Resilience, Environmental Variability, and Institutions in a Multi-Species Artisanal Fishery

ABSTRACT: Social-Ecological Resilience is an increasingly central paradigm for understanding resource sustainability. While previous works on resilience have observed that a system may be forced over a critical threshold by a sudden shock or slow stressors, natural variations may have similar results. This paper aims to better understand the effect of environmental variability on the resilience of fishery systems, and the important role that social institutions play. To explore these issues, we built upon a System Dynamics model by Bueno and Basurto of the mollusk fishery of the Seri Indian people in the Gulf of California, Mexico. In order to increase the resolution of the model, we incorporated the dynamics of the two dominant species in the fishery, several new institutional rules that the Seri use, and a number of key stochastic variables derived from empirical data. We found that modeling of multiple species stocks allows for a more realistic and more resilient picture of the system. However, while we expected stochasticity to be a detriment to resilience, we found that endogenous environmental variability can also increase resilience. We examine why this is, and discuss additional insights the study revealed about managing multiple-species artisanal fisheries.

KEYWORDS: resilience; stochasticity; social-ecological systems; system dynamics models; artisanal fisheries; Gulf of California, Mexico; common-pool resources

INTRODUCTION

Marine social-ecological systems worldwide are plagued with overexploitation and multiple stressors, and as a result many fisheries are in various states of collapse. (Freire 2005) But some fisheries have managed to maintain a higher degree of resilience in the face of these pressures. Resilience is the amount of disturbance or change a system can sustain without shifting from one system state to another, often more degraded, one. (Walker et. al. 2004) The resilience of social-ecological systems is often described as a combination of three characteristics: (1) the magnitude of shock that the system can absorb and remain within a given state; (2) the degree to which the system is capable of self-organization; (3) the degree to which the system can build capacity for learning and adaptation (Folke et al. 2002). Resilience has most commonly been examined with regards to the impact of exogenous and sudden shocks; the slow effect of endogenous feedback loops has received comparatively less attention. (Carpenter et. al. 2001) In such cases, the impact of natural variability, and indeed randomness, gains in importance and deserves further study.

Stochasticity and environmental variability are important elements in understanding resilience. Previous works on resilience have observed that a system may be forced over a threshold into another basin of attraction by a sudden shock, or simply by the slow degradation of the system. However, while shocks and stressors are critical to pushing a system close to a threshold, it may often be natural stochastic variations that push it over the edge. Stochasticity becomes central, then, to our understanding of *when and why* a shift or collapse in a system occurs. (Beisner 2003) Detecting the gradual erosion of the resilience is critical to assessing the vulnerability of a community or ecosystem to stochastic shocks (Scheffer et al. 2001).

Bueno and Basurto (2009) used a System Dynamics (SD) Model to study resilience in the context of the Callos de Hacha fishery of the Seri Indian people in the Gulf of California, Mexico. Their study demonstrated the role of very small, incremental endogenous changes in the relationship between ecological and socio-cultural variables in facilitating the collapse of a seemingly resilient system. In this study, we explore several major elements of the system not previously examined, using an expanded and revised model. The new model incorporates the population dynamics of the two dominant species of the fishery*, Atrina tuberculosa (AT)* and *Pinna rugosa (PR),* as well as additional feedback loops and institutional rules not considered by Bueno and Basurto 2009, and multiple stochastic variables and sources of delays.

Our study has two main hypotheses. First, we hypothesize that disaggregating the system into two species stocks would better capture the inherent resilience of the system—as Seri fishers are able to shift their harvest between the two species according to institutional rules based on their relative abundance. This hypothesis was tested by comparing the results in our model to those of Bueno and Basurto 2009, and by running the model with and without the institutional rules active. Second, we hypothesize that adding elements of environmental variability to the model would degrade the system's resilience, as the increased variability would increase the system's chances of crossing over a threshold into collapse, and that longer delays will increase that instability. In order to test these hypotheses, we ran a series of tests with different combinations of stochastic variables, delays, and rules active. Our results affirmed our first hypothesis, but disputed the second, as well as revealing additional insights about managing multiple-species artisanal fisheries. In the sections below, we discuss in more detail the additions of the model we outlined above, and then discuss in detail the results of our tests and the implications of our findings for the study of resilience and dynamic systems.

STUDY AREA (AND PREVIOUS WORK)

The northern part of Gulf of California is a unique marine biome in the heart of the Sonoran Desert, and is known internationally for its biological richness (Cudney-Bueno et al. 2009), with over 1200 km of desert coastline in the states of Sonora and Baja California in Mexico (Glenn et al. 2006). The Gulf is undergoing rapid development and the health of its diverse marine ecosystems is in question since the degradation of coastal habitats is already severe (Glenn et al 2006). The area around the the Infiernillo Channel, between the Sonora mainland and Tiburon Island, is a protected homeland area for the Seri Indians, and is relatively pristine compared to the rest of the Gulf of California (see Figure 1).

Figure 1: Location of the Infiernillo Channel, the Seri Village, and the Kino Viejo Village

In this region of there are two neighboring artisanal fisheries, the Seri fishery in the Infiernillo Channel and the Kino Viejo fishery just south of the Channel, but the latter has undergone dramatic declines in their fishery while the Seri fishery continues to thrive. Both communities harvest for *Callos de Hacha* (CDH), or Pen Shells, which are large sessile bivalve mollusks that live buried in the sand on the seafloor. Both communities use similar methods of harvesting, primarily diving using underwater breathing devices that are connected via a long hose to a small boat. Typically, a boat crew has one or two divers, plus another two people to steer the boat, monitor the air hoses, and handle the catch once it is brought to the surface. Yet while the Kino fishery was depleted, the Infiernillo Channel remains home to the most abundant CDH beds in the region. (Basurto 2005) This contrast leads to obvious management questions. If they are using the same techniques and harvesting the same organism, what makes the two systems different?

Extensive fieldwork and case studies have argued that the source of the difference lies within the local cultural institutions that the Seri have created to govern their common pool resources. These rules have been able to protect the system from collapsing and these fishing institutions have played a fundamental role in maintaining a regular level of harvest for approximately 30 years (Basurto 2005, 2006, 2008). Seri fishers have devised rules to limit the fishers' harvest, harvest locations, and who can enter and participate in the fishery. They have also created mechanisms to ensure that the rules are followed, including enforcement mechanisms against rule-breakers both from within and outside the community. (Basurto 2005) Additionally, the institutional rules ensure that oversupply or overharvesting problems can be solved quickly by shifting harvesting effort from one species to another, or by evicting Mexican fishers from outside the community. (Basurto 2008)

Models of fisheries, especially artisanal fisheries such as the Seri Callos de Hacha fishery, generally model the fishery as consisting of only one target species, which is modeled either a single stock or multiple stocks representing different age classes. Yet the Seri fishery actually includes two species—*Atrina tuberculosa* and *Pinna rugosa* (AT and PR, respectively). (A third pen shell species, *Atrina maura*, is also present in the environment, but was omitted from the study because it represents less than 1% of the annual harvest. (Basurto 2006) Both PR and AT are pellecypod mollusks of the Pinnidae family. AT is smaller and sells for a much higher price, because it is only sold fresh, while PR is often frozen (AT and PR are roughly analogous to the Bay Scallops and Sea Scallops, which may be more familiar to US and International audiences.) By disaggregating into two species stocks, with an immature and mature stock for each species, for four total stocks, we gain a richer and more realistic view of the system's resilience. The Seri have institutional rules that allow them to communally shift their emphasis from one species to the other, overcoming collective action problems. Moreover, separating the model into two species allows the incorporation of real biological differences between them, which may demand different management techniques.

