,844,946	161,190	50	1,754,155	69,813	50
R Wealth	1,038,373	78,898	50	831,998	72,233	50
Catch	2,327,787	82,249	50	2,132,502	48,527	50
C Catch	1,034,233	14,751	50	992,636	13,529	50
Ha Catch	603,832	36,758	50	515,260	20,649	50
He Catch	472,912	36,011	50	400,700	23,715	50
R Catch	216,811	4,128	50	223,906	6,929	50
Mature Bio	9,227,880	91,335	50	9,419,838	69,772	50
C Mat Bio	1,786,390	95,732	50	2,033,196	120,584	50
Ha Mat Bio	1,474,734	54,901	50	1,362,988	91,031	50
He Mat Bio	1,361,465	43,611	50	1,510,953	100,768	50
R Mat Bio	1,045,789	64,293	50	1,248,957	71,164	50
Sl Mat Bio	3,559,502	173,492	50	3,263,744	86,170	50
Fleet Size	1,048	87	50	917	42	50
C Fleet	394	26	50	351	21	50
Ha Fleet	277	27	50	265	19	50
He Fleet	236	26	50	181	22	50
R Fleet	141	9	50	120	6	50
System Bio	13,427,987	34,676	50	13,487,762	19,188	50
C Bio	3,213,549	74,632	50	3,394,163	111,795	50
Ha Bio	2,652,404	32,800	50	2,391,478	118,374	50
He Bio	1,822,274	27,471	50	1,940,301	101,028	50
R Bio	2,180,259	95,249	50	2,498,076	117,044	50
Sl Bio	3,559,502	173,492	50	3,263,744	86,170	50

Averages are for the last 400-years of N runs

Variability Under Baseline Conditions

Inter-annual changes in recruitment were used as the indicator of variability (Table 4). Recruitment here is defined as entry into the harvestable population, except for "sand lance" for which recruitment is entry into the "adult" population. Table 4 shows the average inter-annual variability in the baseline models for each species in one system and for recruitment into harvestable population of one system. Variability in each system is nearly identical.

Table 4: Average Percent Change in Recruitment by Species

	Big Box		Little Box		
	Ave	Stdev	Ave	Stdev	N
Cod	16.52	0.89	17	0.97	50
Haddock	21.86	1.11	24.06	1.10	50
Herring	37.74	2.49	41.92	2.59	50
Redfish	4.94	0.37	5.5	0.54	50
Sand lance	122.9	6.09	103.56	10.96	50
Harv Bio.	5.24	0.43	5.02	0.25	50
Averages are for the last 400-years of N runs					

Recruitment is more variable at the species level in the system than at the system level (i.e., harvestable recruitment) except for "redfish". This means that in trying to capture feedback from the system[37], the Big Box sole owner is dealing with "less" variability (at least compared to the Little Box "cod", "herring", and "haddock" fisheries). This may be one reason why the Big Box sole owner average total profits were slightly greater compared to the Little Box sole owner.

One would expect the Little Box to do better in the "redfish" fishery because the "redfish" population is very stable. However, the slow growing nature of "redfish" makes it very relatively easy to fish this species down. This is because this species is less resilient to fishing and if the sole owner overshoots its effort in one year, this species will take longer

to recover compared to the other species. The "herring" and "haddock" fisheries are more variable, which is why the Little Box sole owner may have had a more difficult time in these fisheries, compared to the "cod" fishery. It is possible that the Little Box sole owner does well in "cod" because it is not too variable and is fast growing – which means it is more resilient to fishing. It is likely that the Big Box sole owner did not do as well (compared to the Little Box) in the "cod" fishery because by focusing on the average harvestable biomass (as an aggregate) it is not able to take advantage of the species individual stability and fast growth.

Unfortunately, we could not explore questions of high levels of variability with this model. We found that increasing variability was impossible without killing off one or more of the harvested species. In particular, "redfish" was very sensitive to changes in variability. This is because this species is very slow growing and thus less resilient. Because the species exhibit compensation, an "unusual" increase in one species reduces the space available for other species. "Redfish" cannot easily take advantage of openings in the system and so is often eliminated by consecutive growth "spurts" of other populations.

Sole Owner Response to Impaired Feedback

In the baseline, the feedback problem faced by the sole owner is minimal. The sole owner is assumed to have perfect knowledge of the biological and the economic conditions of the resource. It receives accurate information, which it is then able to analyze and use to make a decision in a timely manner. This means that economic and biological data are up to date and without flaw. The sole owner is further able to implement that decision immediately. That is, it adds or removes boats or switches fisheries as soon as it makes its decision. This further means that users (employees of the sole owner, members of the cooperative, etc.) are made aware of the new rules and are expected to change their

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[37] The sole owner looks at changes in profits for feedback. Since prices, costs, and harvesting efficiencies

harvesting strategies in a moment's notice. In addition, there is no cost associated with entering and exiting the fishery.

This is obviously not realistic of what could happen with a "real world" sole owner situation and does not reflect the problems faced in trying to capture and understand feedback from the system. Rarely does a resource manager have completely accurate, up-to-date information on which to base its decisions. Furthermore, once a decision is made, there is a period of time before the decision can be implemented. Also, there are costs and difficulties involved in entering and exiting the fishery. For example, buying a new boat is a relatively long-term investment. Users would not likely be so quick to enter and exit a fishery, given that the boat has little use when not harvesting. In summary, in its baseline form, the model strongly understates the feedback problem.

In order to make the model more realistically simulate the feedback problem several changes were made. These changes were made and run independently of each other in order to understand the effect they have on the sole owner's ability to make decisions.

First, the ability of the sole owner to make and implement decisions (i.e., make adjustments to its fleet) was made more difficult. The first alteration was to only allow the sole owner to make adjustments to the size of its fleet only every 5 years (instead of every year). This change was made to entry and exit, not switching. By only making adjustments every five years, the sole owner's flexibility is reduced, as it is unable to respond as quickly to changes in the system. By only readjusting its fleet every five years, the sole owner cannot track changes in the system as well as it can if it adjusts its fleet every year. Another way to impair the sole owner's ability to adjust or respond to feedback is to delay the implementation of its decision by 5 years. This represents some barriers to entry and exit. For example, it may take 5 years to build a boat and find someone to fish it. Also, the delay in exit could also represent problems associated with implementing the decision (e.g., perhaps the sole owner must give its captains 5-years notice before dismissing them). By

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are held constant, profits are a linear function of the harvestable biomass available. Therefore, variability in

delaying the sole owner's decision by 5 years, its ability to track changes will be greatly diminished. For example, in a given year there may be a bloom in "herring", but the sole owner may be responding to a bloom in "haddock" that occurred 5 years ago that has already been depleted.