METHODS

Model Structure

The basic model is a stock-flow model with four stocks and four pairs of key feedback loops. The full copy of the model is available on request; the full list of equations is provided in Appendix B. The model was built using the Vensim software, produced by Ventana Systems, Inc. (Vensim DSS 5.7 for Windows and Vensim PLE 5.10e for Mac OS X). . All the parameters and assumptions in the model are based in real data, to the extent feasible. Most of the parameter estimates have been revised since Bueno and Basurto (2009), or are all-new to this version of the model; a few are unchanged but have been verified as realistic. The underlying data was gathered through a combination of primary data collected by Basurto and colleagues in the Gulf of California over the past decade, secondary source literature review, and the informed estimates of experts in the field. The table in Appendix A lists all the relevant parameter estimates. A simplified causal feedback loop diagram below explains the major dynamics in the system:

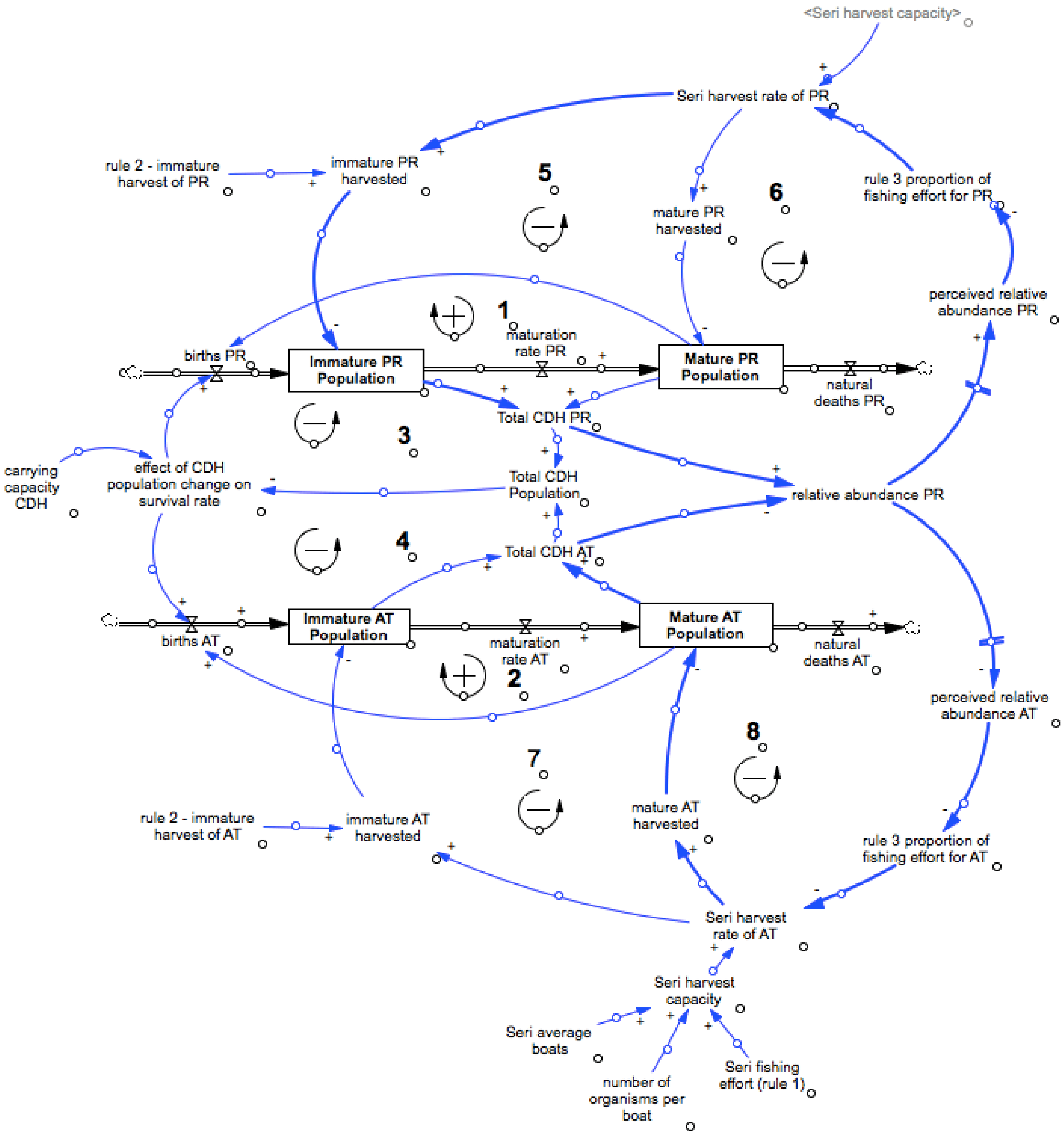

Figure 2: Causal Loop Diagram

Due to the two-species structure of our problem, most variables and all feedback loops are paired.

Two pairs of feedback loops drive the ecological component of the system. Population growth is driven by two positive, or reinforcing, feedback loops (loops 1 and 2), wherein an increase in births leads to a corresponding increase in the immature population, and then, within 1-2 years, the mature population, which then in turn leads to an increase in births. However, if the number of individuals taken through fishing plus natural causes repeatedly exceeds the number of individuals being born, the population will collapse. Population growth is moderated by two negative, or balancing, feedback loops (loops 3 and 4) where an increase in population causes a shrinking of the space available to both species, resulting in fewer newly born pen shells surviving, thus slowing the population growth. Because the species compete for a similar ecological niche, their survival rate is based on a shared carrying capacity. The *survival function* for newly recruited individuals is a smoothed curve based on the Beverton-Holt equation, and takes as its argument the *total CDH population divided by carrying capacity*. (Ricker 1975) Thus, through the interaction of their balancing feedback loops, the growth of one species, driven by its positive feedback loop, can force the other species' reinforcing feedback loop onto a collapse trajectory.

The two species compete for the same space and resources, and so share one carrying capacity, which was estimated in Bueno and Basurto by extrapolating the number of CDH found in one sample area to the total area. This may not seem ideal, since PR and AT grow to different sizes, and thus likely consume different amounts of food and occupy different amounts of physical space. However, in order to capture this level of detail while still allowing the two species to compete for food and resources, it would be necessary to model the carrying capacity for these populations dynamically. To do this for bivalves would require data on several characteristics of the habitat and physiology of these species (e.g., the flow rate of the channel, the food content suspended in the water, the growth rates of the mollusks, and water temperature over time)—and this data is simply not available in a systematic form for these species or for the Infiernillo Channel. (Botsford et al., 1994; Pineda, 1994, 1999, 2000; Pineda and Caswell, 1997; Pineda and Lopez, 2002)

Institutional Rules

The Seri have several institutional rules for governing their common pool resource. Five rules were explicitly or implicitly modeled:

1. A rule governing the number of days during the year spent fishing pen shells
2. Rules governing the harvesting of immature individuals.
3. A rule governing the balancing of fishing effort between the two species.
4. Rules governing areas that are not fished, such as seagrass beds, which are difficult and hazardous to gather pen shells in, and sandbars, which are reserved for subsistence fishing by women and children.
5. Rules governing the allowing of outsider fishing boats into the territory, and governing how those outsiders must operate while in the fishery.

Rules one and two are implemented as exogenous constants to the model. *Rule 1,* or fishing effort, is generally set to 50%, but can be decreased to compensate for environmental shocks. Generally, immature individuals make up less than 30% of the catch; *rule 2* represents management strategies to keep immature harvest to this level or well below. In particular, we modeled the effect on the system of a rule banning harvesting of any immature Pina rugosa due to its slower maturation rate, which is discussed below.

Rule three forms the balancing feedback loops labled 5, 6, 7 & 8. In rule three, a decrease in the relative perceived abundance of one species below a (socially determined) critical level causes the Seri to reduce their harvesting of that species in favor of the other. Seri fishers report that they can, and do, distinguish between the two species on the sea floor prior to harvesting, and can shift their harvesting accordingly. Loops 5 and 6 are the balancing feedback loops for immature and mature PR, respectively, while loops 7 and 8 are the balancing feedback loops for immature and mature AT. For clarity's sake only, we have made the arrows in loops 5 and 8 bold, to demonstrate the immature and mature feedback loop structure, respectively. We model this rule in two mutually exclusive ways. The simplest way, hereafter referred to as the *threshold rule*, sets a minimum threshold for the *perceived abundance* on the sea floor—25% for AT, and 40% for PR, due to its greater abundance and lesser commercial value. When the fishers perceive that one species is below this level, they decrease their harvest of it by 85% and 95% respectively. Because of the time needed for the community to notice *and* respond to the change in relative abundance, *perceived relative abundance* is modeled with a one-month *delay*, which is reasonable based on conversations with Seri fishers.