The second way to impair feedback to the sole owner is to reduce the quality of the information getting to the sole owner. This was done by creating errors in the information and delaying the information getting to the sole owner. For example, creating errors might represent poor stock assessments, including measurement (sampling) and model/statistical errors. Delaying the information is meant to represent decision-making based on old information (e.g., due to lags between when assessments are done and when they are interpreted). By degrading the quality of the feedback, the sole owner should have a more difficult time learning how to respond appropriately to changes in the system.

Allowing the Sole Owner to Adjust Fleet Size Only Every 5 Years

By decreasing the frequency that the sole owner is able to make adjustments to the size of its fleet, average wealth decreased substantially in both models (Table 5). The only improvement in wealth was seen in the Big Box in the "redfish" fishery (Table 5). However, average wealth in both models was still significantly higher than the wealth generated under open access fishing (Table 1,Table 5). Average catch decreased in all

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recruitment to the fishery reflects the variability that the sole owner faces in trying to capture feedback.

Table 5: Big Box vs. Little Box: Baseline vs. Delayed Sole Owner Decision Frequency

	Baseline Big Box			Baseline Little Box			5 year Entry/exit frequency Big Box			5 year Entry/exit frequency Little Box		
	Average	Stdev	N	Average	Stdev	N	Average	Stdev	N	Average	Stdev	N
Wealth	14,892,498	218,261	50	14,721,389	234,792	50	12,369,235	311,696	50	11,410,830	574,291	50
C Wealth	7,190,082	141,639	50	9,101,447	197,731	50	6,939,829	64,963	50	6,668,401	307,213	50
Ha Wealth	3,819,098	166,913	50	3,033,790	192,550	50	2,399,751	182,538	50	2,087,911	203,705	50
He Wealth	2,844,946	161,190	50	1,754,155	69,813	50	1,698,175	124,329	50	1,690,059	94,460	50
R Wealth	1,038,373	78,898	50	831,998	72,233	50	1,331,479	33,132	50	964,459	68,208	50
Catch	2,327,787	82,249	50	2,132,502	48,527	50	1,720,429	58,469	50	1,524,944	86,795	50
C Catch	1,034,233	14,751	50	992,636	13,529	50	932,546	12,166	50	799,371	48,843	50
Ha Catch	603,832	36,758	50	515,260	20,649	50	342,315	27,823	50	294,257	29,671	50
He Catch	472,912	36,011	50	400,700	23,715	50	247,858	19,506	50	255,110	16,319	50
R Catch	216,811	4,128	50	223,906	6,929	50	197,711	5,619	50	176,207	6,874	50
Mature Bio	9,227,880	91,335	50	9,419,838	69,772	50	9,761,751	64,710	50	10,249,268	117,763	50
C Mat Bio	1,786,390	95,732	50	2,033,196	120,584	50	2,092,568	54,187	50	3,299,004	264,128	50
Ha Mat Bio	1,474,734	54,901	50	1,362,988	91,031	50	1,786,526	27,124	50	1,849,281	106,273	50
He Mat Bio	1,361,465	43,611	50	1,510,953	100,768	50	1,697,755	25,690	50	1,588,944	62,056	50
R Mat Bio	1,045,789	64,293	50	1,248,957	71,164	50	1,637,548	38,293	50	1,176,990	52,276	50
Sl Mat Bio	3,559,502	173,492	50	3,263,744	86,170	50	2,547,354	94,767	50	2,335,049	124,657	50
Fleet Size	1,048	87	50	917	42	50	604	35	50	480	37	50
C Fleet	394	26	50	351	21	50	298	11	50	166	24	50
Ha Fleet	277	27	50	265	19	50	128	12	50	107	14	50
He Fleet	236	26	50	181	22	50	98	9	50	108	10	50
R Fleet	141	9	50	120	6	50	81	4	50	100	3	50
System Bio	13,427,987	34,676	50	13,487,762	19,188	50	13,630,474	17,290	50	13,645,251	18,126	50
C Bio	3,213,549	74,632	50	3,394,163	111,795	50	3,350,449	42,567	50	4,416,185	225,378	50
Ha Bio	2,652,404	32,800	50	2,391,478	118,374	50	2,688,149	23,161	50	2,707,018	129,561	50
He Bio	1,822,274	27,471	50	1,940,301	101,028	50	2,056,528	21,930	50	1,938,200	65,603	50
R Bio	2,180,259	95,249	50	2,498,076	117,044	50	2,987,993	50,844	50	2,248,800	92,374	50
Sl Bio	3,559,502	173,492	50	3,263,744	86,170	50	2,547,354	94,767	50	2,335,049	124,657	50

Averages are for the last 400-years of N runs

fisheries in both models, and consequently, average mature biomass increased (in all species besides "sand lance") (Table 5). Average system biomass (ages 2+) similarly increased in both models (Table 5). In the Big Box, system biomass (ages 2+) increased for all species besides "haddock" and "sand lance" (Table 5). In the Little Box, system biomass (ages 2+) decreased in "redfish" and "sand lance" (Table 5). In both models, the fleet size decreased, but the Big Box continued to have a larger fleet than the Little Box (Table 5). The slight advantage seen in the Big Box (i.e., in wealth generated) appears to be due to the increased catch, which resulted from the slightly larger fleet. This suggests that the Big Box's greater ability to switch makes it able to employ more boat profitably.

Delay the Implementation of the Sole Owner's Decision

When the sole owner's entry or exit decision was not implemented for 5 years, less wealth was generated in both models (Table 6). The loss was significantly greater in the Little Box compared to the Big Box (Table 6). The Big Box generated slightly more average total wealth compared to the Little Box under this simulation, in all fisheries (Table 6). Average catch was also less in both models under this simulation and was greater in the Big Box (Table 6). Average mature biomass was higher in the Little Box (in the "cod" fishery) (Table 6). Average system biomass (ages 2+) decreased only slightly in both models (Table 6). In both models, "cod" and "sand lance" system biomass increased (Table 6). Average Fleet size increased in both models and was greater in the Little Box (Table 6), in the "haddock" and "herring" fisheries.

Error in the Information Used by Sole Owner

Introducing error into the models (i.e., degrading the quality of feedback), resulted in a slight decrease in average total wealth in the Little Box model and a slight increase in average total wealth in the Big Box model (Table 7). Thus, the Big Box model continued to generate slightly more wealth compared to the Little Box (Table 7). The Little Box

Table 6: Big Box vs. Little Box: Baseline vs. Delay Implementation of Sole Owner Decision

| | Baseline | | | | | | Delay Sole Owner Implementation | | | | | |
| | Big Box | | | Little Box | | | Big Box | | | Little Box | | |
	Average	Stdev	N	Average	Stdev	N	Average	Stdev	N	Average	Stdev	N
Wealth	14,892,498	218,261	50	14,721,389	234,792	50	14,521,019	160,413	50	10,324,020	489,492	50
C Wealth	7,190,082	141,639	50	9,101,447	197,731	50	7,024,334	133,323	50	5,629,718	304,873	50
Ha Wealth	3,819,098	166,913	50	3,033,790	192,550	50	3,898,365	101,444	50	1,735,754	336,653	50
He Wealth	2,844,946	161,190	50	1,754,155	69,813	50	3,048,831	103,651	50	2,053,447	240,994	50
R Wealth	1,038,373	78,898	50	831,998	72,233	50	560,555	108,480	50	931,906	77,949	50
Catch	2,327,787	82,249	50	2,132,502	48,527	50	2,427,385	39,999	50	2,059,026	42,175	50
C Catch	1,034,233	14,751	50	992,636	13,529	50	1,043,669	11,137	50	894,585	21,682	50
Ha Catch	603,832	36,758	50	515,260	20,649	50	653,360	20,854	50	495,640	13,662	50
He Catch	472,912	36,011	50	400,700	23,715	50	538,899	22,247	50	466,986	20,779	50
R Catch	216,811	4,128	50	223,906	6,929	50	191,457	7,730	50	201,814	10,287	50
Mature Bio	9,227,880	91,335	50	9,419,838	69,772	50	9,217,227	43,884	50	9,549,873	54,869	50
C Mat Bio	1,786,390	95,732	50	2,033,196	120,584	50	1,769,128	59,962	50	2,440,823	109,587	50
Ha Mat Bio	1,474,734	54,901	50	1,362,988	91,031	50	1,380,731	29,660	50	1,196,222	88,446	50
He Mat Bio	1,361,465	43,611	50	1,510,953	100,768	50	1,274,793	25,638	50	1,211,316	92,591	50
R Mat Bio	1,045,789	64,293	50	1,248,957	71,164	50	799,585	54,307	50	1,164,230	42,057	50
Sl Mat Bio	3,559,502	173,492	50	3,263,744	86,170	50	3,992,990	128,875	50	3,537,283	94,842	50
Fleet Size	1,048	87	50	917	42	50	1,219	55	50	1,287	79	50
C Fleet	394	26	50	351	21	50	427	16	50	415	28	50
Ha Fleet	277	27	50	265	19	50	329	17	50	403	42	50
He Fleet	236	26	50	181	22	50	293	17	50	327	39	50
R Fleet	141	9	50	120	6	50	171	7	50	143	7	50
System Bio	13,427,987	34,676	50	13,487,762	19,188	50	13,358,943	19,744	50	13,437,263	18,657	50
C Bio	3,213,549	74,632	50	3,394,163	111,795	50	3,223,878	56,882	50	3,735,812	107,658	50
Ha Bio	2,652,404	32,800	50	2,391,478	118,374	50	2,612,807	29,878	50	2,178,006	106,738	50
He Bio	1,822,274	27,471	50	1,940,301	101,028	50	1,775,637	21,070	50	1,663,483	92,000	50
R Bio	2,180,259	95,249	50	2,498,076	117,044	50	1,753,630	99,973	50	2,322,680	70,491	50
Sl Bio	3,559,502	173,492	50	3,263,744	86,170	50	3,992,990	128,875	50	3,537,283	94,842	50

Averages are for the last 400-years of N runs

Table 7: Big Box vs. Little Box: Baseline vs. Informational Errors

| | Baseline | | | | | | Information Errors | | | | | |
| | Big Box | | | Little Box | | | Big Box | | | Little Box | | |
	Average	Stdev	N	Average	Stdev	N	Average	Stdev	N	Average	Stdev	N
Wealth	14,892,498	218,261	50	14,721,389	234,792	50	14,992,370	212,236	50	14,277,339	227,243	50
C Wealth	7,190,082	141,639	50	9,101,447	197,731	50	6,908,292	171,248	50	7,261,890	173,671	50
Ha Wealth	3,819,098	166,913	50	3,033,790	192,550	50	4,066,948	93,864	50	3,139,493	228,200	50
He Wealth	2,844,946	161,190	50	1,754,155	69,813	50	3,178,739	130,177	50	2,724,144	115,114	50
R Wealth	1,038,373	78,898	50	831,998	72,233	50	838,409	113,504	50	1,151,812	92,844	50
Catch	2,327,787	82,249	50	2,132,502	48,527	50	2,506,130	58,454	50	2,287,937	59,008	50
C Catch	1,034,233	14,751	50	992,636	13,529	50	1,054,735	11,120	50	1,011,199	20,611	50
Ha Catch	603,832	36,758	50	515,260	20,649	50	680,775	26,791	50	562,424	25,004	50
He Catch	472,912	36,011	50	400,700	23,715	50	556,516	31,802	50	491,222	21,208	50
R Catch	216,811	4,128	50	223,906	6,929	50	214,105	6,250	50	223,092	7,299	50
Mature Bio	9,227,880	91,335	50	9,419,838	69,772	50	9,037,941	61,189	50	9,316,128	84,382	50
C Mat Bio	1,786,390	95,732	50	2,033,196	120,584	50	1,572,840	78,130	50	2,135,890	129,132	50
Ha Mat Bio	1,474,734	54,901	50	1,362,988	91,031	50	1,343,171	51,737	50	1,282,165	102,496	50
He Mat Bio	1,361,465	43,611	50	1,510,953	100,768	50	1,261,485	42,080	50	1,259,695	79,622	50
R Mat Bio	1,045,789	64,293	50	1,248,957	71,164	50	896,695	63,320	50	1,118,431	72,405	50
Sl Mat Bio	3,559,502	173,492	50	3,263,744	86,170	50	3,963,750	186,270	50	3,519,948	109,314	50
Fleet Size	1,048	87	50	917	42	50	1,259	83	50	1,075	59	50
C Fleet	394	26	50	351	21	50	455	24	50	356	22	50
Ha Fleet	277	27	50	265	19	50	343	26	50	311	26	50
He Fleet	236	26	50	181	22	50	298	26	50	274	27	50
R Fleet	141	9	50	120	6	50	163	8	50	135	7	50
System Bio	13,427,987	34,676	50	13,487,762	19,188	50	13,345,290	32,006	50	13,435,710	26,785	50
C Bio	3,213,549	74,632	50	3,394,163	111,795	50	3,051,750	65,992	50	3,525,442	113,880	50
Ha Bio	2,652,404	32,800	50	2,391,478	118,374	50	2,601,793	35,609	50	2,361,007	127,523	50
He Bio	1,822,274	27,471	50	1,940,301	101,028	50	1,770,333	29,413	50	1,724,303	78,765	50
R Bio	2,180,259	95,249	50	2,498,076	117,044	50	1,957,665	106,540	50	2,305,010	119,380	50
Sl Bio	3,559,502	173,492	50	3,263,744	86,170	50	3,963,750	186,270	50	3,519,948	109,314	50

Averages are for the last 400-years of N runs

generated higher average profits in the "redfish" fishery (Table 7). In the Big Box, wealth increased in the "haddock" and "herring" fisheries, while in the Little Box wealth increased in "herring" fishery and remained the same in the "haddock" fishery (Table 7).