The second mutually exclusive approach to rule 3, hereafter referred to as the OFT rule, uses a Type III Functional Response curve to determine relative fishing effort. We applied optimal foraging theory to create a curve along which the Seri shift their harvest effort based on relative availability, just as predators will switch from one prey to another based on the relative availability, using a type III functional response curve (see figure 4) "Optimal foraging models assume that a forager's decisions made during foraging are formulated to maximize short-term gains, whether in energy (for animals and subsistence hunters/fishers) or revenue (for commercial artisanal fishers).” (Stephens & Krebs, 1986) As currently implemented in the model, the only input is the perceived abundance, without incorporating kilocalories (kcals) expended and gained or costs incurred and profit earned, as other studies have done. (Bene and Tewfik 2001, Aswani 1998)

Because PR and AT are the only species being modeled, and all questions of abundance are relative, the same curve drives harvesting effort for both species. The OFT curve based on the idea that the Seri have certain thresholds, below which they reduce their harvesting, in part to allow that species to replenish, and in part because that species is simply too infrequently found to be worth concentrating on. As noted above, AT is more valuable, and they will be more likely to expend effort catching it at lower densities. Thus, When the Seri perceive the relative abundance if PR be less than 40%, they reduce the percentage of overall fishing effort they devote to PR to only 5%, and when they perceive the relative abundance of AT to be only 25%, they devote 15% of their overall effort to catching AT. In between, the curve converges on a level of effort that matches the relative abundance of the two species. These percentages are then multiplied by the total amount of catch the Seri boats are capable—*harvest capacity*—of to determine the actual apportionment of effort. These harvest rates are then multiplied by the density of the respective species to determine the actual harvest.

The rule about seagrass beds is implemented implicitly in the model by reducing the harvest by a percentage equal to that of the area covered by seagrass. The sandbars are simply not considered to be part of the geographical area within the bounds of the model.

Just as the Seri manage their own fishing effort, they also regulate how many outsider boats are allowed in their territory—and reserve the right to evict them on short notice, which is a perennial source of tension. A Seri fisherman must ride on each outsider boat to ensure it follows the community's rules. The increase in number of boats in the channel is one of the main stressors on Seri's CDH fishery, and it is by modeling this increase that we test the resilience of our model. Moreover, not all outsiders follow the rules; we have accounted for this by creating a variable, *outsider boat percentage* that controls how many boats are outsider boats, which have the distinction of not being affected by rules 2 and 3. This rule was used to model the effect on the system of fishing without these rules being in place. The influx of outsiders is modeled as an exogenous constant. We leave the implementation of any more complex, dynamic rules governing outsiders to future studies.

INCORPORATING STOCHASTICITY INTO THE DYNAMIC MODEL

Systems Dynamics models have sometimes been criticized as being overly deterministic, with the outcomes resulting purely from the differential equations defined in the model. Social-ecological systems are not deterministic, nor are they precisely at an equilibrium; rather, they are constantly bouncing around a 'point of attraction,' pushed by both minor and major changes. (Walker et. al. 2004) Variability in the environment is never truly random, despite how it may appear; it is always based on a complex intersection of variables. In order to better capture environmental variability, we have replaced constants with a set of random numbers derived from probability distribution functions (PDF) in a couple key areas. The PDFs are random normal functions whose mean and standard deviation are derived from real data collected by Basurto. We term this fluctuation *stochasticity*, to distinguish this approach from pure randomness, and have introduced it to the areas of lifespan and fishing luck.

In Bueno and Basurto 2009, both AT and PR were modeled as having a constant lifespan of 10 years, including a one-year maturation period. However, a literature review suggests that the species, which differ greatly in size, may also differ in lifespan. Unfortunately, natural populations of these species have not been studied, with the exception of some research on the reproductive cycle. (Baqueiro and Castagna 1988; Noguera and Gomez 1972) Scholars have reported that *AT* and related species grow rapidly and reach sexual maturation rate at one year of age. (Bueno and Basurto 2009) The genus *Atrina* reaches sexual maturity at ~10 cm in shell length (Ahumada-Sempoal et al. 2002), which suggests that the AT harvested in the Channel had a chance to reproduce at least once before harvesting, as that the great majority of them (70.2% n = 3261) measured at least twice the minimum size for sexual maturity (average size= 20.8, SD = 2.53). PR can reach an age of at least 12 years, and may live up to 20, like *Pinna noblis. Spondylus calcifer*, another similar species, also lives to at least 12 years but reproduces only after taking 2.5 to 4 years to mature. (Moreteau and Vicente 1982; Butler et al. 1993)

As a conservative estimate, we modeled *AT's mature lifespan* as a random normal function with an average of nine years (because it takes one year to mature) and standard deviation of two years. *PR's mature lifespan* is modeled with a random normal function with an average of 12 years and a standard deviation of 3 years, with a time to mature of 2 years We acknowledge that the realism added by this approach is limited by the structure of SD models. An agent-based model would assign a lifespan to each individual mollusk. In a SD model, however, the stock is not disaggregated into individual agents, so instead model variable pulls a random number from the PDF at each time-step (DT), which results in a variable number of individuals being subtracted from the stock via natural death at a given DT. Aggregated over time this results in a plausible approximation of environmental variability.

The other place we introduced Stochasticity is in the *fishing luck* variable, which captures those influences on the success of a given harvest not captured by other areas of the model, such as weather, uneven geographic distribution of good fishing sites, malfunctioning equipment, skill of the crew, or turbidity of the water. Fishing teams tend to choose minimum-risk strategies because of these occurrences, but that still does not guarantee every day will be a success. Fishing luck is modeled as a random normal distribution oriented around one with a standard deviation of 40% that was derived from the variation in harvests over time in Seri pen shell harvest data collected by Basurto and colleagues in 2000, 2001, and 2009.

RESULTS

The traditional and frequently used form of sensitivity analysis has been to vary model parameters and to observe how behavior changes. This is a very useful procedure for model testing, learning, and validation (Moxnes 2002). In our experiments, we compared model runs with deterministic and stochastic lifetime and/or fishing luck variables, and combined these with the different formulations of institutional rules 2 and 3, for a total of 24 experiments. In each scenario we looked both at the disturbance needed to engender collapse, and the time needed to recover if that disturbance lifted. We used a binary notation to make it easier to keep track of the different experiments.

Table 1: Results of Experiment Set #1, Looking at the number of boats needed to engender collapse.

Experi-ment #	Experi-ment binary	Stochastic Adult Lifetime	Stochastic Fishing Luck	Seri Threshold Abundance rule (rule 3)	Seri OFT Abundance Rule (rule 3)	Seri PR immature harvest rule (rule 2)	Max # of boats before CDH collapse
18	11011	x	x		x	x	52
21	10011	x			x	x	49
8	11010	x	x		x		44
19	00011				x	x	44
20	01011		x		x	x	44
6	10010	x			x		43
10	01010		x		x		42
12	00010				x		39
7	11100	x	x	x			29
16	11001	x	x			x	29
17	11101	x	x	x		x	29
5	10100	x		x			27
15	01001		x			x	27
23	10101	x		x		x	27
3	01000		x				26
4	11000	x	x				26
9	01100		x	x			26
14	100001	x				x	26
24	01101		x	x		x	26
2	10000	x					25
11	00100			x			25
13	00001					x	23
22	00101			x		x	22
1	00000						21

The base case is the model in a deterministic mode, with no feedbacks or rules active (in this scenario, *Mature AT lifespan* is set to the constant of 9, *Mature PR lifespan* to the constant 13, and *fishing luck* set to 1). In this setup, it takes 21 boats to overharvest the system to the point of collapse within 100 years, though the *P. rugosa* population heads towards collapse almost immediately, as it is overharvested and outcompeted by *A. tuberculosa*, (see figure 2), even when the overall CDH population is stable. We will return to how to sustain the PR population with rule 2 below.