Average catch in both models also increased and there was more catch in the Big Box than in the Little Box (Table 7). In the Big Box, average catch increased in all fisheries besides "redfish", while in the Little Box average catch increased in all fisheries (Table 7). Average mature biomass and system biomass (ages 2 and up) declined in both models, and there was more biomass in the Little Box than in the Big Box (Table 7). Average fleet size also increased in both models (in all fisheries), with slightly more boats in the Big Box fisheries (Table 7).

Delay Information getting to Sole Owner

When the sole owner based its decision on 5-year old data (i.e., delays due to data collection and analysis), average total wealth in the Big Box sole was nearly the same as was generated under baseline conditions (Table 8). The Little Box, on the other hand, generated significantly less wealth (Table 8). In the Big Box, improvements were seen in the "haddock" and "herring" fisheries, while in the Little Box all fisheries produced less wealth (Table 8). Average total catch increased slightly in the Big Box, while it decreased in the Little Box (Table 8). In the Little Box, all fisheries experienced a decline in catch (Table 8). In the Big Box, average mature biomass did not change significantly, but there was an increase in average mature biomass in the Little Box (Table 8). In the Little Box, total mature biomass increased for all species besides "sand lance" (Table 8). Average system biomass (ages 2 and up) did not change and remained similar between models (Table 8). Average total fleet size declined significantly with information delays in the Little Box, while in the Big Box fleet size remained nearly the same (Table 8).

Table 8: Big Box vs. Little Box: Baseline vs. Information Delay

| | Baseline | | | | | | Information Delay | | | | | |
| | Big Box | | | Little Box | | | Big Box | | | Little Box | | |
	Average	Stdev	N	Average	Stdev	N	Average	Stdev	N	Average	Stdev	N
Wealth	14,892,498	218,261	50	14,721,389	234,792	50	15,059,988	224,900	50	9,354,834	1,082,520	50
C Wealth	7,190,082	141,639	50	9,101,447	197,731	50	7,175,397	178,719	50	5,235,537	529,203	50
Ha Wealth	3,819,098	166,913	50	3,033,790	192,550	50	3,929,198	178,057	50	1,752,541	377,554	50
He Wealth	2,844,946	161,190	50	1,754,155	69,813	50	2,946,907	178,726	50	1,457,619	316,297	50
R Wealth	1,038,373	78,898	50	831,998	72,233	50	1,008,487	72,995	50	909,164	135,478	50
Catch	2,327,787	82,249	50	2,132,502	48,527	50	2,387,548	94,808	50	1,409,304	184,544	50
C Catch	1,034,233	14,751	50	992,636	13,529	50	1,045,349	17,819	50	720,020	81,700	50
Ha Catch	603,832	36,758	50	515,260	20,649	50	628,816	41,177	50	298,704	61,619	50
He Catch	472,912	36,011	50	400,700	23,715	50	495,762	40,701	50	227,440	57,961	50
R Catch	216,811	4,128	50	223,906	6,929	50	217,622	5,539	50	163,139	18,722	50
Mature Bio	9,227,880	91,335	50	9,419,838	69,772	50	9,154,548	117,606	50	10,223,148	193,795	50
C Mat Bio	1,786,390	95,732	50	2,033,196	120,584	50	1,735,165	124,317	50	3,053,345	401,595	50
Ha Mat Bio	1,474,734	54,901	50	1,362,988	91,031	50	1,439,530	65,487	50	1,570,332	280,564	50
He Mat Bio	1,361,465	43,611	50	1,510,953	100,768	50	1,331,276	49,676	50	1,687,377	209,936	50
R Mat Bio	1,045,789	64,293	50	1,248,957	71,164	50	1,010,952	63,480	50	1,448,408	435,000	50
Sl Mat Bio	3,559,502	173,492	50	3,263,744	86,170	50	3,637,626	187,992	50	2,463,686	270,821	50
Fleet Size	1,048	87	50	917	42	50	1,102	101	50	592	100	50
C Fleet	394	26	50	351	21	50	410	31	50	246	43	50
Ha Fleet	277	27	50	265	19	50	295	31	50	154	43	50
He Fleet	236	26	50	181	22	50	251	29	50	102	35	50
R Fleet	141	9	50	120	6	50	146	10	50	90	23	50
System Bio	13,427,987	34,676	50	13,487,762	19,188	50	13,406,552	43,311	50	13,651,437	56,515	50
C Bio	3,213,549	74,632	50	3,394,163	111,795	50	3,185,431	98,445	50	4,158,200	351,806	50
Ha Bio	2,652,404	32,800	50	2,391,478	118,374	50	2,644,429	39,032	50	2,370,553	355,348	50
He Bio	1,822,274	27,471	50	1,940,301	101,028	50	1,804,484	30,167	50	2,036,278	219,117	50
R Bio	2,180,259	95,249	50	2,498,076	117,044	50	2,134,582	88,890	50	2,622,720	614,949	50
Sl Bio	3,559,502	173,492	50	3,263,744	86,170	50	3,637,626	187,992	50	2,463,686	270,821	50

Averages are for the last 400-years of N runs

Conclusions - Imperfect Sole Owner Conditions

In general, these results suggest when the sole owner's ability to make and implement decision is made more difficult, the Big Box sole owner is better able to capture and respond to feedback from the system (Figure 5). Under these imperfect conditions, the Big Box sole owner is slightly better able to track changes in biomass than the Little Box sole owner.