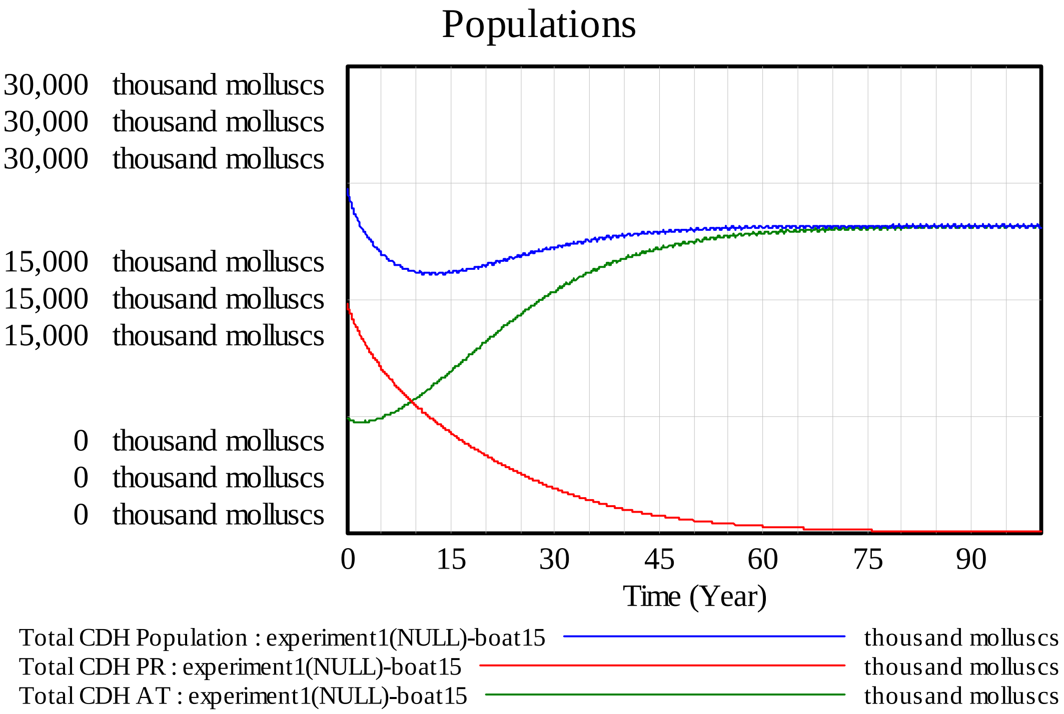

Figure 2: *Total CDH, PR, and AT populations with 15 boats and no stochasticity or institutional rules active.*

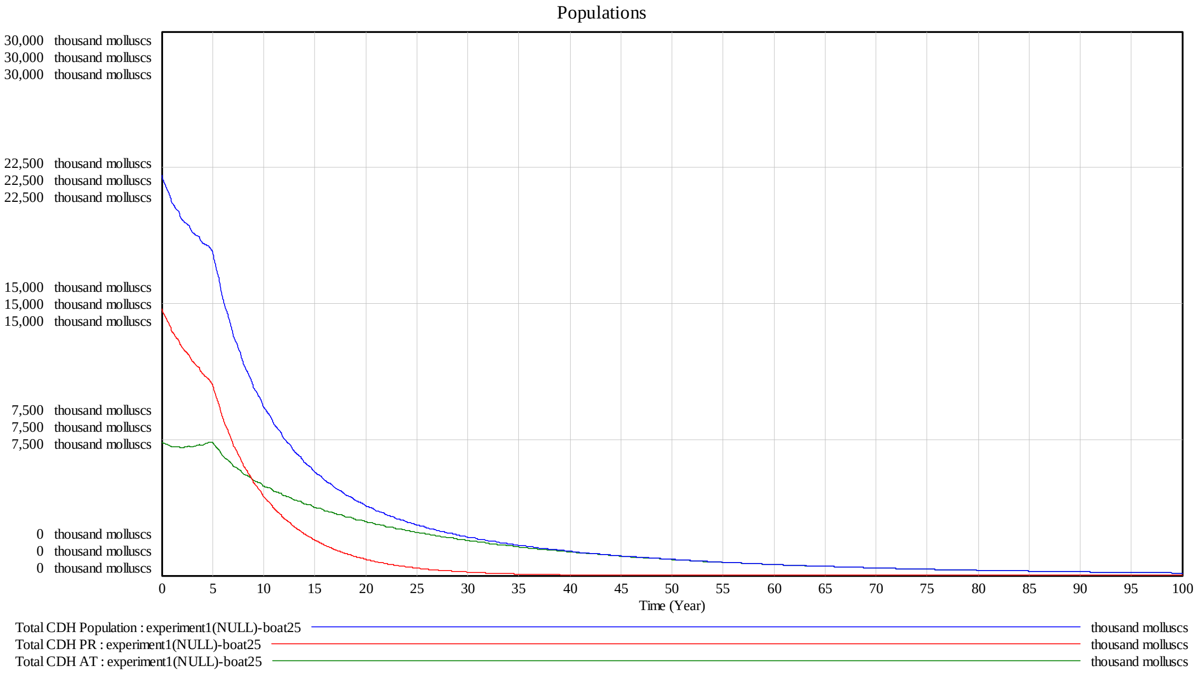

Figure 3: Experiment 1—the base case--with 25 boats; well past the point of collapse.

In experiment 2, we switched the mature lifetime for AT and PR to be stochastic, with a mean of 9 and 13 and a standard deviation of 2 and 3, respectively. (The average lifetime for these species is modeled as 10 and 15, but the mature lifetime distribution is 9 and 13 because AT takes one year to reach maturity and PR takes 2 years.) The results show that adding stochasticity to the average lifetime makes the system slightly more resilient, requiring 26 boats to reach complete collapse. The same is true when mature lifespan is a deterministic constant but fishing luck in enabled. However, while the collapse scenario is unchanged, fishing luck does have a dramatic effect on the tons harvested, as shown in figure 4.

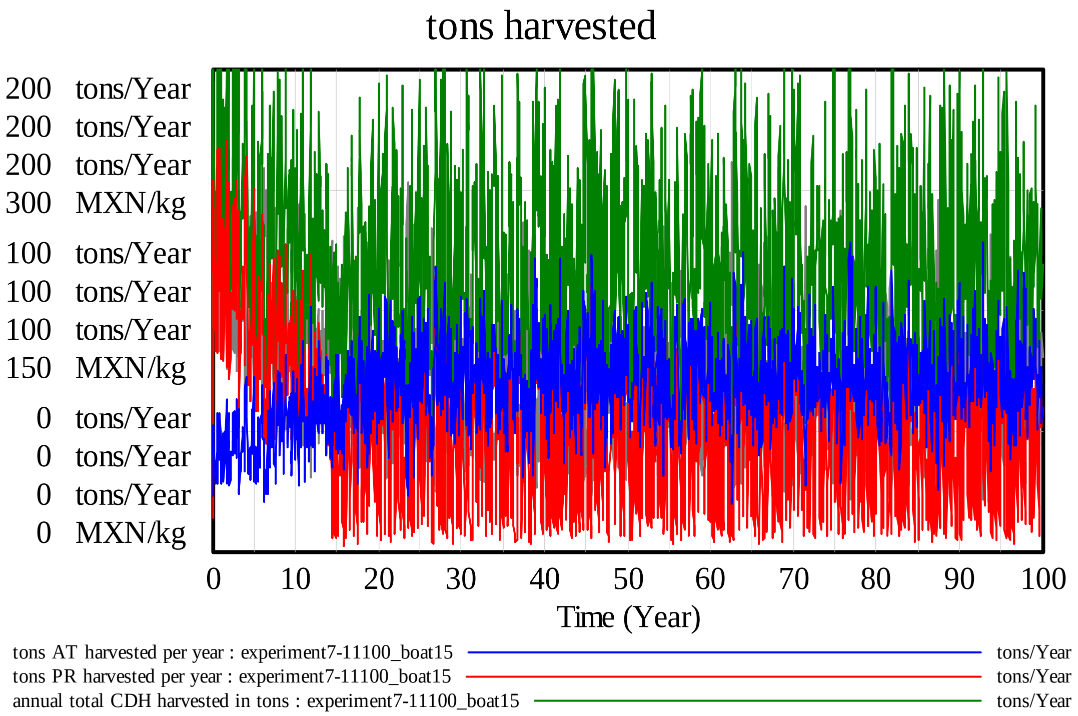

Figure 4: tons harvested of AT PR, and total CDH

Absent any institutional management strategy, PR's population suffers an early collapse, because it takes longer to mature and reproduces more slowly, and yet is being harvested at the same rate as AT. (This slower reproduction rate is a plausible but by no means certain interpretation of the natural system. It is possible that PR to reproduces at the same rate per year as AT, or even faster, since bivalves tend to spawn more, not less, as they get older and larger. However, if PR is set to reproduce faster by raising its fecundity rate, when no harvesting occurs, it will dominate the system and crowd out AT.) Empirical data indicates that the percentage of the total harvest that is made of immature individuals is usually well under 30%. When run without any immature harvesting limits, immature ATs make up an average of ~25% of the overall harvest, but immature PRs make up close to 40% of the overall harvest. This suggests that there is a need for an institutional limit on harvesting of immature PRs.