Figure 5: Average Total Wealth Under Imperfect Sole Owner Simulations.
Error Bars indicate standard deviations.
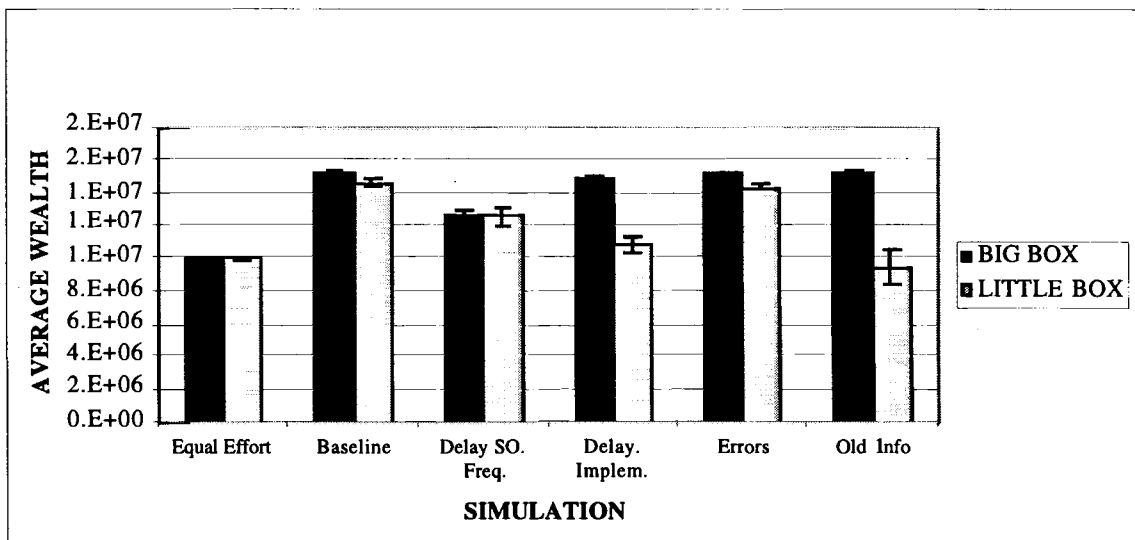
In each of the imperfect sole owner scenarios, the Little Box sole owner does worse in the "cod" fishery, compared to its baseline. Recall that it is probably the fast growing, stable nature of the "cod" population that allows the Little Box to do so well in that fishery under baseline conditions. When the Little Box sole owner's ability to make decisions is impaired, it is less able to take advantage of the "cod" population's fast growth and stability.

It is important to note again that the variability in the system is not very reflective of real world system variability. These results suggest that if system variability were increased, then the Little Box sole owner would have a more difficult time trying to capture and

respond to feedback in the system. It was not possible to test this hypothesis with the model because increasing variability was impossible without killing of one or more of the harvested species. Nonetheless, we suspect that as the variability is increased, the Little Box sole owner would have a more difficult time dealing with system variability than the Big Box sole owner.

Limited Entry

In considering these results we wanted to try to determine the importance of entry and exit to the sole owner in both models. In the limited entry system with switching, initial fleet sizes were set approximately to the fleet sizes observed under baseline conditions and the same for each model (total fleet size in both models was 1000 boats). Switching still occurred within the system in the Big Box model and across systems in the Little Box model. The initial total fleet size was slightly less than the baseline average in the Big Box and slightly more than the baseline average in the Little Box (Table 9). In the Little Box, only the "herring" fleet was slightly reduced. With switching, average fleet size in the Big Box that resulted in the limited entry system was less boats in all fisheries besides "cod". In the Little Box, average total fleet size was less in all fisheries compared to baseline averages.

The Big Box did much worse under the limited entry system (Table 9). Average total wealth in the Big Box decreased significantly compared to the baseline conditions and was significantly less than was generated in the Little Box. Only "redfish" wealth increased in the Big Box (Table 9), this is possibly due to decreased costs with the smaller fleet. On the other hand, average wealth increased in the Little Box (Table 9). The two fisheries in the Little Box that produced less wealth were "cod" and "redfish" (Table 9). Average catch decreased in the Big Box (in all fisheries besides "redfish") and increased in

the Little Box (in the "cod" fishery) (Table 9). Again, this may be due to the smaller fleet in the Big Box and the larger fleet in the Little Box (compared to baseline averages).

Average mature biomass increased in the Big Box and decreased in the Little Box (Table 9). In the Big Box, "herring" and "redfish" mature biomass increased, while in the Little Box, only "herring" mature biomass increased (Table 9). In both models, average system biomass (ages 2 and up) remained nearly the same as under baseline (Table 9). However, in the Little Box there was more "sand lance" biomass than in the Big Box. In the Big Box, average system biomass decreased for all species besides "redfish" and "herring" (Table 9). In the Little Box, "herring", "haddock", and "sand lance" system biomass increased (Table 9). Again, these results are probably due to the size of the fleet. If the Big Box fleet were set slightly larger, average catch would probably increase (generating more revenue, and possibly higher profits depending on the total costs) and the biomass of the harvested species would be reduced. It is not surprising that the only species to increase in size was "herring", which had a smaller fleet compared to its baseline. If the Little Box were allocated fewer vessels then there may be more harvestable biomass and less "sand lance".

The results do not indicate whether entry and exit is more important to one model than the other. However, the results do suggest that the size of the fleet set by a limited entry system is important and should be considered when implementing such a management system. For example, if the Big Box were given a slightly larger fleet then it would likely have done better. The fleet size set under this simulation was probably too small for the Big Box sole owner and "good" for the Little Box. Given the dynamic and complex nature of marine systems, determining the levels that effort should be limited to in a limited entry system is a difficult, if not impossible, task. Consequently, unlike conventional fisheries models, the models used in this thesis suggest that altering effort levels may not be sufficient enough for capturing feedback and learning in complex marine systems.

Table 9: Big Box vs. Little Box: Baseline vs. Limited Entry

| | Baseline | | | | | | Limited Entry | | | | | |
| | Big Box | | | Little Box | | | Big Box | | | LITTLE BOX | | |
	Average	Stdev	N	Average	Stdev	N	AVE	STDEV	N	AVE	STDEV	N
Wealth	14,892,498	218,261	50	14,721,389	234,792	50	14,247,432	74,695	50	15,094,584	99,114	50
C Wealth	7,190,082	141,639	50	9,101,447	197,731	50	6,497,110	62,730	50	7,173,514	95,274	50
Ha Wealth	3,819,098	166,913	50	3,033,790	192,550	50	3,601,011	65,791	50	4,262,190	108,872	50
He Wealth	2,844,946	161,190	50	1,754,155	69,813	50	2,704,118	52,496	50	2,878,885	57,516	50
R Wealth	1,038,373	78,898	50	831,998	72,233	50	1,445,194	26,112	50	779,995	55,633	50
Catch	2,327,787	82,249	50	2,132,502	48,527	50	2,224,743	7,470	50	2,309,458	9,911	50
C Catch	1,034,233	14,751	50	992,636	13,529	50	992,384	8,294	50	1,037,351	9,527	50
Ha Catch	603,832	36,758	50	515,260	20,649	50	564,340	9,250	50	626,219	10,887	50
He Catch	472,912	36,011	50	400,700	23,715	50	430,264	7,364	50	447,889	5,752	50
R Catch	216,811	4,128	50	223,906	6,929	50	237,755	3,921	50	197,999	5,563	50
Mature Bio	9,227,880	91,335	50	9,419,838	69,772	50	9,179,656	17,902	50	9,283,058	22,979	50
C Mat Bio	1,786,390	95,732	50	2,033,196	120,584	50	1,545,141	6,512	50	1,729,079	15,871	50
Ha Mat Bio	1,474,734	54,901	50	1,362,988	91,031	50	1,473,159	7,667	50	1,669,968	29,006	50
He Mat Bio	1,361,465	43,611	50	1,510,953	100,768	50	1,435,750	6,869	50	1,492,986	19,136	50
R Mat Bio	1,045,789	64,293	50	1,248,957	71,164	50	1,360,012	7,001	50	879,915	24,724	50
Sl Mat Bio	3,559,502	173,492	50	3,263,744	86,170	50	3,365,594	32,720	50	3,511,109	39,012	50
Fleet Size	1,048	87	50	917	42	50	1,000	0	50	1,000	0	50
C Fleet	394	26	50	351	21	50	428	3	50	400	0	50
Ha Fleet	277	27	50	265	19	50	255	4	50	250	0	50
He Fleet	236	26	50	181	22	50	200	3	50	200	0	50
R Fleet	141	9	50	120	6	50	117	2	50	150	0	50
System Bio	13,427,987	34,676	50	13,487,762	19,188	50	13,463,067	9,208	50	13,429,117	8,227	50
C Bio	3,213,549	74,632	50	3,394,163	111,795	50	2,927,977	16,659	50	3,163,237	29,005	50
Ha Bio	2,652,404	32,800	50	2,391,478	118,374	50	2,593,229	19,667	50	2,921,017	50,703	50
He Bio	1,822,274	27,471	50	1,940,301	101,028	50	1,874,485	11,483	50	1,949,561	25,027	50
R Bio	2,180,259	95,249	50	2,498,076	117,044	50	2,701,781	18,057	50	1,884,193	52,973	50
Sl Bio	3,559,502	173,492	50	3,263,744	86,170	50	3,365,594	32,720	50	3,511,109	39,012	50

Averages are for the last 400-years of N runs

Summary and Future Considerations

The purpose of this thesis was to explore and learn about feedback in complex marine systems. Exploration of these two models suggest that allocating harvesting rights at the system level may allow users to capture and respond to variability in complex marine systems. Under initial sole owner conditions, feedback is captured and understood perfectly. It appears that under perfect sole owner conditions (i.e., when feedback is captured and not ambiguous) both management approaches are approximately equal in their abilities to deal with system variability. As the sole owner's ability to capture and understand feedback is made more imperfect (as is the case in real world situations), the Big Box approach to management appears to result in slightly better decision-making. Continued exploration of the models would have provided a better understanding of these results, and consequently greater learning about the nature of the feedback problem in complex systems.

Future explorations with these models should continue to look at the conditions of imperfect feedback and imperfect response abilities, specifically how the sole owner is able to cope under increasingly difficult conditions. For example, the profit trend signals to the sole owner what is happening in the biological sector of the model because profits are a function of the harvestable biomass available. If the signal between profits and the biological status of the resource included more "noise", it would be more difficult for the sole owner to harvest the resource in the most sustainable manner. "Noise" could be easily introduced by non-constancies in prices, costs, and harvesting efficiencies. Another way to make the sole owner's response ability more difficult in the model would be to introduce costs associated with switching fisheries (both across regions and across species). Similarly, exploring the assumption of non-perfectly fungible capital, by giving vessels a 20-year life span, would offer insight into the feedback problem by making it costly and difficult to undo entry/exit decisions.

It would also have been useful to explore questions regarding the significance of recruitment variability in the fish populations. Although it is impossible to make the species more variable without killing off one or more species, the individual growth rates and natural mortality rates of the species could be altered to determine their influence on the sole owner's ability to capture and respond to feedback. In particular, it would be interesting to reduce the growth rate of "sand lance" so that it was not able to quickly take up available space in the system. This would likely influence the variability in the other species. It would also be interesting to find out what kind of variability would result if all five species were harvested or if a different species was chosen as the unharvested species (e.g., "redfish", with a much slower growth rate and turn over rate). The question of how individual life history strategies influence system variability, and thus the sole owner's ability to understand and respond to feedback is important and should be explored further.

Another interesting aspect of complex systems that was not explore in this thesis, but could easily be explored with the models is flow between subsystems. Flow between subsystems is one way feedback is lost. Larval drift was built into the model, but was turned off for the purposes of this thesis. If turned on, the consequence of leakages between subsystems could be explored. Depending on how larval drift is modeled, this leakage could result in additional "noise" that the sole owner would have to deal with. Also, adding an additional subsystem would not be extremely difficult and would allow for more sophisticated exploration of flows between subsystems, and of the feedback problem in general.

There are some questions raised with these models that cannot be addressed without altering the entire design of the models. If time permitted, or if the models were to be recreated from scratch, the most fundamental change would be to include system factors. Although the models improve upon the conventional assumption that recruitment is determined only by changes in the adult populations, by including the influence of a system induced constraint, the model is only concerned with feedback gained from changes in

fishing effort. Other kinds of feedback that are not species specific include, among other things, habitat, spatial distributions, and stock structure. Much of the ecosystem-based management and scientific literature is focused on the importance of managing these system factors. For example, Fogarty and Murawski (1998) noted the significance of protecting habitat structure and complexity. Ames (1997) described how spatial distributions and stock structure are important indicators of ecosystem health. Wilson et al. (1999) also described how scale misperceptions can lead to a different kind of overfishing than is typically recognized in fisheries management. Pauly et al (2000) described the need to prevent what was called "fishing down the foodweb", which is described as a decline in the average trophic level. These are only a few of many examples of kinds of system factors that are important to understanding the feedback problem in complex marine systems and should be included in future models.

Many marine resource management agencies (federal, regional, and state) are moving towards or are considering an ecosystem approach in their attempt to provide a holistic framework for managing fisheries.[38] An ecosystem approach to management, which would include humans as part of the system, needs to appreciate "multispecies relationships as opposed to the single-species focus inherent in the notion of maximum sustainable yield or optimal yield," or the conventional approach to management (Langton and Haedrich, 1997). The Big Box approach to management explored in this paper is more compatible with such an ecosystem approach than the conventional, Little Box approach to management.

The results of this thesis suggest that in highly variable complex marine systems we can better capture feedback and consequently learn more by observing changes that occur at the system level than at the species level. This suggests that a Big Box licensing system should be considered as part of an ecosystem approach to management.

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[38] See Ecosystem-Based Fishery Management. A Report to Congress by the National Marine Fisheries Service Ecosystem Principles Advisory Panel as mandated by the Magnuson-Stevens Fisheries Conservation and Management Act. July 1998.