Figure 5 shows the effect on the *total CDH population* of using rule 2 to cut the harvest of immature by 25, 50, 75, or 100%.

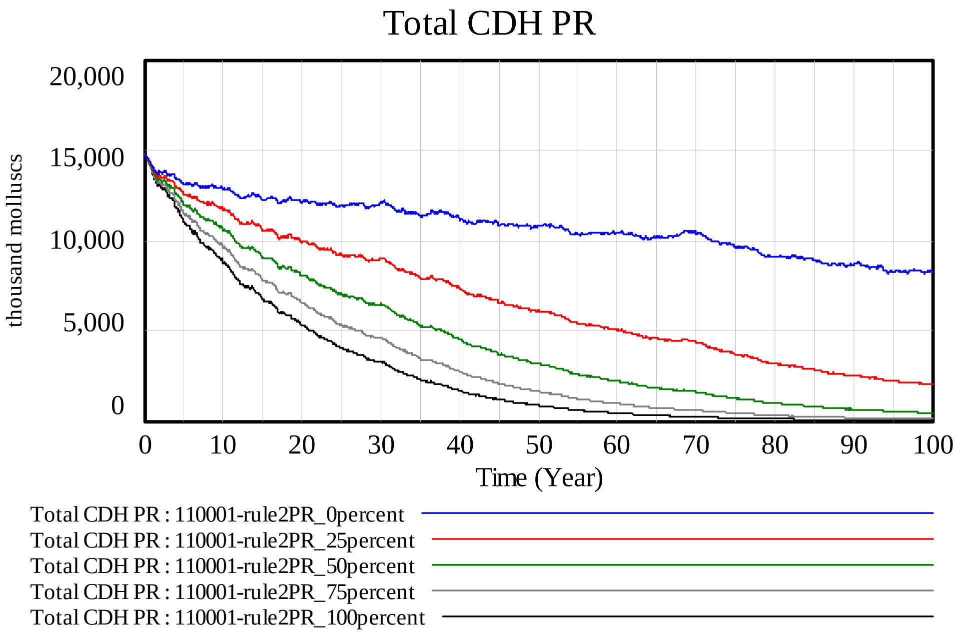

Figure 3: Total CDH population when harvesting either no immature individuals (0%), 25%, 50% or 75% as many as normal, and with no rule controlling immature harvest rate (100%).

By reducing the harvesting of immature specimens of P. rugosa, the Seri can compensate for the lower resilience of PR. Because more PRs are surviving, they occupy some of the space that AT could otherwise occupy, and the AT population does not surge. (Figure 12) This in turn increases the stress required to destabilize the system. However, this effect only occurs if immature ATs are harvested as normal. If the same rule 2 is applied to both species, such that no immature of either species are harvested, the PR population is once again out-competed by AT and collapses just as it does with no rule 2. In all of experiments where rule 2 in active, the rule is modeled as a complete ban on harvesting of *immature PR.*

Experiments 5-12 examined the effects of two different forms of institutional rule 3 for perceived abundance. This rule represents the Seri people's monitoring of the relative abundance of the two species, and their decision to cut the harvest of one species or the other if its relative abundance gets too low. The simple form of this is a pair of if-the-else formulations, where harvesting of PR is decreased by 95% when the Seri perceive its relative abundance to be less than 40% of the total CDH population, and the harvesting of AT is decreased by 85% when the Seri perceive its relative abundance to be less than 20%. Experiments 5, 7, 9, and 11 combine this rule with the combinations for stochastic and deterministic mature lifespan and fishing luck. At fifteen boats, this feedback loop stabilizes the PR population, as seen in figure 6:

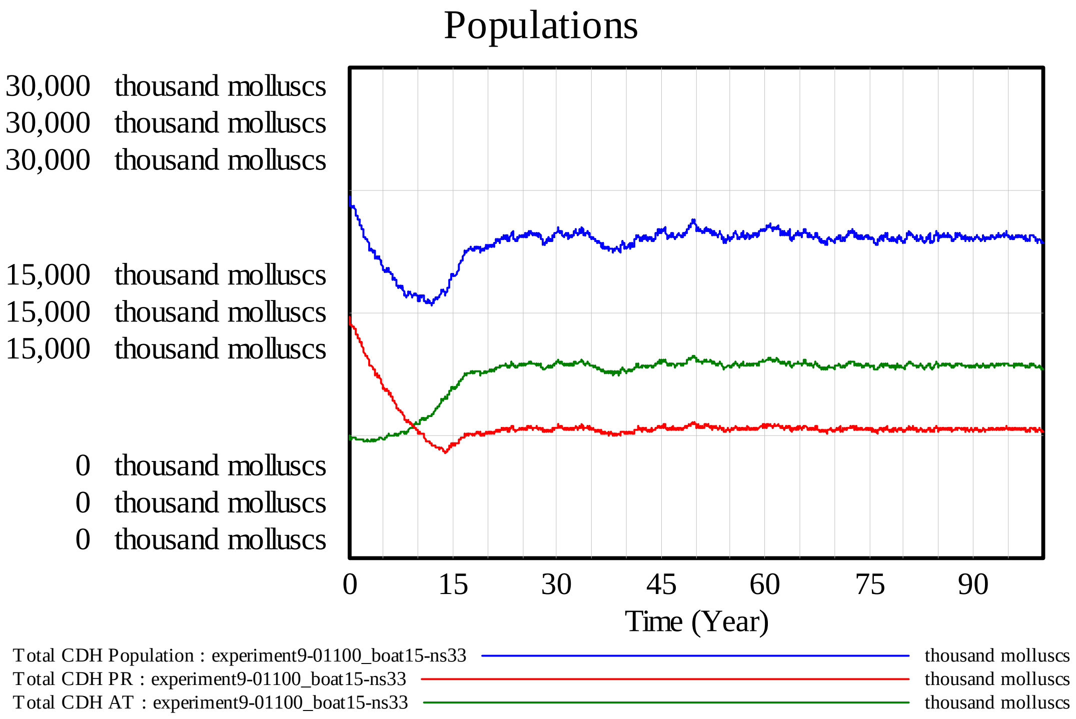

Figure 4: Populations for Experiment 5 (threshold rule 3, stochastic lifetime) with 15 boats

When no stochasticity is introduced, it takes 25 or 26 boats to collapse the system, just as in experiments 1-3. But with stochastic mature lifespan and the threshold rule, it takes 27 boats, and with both stochastic variables, it takes 29 boats. In all cases, just as with rule 2, the rule succeeds at its main goal of keeping PR from collapsing. Moreover, the slightly higher resilience of the overall CDH population indicates that allowing the Seri to trade off between the two species creates a more resilient system than with just one species.

As described in the methods section, rule 3 can also be modeled with a Type III functional response curve. The OFT curve causes the relative ratios of the two species to converge on 50/50, as seen in figure 7.

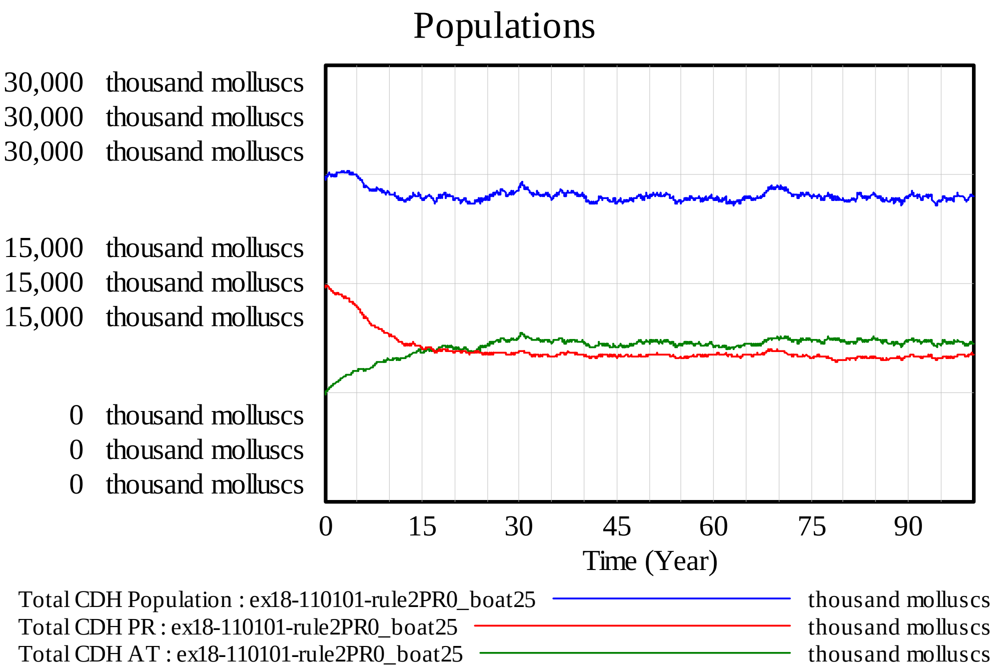

Figure 5: OFT model with stochasticity and no harvesting of immature PR

However, this formulation adds much greater resilience to the system. All OFT scenarios have maximum boat rates of *at least* 39 boats, and, when both lifetime and fishing luck are set as stochastic and harvesting of immature PR is prohibited according to rule 2, the maximum number of boats rises to 52 (see figure 8):

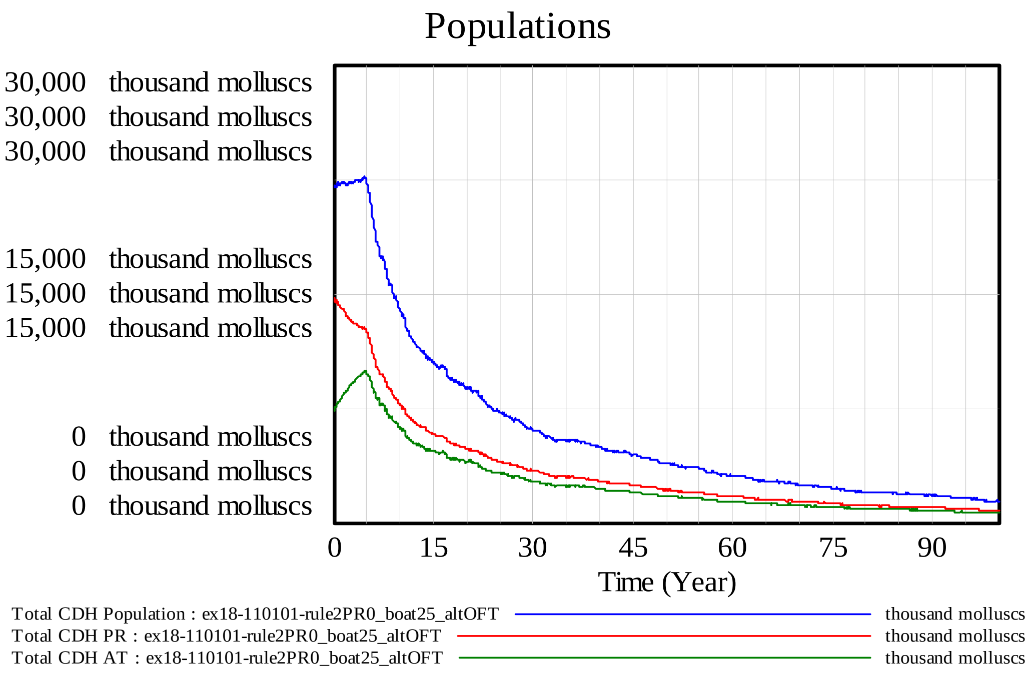

Figure 6: The final collapse of the system with an OFT-based rule 3, not immature PR harvesting, and stochasticity—only at 52 boats!

Resilience is not just a measure of how strong a disruption is required to push the system over a critical threshold; it is also a measure of the system's ability to bounce back. To look at this, we ran the many of the experiments again, with the boats set to increase from 15 to 25 in year 5 and then return to 15 in year 30, simulating what would happen if the Seri decided to no longer allow outside fishers into their channel. (As noted earlier, the Seri will sometimes revoke the rights of Mexicans to fish in the channel.) In order to compare like items, we only used the same number of maximum boats—25—in all scenarios, and only used scenarios whose natural collapse points were between 20 and 30 boats (thus excluding the OFT scenarios). We then looked at how many years it took the system to recover and stabilize. Results are shown in Table 2 and Figure 9. The spread is impressive; in the best four scenarios they CDH population recovered 35 years faster than in the base case.

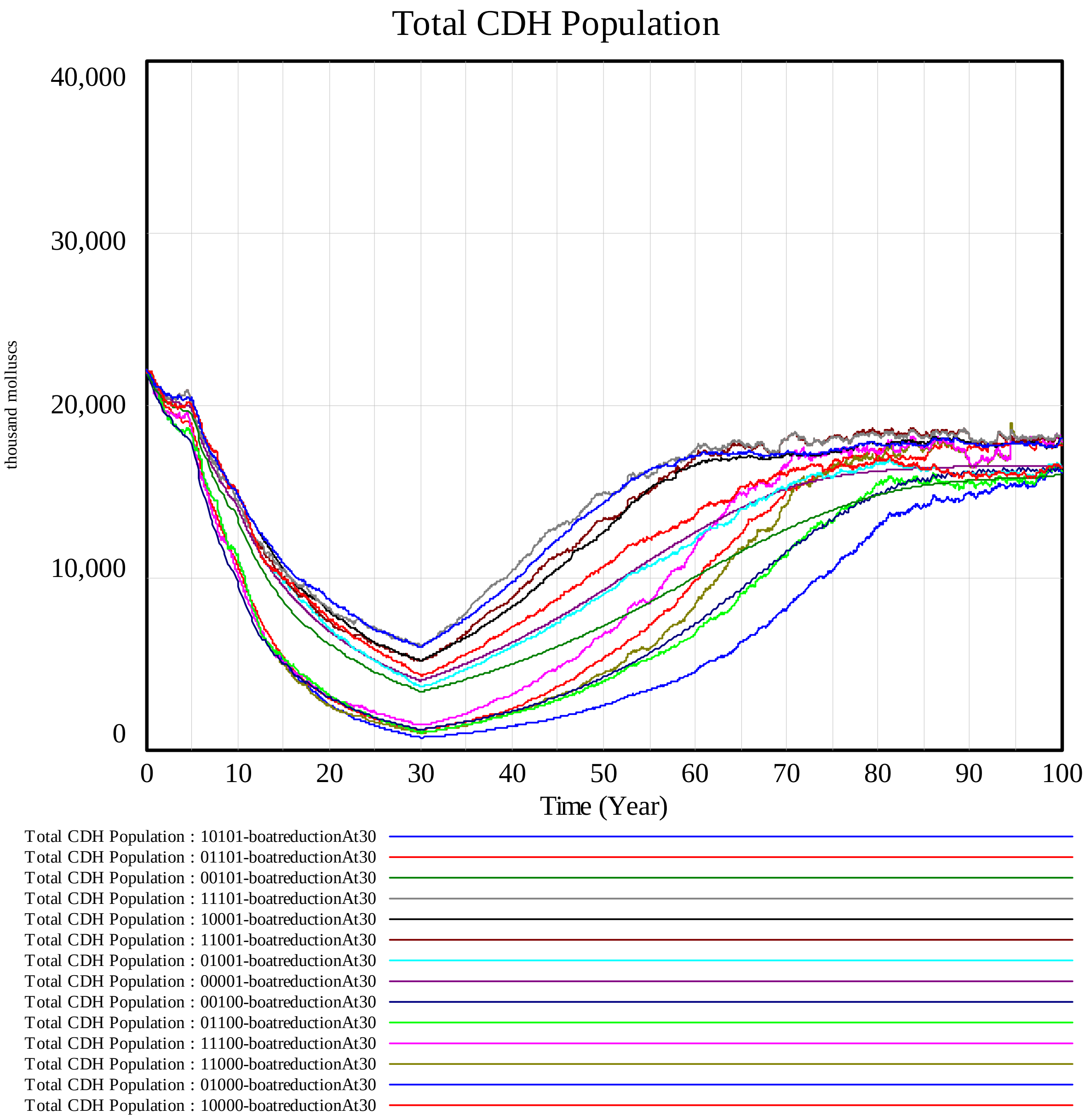

Figure 7: The decline and recovery of the total CDH population when boats increase from 15 to 25 at year 5 and then decrease back down to 15 at year 30. Note the two clusters of inflection points at year 30. Scenarios where the PR population did not collapse prior to year 30—and thus is able to recover—form the top cluster. Scenarios where the PR population collapsed and all the recovery comes from the AT population form the bottom cluster.