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71

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APPENDIX

SUMMARY OF MODEL SIMULATIONS

Table A.1: Summary of Big Box Model Simulations

	Open Access	Same Effort	Baseline	Delay Freq.	Delay Implem.	Info. Errors	Delay Info.	Limit Entry
PROFITS ALL	119,502.23	15,077,081.62	14,892,498.43	12,369,234.72	14,521,019.11	14,992,369.76	15,059,988.36	14,247,432.39
PROFS 1	65,028.42	7,527,215.62	7,429,276.77	6,181,828.64	7,252,907.31	7,481,623.09	7,526,778.59	7,129,066.86
PROFS2	66,362.61	7,549,866.00	7,463,221.67	6,187,406.07	7,268,111.80	7,510,746.67	7,533,209.78	7,118,365.53
PROF C	737,903.83	7,133,770.13	7,190,081.62	6,939,829.11	7,024,333.72	6,908,291.92	7,175,396.85	6,497,110.23
PROF HA	347,318.32	4,300,887.26	3,819,098.01	2,399,751.43	3,898,365.35	4,066,947.74	3,929,197.83	3,601,010.82
PROF HE	857,739.21	2,874,349.71	2,844,945.91	1,698,174.82	3,048,831.30	3,178,738.71	2,946,907.07	2,704,117.61
PROF R	0.00	768,074.52	1,038,372.89	1,331,479.36	560,555.31	838,409.02	1,008,486.61	1,445,193.74
CATCH ALL	2,705,801.06	2,307,708.16	2,327,786.68	1,720,429.08	2,427,384.83	2,506,130.16	2,387,548.42	2,224,743.24
CATCH 1	1,350,597.45	1,152,721.56	1,155,760.36	859,193.18	1,213,708.73	1,250,474.32	1,193,480.95	1,112,906.69
CATCH2	1,355,203.61	1,154,986.60	1,172,026.32	861,235.89	1,213,676.11	1,255,655.84	1,194,067.47	1,111,836.55
CATCH C	1,089,846.00	1,033,377.01	1,034,232.64	932,545.70	1,043,668.82	1,054,734.81	1,045,348.82	992,384.45
CATCH HA	744,856.11	630,088.73	603,831.79	342,314.82	653,360.22	680,774.54	628,816.06	564,339.62
CATCH HE	870,957.63	447,434.97	472,911.59	247,857.93	538,898.66	556,515.89	495,761.98	430,263.91
CATCH R	141.32	196,807.45	216,810.65	197,710.62	191,457.13	214,104.92	217,621.56	237,755.26
MAT BIO ALL	9,387,707.66	9,291,024.19	9,227,879.68	9,761,750.55	9,217,227.07	9,037,941.12	9,154,548.00	9,179,656.46
MAT BIO1	4,698,193.05	4,648,312.63	4,626,038.64	4,881,755.41	4,607,030.54	4,520,699.58	4,577,010.16	4,587,356.91
MAT BIO2	4,689,514.61	4,642,711.56	4,601,841.04	4,879,995.13	4,610,196.53	4,517,241.54	4,577,537.84	4,592,299.55
MAT BIOC	1,089,846.00	1,722,295.02	1,786,389.72	2,092,567.66	1,769,127.81	1,572,839.59	1,735,165.26	1,545,140.94
MATBIO HA	744,856.11	1,680,236.60	1,474,733.66	1,786,525.91	1,380,731.49	1,343,170.75	1,439,529.56	1,473,158.82
MAT BIO HE	870,957.63	1,491,449.90	1,361,465.13	1,697,755.04	1,274,793.03	1,261,485.44	1,331,275.54	1,435,750.02
MAT BIO R	282.25	874,699.79	1,045,789.45	1,637,547.61	799,584.76	896,695.07	1,010,951.56	1,360,012.28
MAT BIO SL	6,681,765.68	3,522,342.87	3,559,501.73	2,547,354.33	3,992,989.99	3,963,750.27	3,637,626.09	3,365,594.39
FLEET SIZE	3,767.26	1,000.00	1,048.17	604.38	1,219.10	1,258.62	1,101.94	1,000.00
C BOAT	1,332.43	400.00	394.03	298.20	426.54	454.88	409.76	428.34
HA BOAT	986.93	250.00	277.40	127.92	329.40	342.60	294.87	255.30
HE BOAT	1,095.43	200.00	235.52	97.55	292.52	298.30	251.34	199.82
R BOAT	352.47	150.00	141.22	80.70	170.64	162.83	145.97	116.54
2 UP BIO ALL	12,986,070.11	13,432,320.93	13,427,986.72	13,630,473.51	13,358,942.88	13,345,290.33	13,406,552.50	13,463,066.78
2UP BIO	6,494,213.20	6,716,594.49	6,717,996.71	6,815,836.18	6,678,461.18	6,672,859.02	6,703,634.94	6,730,378.28
2UPBIO2	6,491,856.91	6,715,726.43	6,709,990.01	6,814,637.34	6,680,481.69	6,672,431.31	6,702,917.56	6,732,688.50
C BIO	2,694,464.11	3,150,920.25	3,213,548.97	3,350,449.20	3,223,878.42	3,051,749.50	3,185,431.49	2,927,976.85
HA BIO	2,002,674.26	2,938,818.68	2,652,403.73	2,688,149.31	2,612,806.97	2,601,793.08	2,644,429.24	2,593,229.44
HE BIO	1,606,312.02	1,947,608.65	1,822,273.77	2,056,528.00	1,775,637.06	1,770,332.68	1,804,483.52	1,874,485.00
R BIO	854.03	1,872,630.48	2,180,258.52	2,987,992.67	1,753,630.44	1,957,664.80	2,134,582.17	2,701,781.10
SL BIO	6,681,765.68	3,522,342.87	3,559,501.73	2,547,354.33	3,992,989.99	3,963,750.27	3,637,626.09	3,365,594.39