Experiment Number	Experiment binary	Stochastic Adult Lifetime	Stochastic Fishing Luck	Seri Threshold Abundance rule	Seri PR immature harvest rule	Years Required for recovery and stabilization.
17	11101	x	x	x	x	55
23	10101	x		x	x	55
16	11001	x	x		x	55
14	10001	x			x	60
24	01101		x	x	x	65
5	10100	x		x		70
7	11100	x	x	x		70
15	01001		x		x	70
2	10000	x				75
4	11000	x	x			75
13	00001				x	75
9	01100		x	x		80
22	00101			x	x	83
3	01000		x			85
11	00100			x		85
1	00000					90

Table 2: Recovery time experiments

The two important variables were the Stochastic Adult lifetime and the rule limiting harvesting of immature PR. The threshold abundance rule also had an impact strong. Again, the stochastic fishing luck had little influence over the results. Looking at the scenarios on the graph in figure, there are two clusters of minimum total CDH population: the higher one corresponds to scenarios where the population of PR has not been overfished to the pint of collapse, and recovers alongside AT; the lower one corresponds to the set of scenarios where the PR population collapsed, and the recovering population is almost entirely AT. It is thus clear that the survival of the PR population—ensured through *rule 2*, limiting harvesting of immature PR—is a necessary condition for a quicker recovery. But since scenario 13, with only rule 2 in effect, took 75 years to recover, this rule is clearly not sufficient. The stochastic average lifetime plays an equally critical role. Stochasticity in the lifespan has such a large positive effect on population recovery because it contributes to a higher regrowth rate, as discussed below.

DISCUSSION

The concept of resilience is all but meaningless without a rigorous definition. Therefore, it is important to be specific about *what exact system* is being examined (resilience *of what*) and *against what specific impacts* that system's resilience is measured (resilience *to what*). (Carpenter et. al. 2001) The answers are not always intuitive. It might appear that the system being studied is the CDH population, and we are examining the resilience of that ecological system to fishing pressure. However, because we are expressly looking at the Seri community's institutional rules as factors that help maintain or degrade resilience, it is more accurate to say that it is the resilience *of* the social-ecological system of the Seri CDH fishery *to* overfishing that is the subject of this paper. By drawing the system boundary around the entire social-ecological system rather than a subset of it, we see that fishing pressure is actually an endogenous attribute of the system, rather than an exogenous shock of the sort more commonly studied in resilience research. Until recently, the impacts of such endogenous developments on resilience and collapse have been comparatively under-studied in resilience research, when compared to the response of agents and systems to sudden crises and other exogenous shocks.

Our first hypothesis was that disaggregating the system into two species stocks and incorporating institutional rules that the Seri use to shift their harvest between the two species would better capture the resilience of the actual system. This is exactly what our results show. By shifting fishing pressure to keep both species viable, the Seri can keep the whole system going longer with more fishers and larger harvests. The results are clearest with respect to the OFT formulation, where the system is able to withstand the pressure of over 10 additional boats without facing collapse. But the threshold-based model for switching fishing effort also increased the system's resilience. Examining each permutation of scenarios with and without this rule in place, we find that it increased the maximum number of boats between 0 and 3. It also decreased the time the system took to recover after a 25-year burst of increased fishing pressure by about 5 years—and when added to the scenario with stochastic fishing luck and rule 2 for PR (experiments 15 and 24), it decreased the time needed by 15 years (from 70 to 55). (See Table 3)

Experiment Pair	Max Boats	Recovery Time
11100	29	70
11000	26	75
10100	27	70
10000	25	75
01100	26	80
01000	26	85
11101	29	55
11001	29	57
10101	27	55
10001	26	60
01101	26	55
01001	27	70
00100	25	85
00000	21	90

Table 3: Influence of Threshold-based Rule 3

The results also show the importance of differing management strategies for different species. In our model, PR's longer maturation time makes it more susceptible than AT to fishing pressure and absent any management strategy to correct for it, the population of PR is susceptible to an early collapse. However, by using rule 2 to decrease their harvest of immature PR, the Seri can give each PR specimen a greater chance of growing to maturity (in the model, this causes all immature PRs to live to reproduce, as natural premature deaths, which would naturally be small in number, are not modeled due to a lack of relevant data.). However, if the same rule 2 is applied to both species, the effect is equivalent to having no institutional rule at preventing immature harvesting all. As we have said, it is unclear whether PR is actually less resilient than AT in the wild due to a lack of data. Clearly, more studies of bivalves such as these are needed to enable for more targeted management strategies by both artisanal and commercial fishers.

Our second hypothesis was that introducing environmental variability would result in a system more susceptible to collapse, because it would be more prone to cross a critical threshold. However, contrary to our original hypothesis, the experiments show that the addition of stochasticity to mature lifespan actually *increases* the resilience of the system, as measured by the amount of fishing pressure it can sustain and the time it takes to recover from a shock. This is due to the dual nature of the reinforcing feedback loops for species recruitment. If the regrowth rate (which equals births minus natural deaths minus harvested) is positive, then the reinforcing loop operates in a growth trajectory, and repopulates/sustains the species despite fishing pressure. But if the regrowth rate is negative for a sustained period of time, then the loop enters a collapse trajectory with each year's population being smaller than the last. In a deterministic model, this can create a trap, whereby the population is doomed to die out in the area being covered—as happened in Bueno and Basurto 2009. However, when mature lifespan is stochastic, then there are quite a few time periods where the regrowth rate is not only positive, but quite high; as opposed to the deterministic scenario where the regrowth rate, depending on the harvest pressure, ends up being negative or only slightly positive (See Figure 10. The green represents the regrowth rate of CDH under a scenario with stochastic average lifetime.). This finding is consistent with other models, which have drawn clear links between natural variability in growth rates and resilience. (Ives 1995)