Averages are for the last 400-years of N runs

75

Table A.2: Summary of Little Box Model Simulations

	Same Effort	Baseline	Delay Freq.	Delay Implem	Info. Errors	Delay Info.	Limit Entry
PROFITS ALL	15,104,357.83	14,429,574.55	11,410,829.62	10,324,019.52	14,277,338.73	9,354,834.04	15,094,584.43
PROFS 1	7,552,605.18	7,219,326.35	5,698,417.34	5,151,612.17	7,130,547.28	4,676,632.17	7,549,906.61
PROFS2	7,551,752.60	7,210,248.15	5,712,412.24	5,139,306.66	7,146,791.40	4,678,201.83	7,544,677.78
PROF C	7,186,867.06	7,504,343.59	6,668,400.73	5,629,717.78	7,261,889.51	5,235,536.87	7,173,514.06
PROF HA	4,284,761.02	3,139,435.85	2,087,911.32	1,735,754.44	3,139,493.45	1,752,540.51	4,262,190.08
PROF HE	2,876,780.70	2,584,407.05	1,690,058.90	2,053,446.93	2,724,144.13	1,457,619.32	2,878,885.26
PROF R	755,949.01	1,201,388.02	964,458.63	931,906.31	1,151,811.60	909,164.01	779,994.99
CATCH ALL	2,310,435.78	2,202,790.58	1,524,944.18	2,059,026.20	2,287,937.41	1,409,304.36	2,309,458.44
CATCH 1	1,155,260.52	1,101,979.57	761,705.02	1,030,639.72	1,143,086.20	704,718.65	1,155,231.39
CATCH2	1,155,175.26	1,100,811.00	763,239.16	1,028,386.48	1,144,851.21	704,585.71	1,154,227.05
CATCH C	1,038,686.71	1,006,571.42	799,371.48	894,585.39	1,011,199.49	720,020.40	1,037,351.41
CATCH HA	628,476.10	526,840.99	294,256.55	495,640.41	562,424.01	298,704.12	626,219.01
CATCH HE	447,678.07	450,013.68	255,109.55	466,986.43	491,222.13	227,440.40	447,888.53
CATCH R	195,594.90	219,364.48	176,206.60	201,813.97	223,091.78	163,139.44	197,999.50
MAT BIO ALL	9,291,724.11	9,411,753.95	10,249,267.87	9,549,873.32	9,316,128.22	10,223,148.12	9,283,057.98
MAT BIO1	4,645,246.98	4,706,052.72	5,125,822.25	4,776,605.33	4,655,018.71	5,112,221.88	4,638,213.04
MAT BIO2	4,646,477.12	4,705,701.23	5,123,445.62	4,773,268.00	4,661,109.52	5,110,926.24	4,644,844.94
MAT BIOC	1,731,144.51	2,211,805.49	3,299,003.91	2,440,822.71	2,135,889.82	3,053,344.69	1,729,079.38
MATBIO HA	1,675,936.27	1,399,287.52	1,849,280.57	1,196,221.81	1,282,164.60	1,570,332.49	1,669,968.43
MAT BIO HE	1,492,260.23	1,294,699.04	1,588,944.07	1,211,316.11	1,259,694.59	1,687,376.61	1,492,985.86
MAT BIO R	869,310.67	1,186,553.92	1,176,990.38	1,164,229.82	1,118,430.83	1,448,408.20	879,915.47
MAT BIO SL	3,523,072.42	3,319,407.98	2,335,048.94	3,537,282.87	3,519,948.38	2,463,686.13	3,511,108.85
FLEET SIZE	1,000.00	949.79	479.83	1,287.42	1,075.25	592.28	1,000.00
C BOAT	400	320.17	165.66	414.52	356.26	245.58	400
HA BOAT	250	266.12	106.83	403	310.59	154.31	250
HE BOAT	200	239.47	107.63	327.07	273.51	102.1	200
R BOAT	150	124.03	99.7	142.84	134.89	90.28	150
2 UP BIO ALL	13,431,360.25	13,480,366.55	13,645,251.34	13,437,263.06	13,435,710.28	13,651,437.44	13,429,117.24
2UP BIO	6,715,600.61	6,740,360.51	6,822,784.41	6,719,063.20	6,716,148.95	6,826,053.65	6,713,434.72
2UPBIO2	6,715,759.63	6,740,006.04	6,822,466.93	6,718,199.86	6,719,561.33	6,825,383.79	6,715,682.53
C BIO	3,167,218.98	3,581,396.63	4,416,185.15	3,735,812.26	3,525,441.74	4,158,200.45	3,163,236.57
HA BIO	2,931,101.96	2,452,765.38	2,707,017.95	2,178,005.79	2,361,006.78	2,370,553.32	2,921,017.34
HE BIO	1,948,650.87	1,733,251.81	1,938,199.66	1,663,482.61	1,724,303.12	2,036,277.96	1,949,560.99
R BIO	1,861,316.02	2,393,544.75	2,248,799.64	2,322,679.52	2,305,010.26	2,622,719.58	1,884,193.50
SL BIO	3,523,072.42	3,319,407.98	2,335,048.94	3,537,282.87	3,519,948.38	2,463,686.13	3,511,108.85

Table A.3: Summary of Average Change in Recruitment for all Simulations

BIG BOX

	Same Effort	Baseline	Delay Freq.	Delay Implem.	Info. Errors	Delay Info.	Limit Entry
Cod 1	0.17	0.17	0.18	0.17	0.17	0.17	0.17
Cod 2	0.17	0.17	0.17	0.17	0.17	0.17	0.16
Ha 1	0.22	0.22	0.25	0.22	0.21	0.22	0.22
Ha 2	0.22	0.22	0.25	0.21	0.21	0.22	0.22
He 1	0.38	0.39	0.42	0.39	0.38	0.38	0.38
He 3	0.37	0.22	0.42	0.38	0.38	0.38	0.38
R 1	0.05	0.05	0.06	0.05	0.05	0.05	0.05
R 2	0.05	0.05	0.05	0.05	0.05	0.05	0.05
SL 1	1.20	1.19	1.12	1.10	1.09	1.15	1.23
SL 2	1.19	1.17	1.13	1.08	1.09	1.16	1.22
HARV 1	0.05	0.05	0.04	0.06	0.06	0.05	0.05
HARV 2	0.05	0.05	0.04	0.06	0.06	0.05	0.05

LITTLE BOX

	Same Effort	Baseline	Delay Freq.	Delay Implem.	Info. Errors	Delay Info.	Limit Entry
Cod 1	0.17	0.17	0.17	0.18	0.17	0.18	0.17
Cod 2	0.16	0.18	0.17	0.18	0.17	0.18	0.17
Ha 1	0.21	0.23	0.24	0.26	0.24	0.29	0.22
Ha 2	0.21	0.23	0.24	0.26	0.24	0.28	0.21
He 1	0.37	0.4	0.42	0.4	0.39	0.48	0.36
He 3	0.37	0.4	0.42	0.39	0.41	0.51	0.37
R 1	0.05	0.05	0.06	0.06	0.05	0.06	0.05
R 2	0.05	0.05	0.06	0.06	0.05	0.06	0.05
SL 1	1.19	1.24	1.04	1.12	1.2	1	1.18
SL 2	1.19	1.25	1.04	1.09	1.2	0.99	1.2
HARV 1	0.05	0.05	0.04	0.05	0.05	0.04	0.05
HARV 2	0.05	0.05	0.04	0.05	0.05	0.04	0.05

Averages are for the last 400-years of N runs

BIOGRAPHY OF THE AUTHOR

Teresa Johnson, daughter of Ray and Marion Johnson, was born in Colorado Springs, Colorado on October 9, 1975. She was raised in Thomaston, Maine and graduated from Georges Valley High School in 1993. She attended Bowdoin College and graduated in 1997 with an A.B. degree in Biology and Government. After working at the Island Institute in Rockland, Maine, she entered the newly created Marine Policy graduate program in the School of Marine Sciences at The University of Maine in the fall of 1998. After receiving her degree, Teresa plans to pursue a PhD in Ecology and Evolution at Rutgers, The State University of New Jersey. Teresa is a candidate for the Master of Science degree in Marine Policy from The University of Maine in May, 2001.