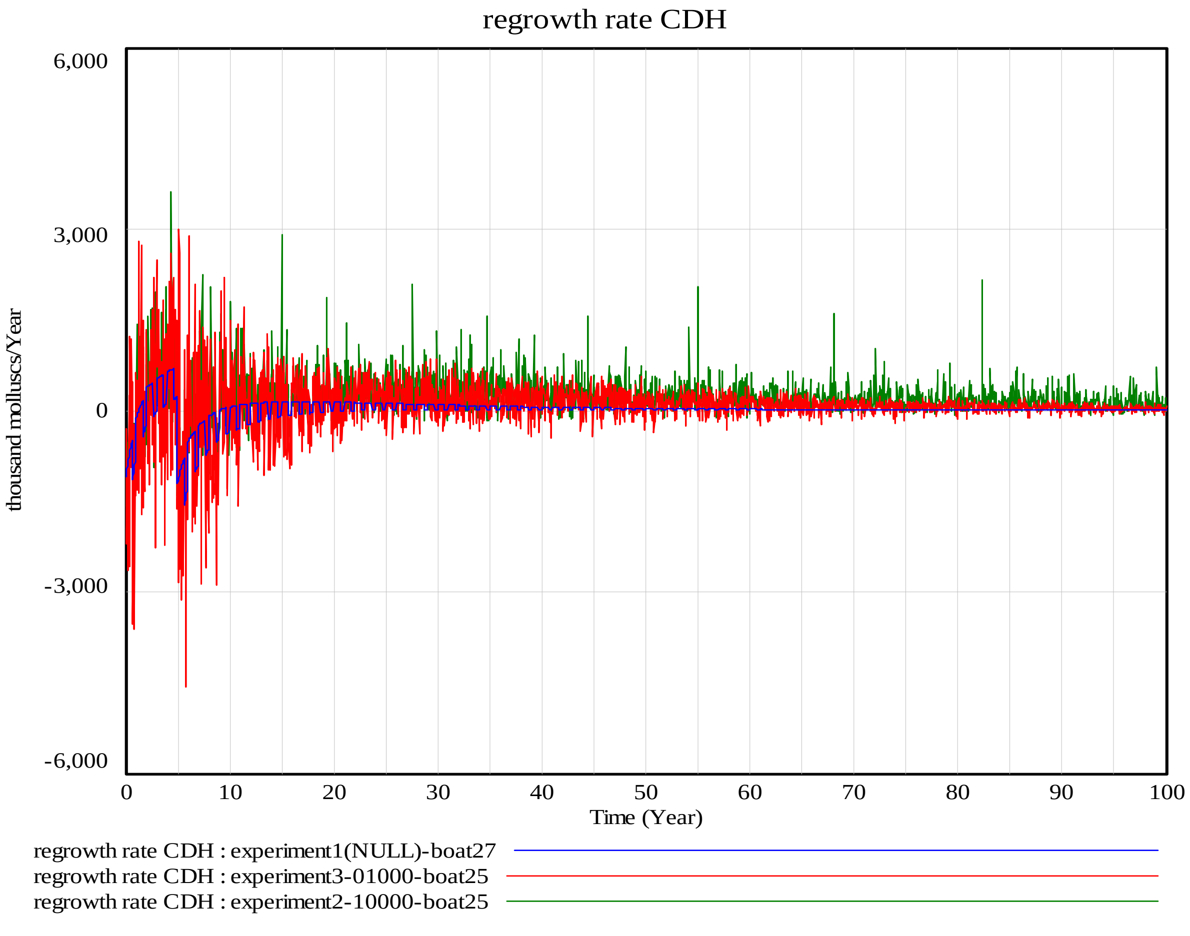

Figure 8: CDH Regrowth rate in deterministic experiment 1 (blue) and experiment 2 with stochastic mature lifespans for AT and PR (green), and experiment 3 with stochastic fishing luck (red). Note how both stochastic scenarios have higher regrowth rates; than the determinisc scenario, especially experiment 2..

While the stochastic fishing luck has a big impact on harvest levels, at low population levels, it is the variation (or lack thereof) in the mature lifespan—and from that, the variation in the birth rate—that is more influential. And this does help explain the high numbers it took to collapse our system completely. Whereas a deterministic model collapses once it gets below a critical threshold, our model stays functioning at a very low population level for a long time.

The stochasticity dealt with in this model is in some ways different from that often studied in resilience science. Usually, stochasticity is used to refer to shocks coming from outside the system. This is somewhat the case for the variable *fishing luck*, which represents exogenous, non-modeled and hard to predict risks. The *mature lifetime* variables, on the other hand, are endogenous to the system, and not shocks at all. While *fishing luck* does not exert much influence in either a positive or negative direction on the regrowth rate, the *mature lifetime* variables exert a somewhat strong upward pull on the regrowth rate. What this study does show is that environmental stochasticity can have an effect on the dynamics of the system even if it isn't a dramatic shock.. Depending on what sort of variable it is, it may amplify of decrease the resilience. But it matters. Most of all, the model shows that no one element is responsible for the resilience of artisan fisheries. It is the interaction of the stochasticity and institutional rules that give the system its strength.

CONCLUSION

Common pool resources must be managed carefully to avoid falling into a collapse trajectory. Yet because collapse can be engendered by what seem like small changes, it is easy for community members to lose sight of the importance of resilience and careful management.

Paying attention to the existence of environmental variability in the system, and how it is buffered or accelerated by institutional rules, is also critical to effective management and modeling. In the context of vulnerability and resilience, we need to pay attention to the interaction of environmental variability with institutional rules, not only whether such rules exist and are observed to work within a limited time frame.

LITERATURE CITED

Adger, N. (2000) Social and ecological resilience: are they related?. *Progress in Human Geography*, vol. 24 (3) pp. 347

Aswani. (1998) The use of optimal foraging theory to assess the fishing strategies of Pacific Island artisanal fishers: A methodological review. *SPC Traditional Marine Resource Management and Knowledge Information Bulletin*. vol. 9 pp. 19-26

Baqueiro E. *&* Castagna M. (1988) Fishery and culture of selected bivalves in Mexico: past, present and future. J*ournal of Shellfish Research* 7 , 433 – 43.

Basurto, Xavier, Biological and Ecological Mechanisms Supporting Marine Self-Governance: The Seri Callo de Hacha Fishery in Mexico, *Ecology and Society*, vol. 13 no. 2 (2008), pp. 20

Basurto, Xavier, Commercial Diving and the Callo de Hacha Fishery in Seri Territory, *Journal of the Southwest*, vol. 48 no. 2 (2006), pp. 189-209

Basurto. How Locally Designed Access and Use Controls Can Prevent the Tragedy of the Commons in a Mexican Small-Scale Fishing Community. Society & Natural Resources (2005) vol. 18 (7) pp. 643-659

Beisner, B. E., D.T. Haydon, and K. Cuddington. 2003. "Review: Alternative Stable States in Ecology." *Front Ecol. Environ* **1**(7): 376-382.

Bene and Tewfik. Fishing Effort Allocation and Fishermen's Decision Making Process in a Multi-Species Small-Scale Fishery: Analysis of the Conch and Lobster Fishery in Turks and Caicos Islands. Human Ecology (2001) vol. 29 (2) pp. 157-186

Botsford, L.W., Moloney, C.L., Hastings, A., Largier, J.L., Powell, T.M., Higgins, K., Quinn, J.F., 1994. The influence of spatially and temporally varying oceanographic conditions on meroplanktonic metapopulations. *Deep-Sea Research* II 41, 107– 145.

Bueno, N. and X. Basurto, Resilience and Collapse of Artisanal Fisheries: A System Dynamics Analysis of a Shellfish Fishery in the Gulf of California, Mexico*, Journal of Sustainability Science, vol. 4 no. 2* (2009), pp. 139-149

Carpenter et al. From Metaphor to Measurement: Resilience of What to What?. *Ecosystems* (2001) vol. 4 pp. 765-781

Cudney-Bueno and Basurto. Lack of cross-scale linkages reduces robustness of community-based fisheries management. *PLoS ONE* (2009) vol. 4 (7) pp. 1-8

Cudney-Bueno, R., L. Bourillón, A. Sáenz-Arroyo, J. Torre-Cosío, P. Turk-Boyer and W.W. Shaw. (2009) Governance and effects of marine reserves in the Gulf of California, Mexico. *Ocean & Coastal Management*; 52: 207–18.

Ferrandis, E. (2007) On the stochastic approach to marine population dynamics. *Sciencia Marina.* 71 (1) 153-174

Folke C, Carpenter S, Elmqvist T, Gunderson L, Holling CS, Walker B (2002) Resilience and sustainable development: building adaptive capacity in a world of transformations. Ambio 31(5):437–440

Glenn, E. P. 2006. Coastal wetlands of the northern Gulf of California: inventory and conservation status. *Aquatic Conservation: Marine Freshwater Ecosystems.* l6: 5-28.

Holling, C. S. (1973) Resilience and stability of ecological systems. *Annual Review of Ecological Systems* (4) pp. 1-23

Holling, C. S. (2001) Understanding the Complexity of Economic, Ecological, and Social Systems. *Ecosystems* vol. 4 (5) pp. 390-405

Ives, A. R. (1996.) Measuring resilience in stochastic systems. Ecological Monographs. *Ecological Monographs,* 65: 2 217-233.

Moxnes, Erling. 2002. *Working Paper No. 88/02. Policy Sensitivity Analysis: Simple Versus Complex Fishery Models.* SNF-project No. 5660. Centre for Fisheries Economics Discussion paper No. 13/2002. Institute for Research in Economics and Business Administration. Bergen, December 2002. ISSN 1503-2140.

Noguera 0. & Gomez S. (1972) Ciclo sexual de *Pinna rugosa* de La Paz, BCS. In: *Memorias del IV Congreso de Oceanografia.* Mexico, pp. 273-283.

Paredes-Rios and Balart. Corroboration of the Bivalve, Pinna rugosa, as a Host of the Pacific Pearlfish, Encheliophis dubius (Ophidiiformes: Carapidae), in the Gulf of California, México. *Copeia* (1999) vol. 1999 (2) pp. 521-522

Pineda, J., 1994. Spatial and temporal patterns in barnacle settlement rate along a southern California rocky shore. *Marine Ecology Progress Series* 107, 125– 138.

Pineda, J., 1999. Circulation and larval distribution in internal tidal bore warm fronts. *Limnology and Oceanography* 44 (6), 1400–1414.

Pineda, J., 2000. Linking larval settlement to larval transport: assumptions, potentials and pitfalls. *Oceanography of the Eastern Pacific* 1, 84–105.

Pineda, J., Caswell, H., 1997. Dependence of settlement rate on suitable substrate area. *Marine Biology* 129, 541–548.

Pineda, J., López, M., 2002. Temperature, stratification and barnacle larval settlement in two Californian sites. *Continental Shelf Research* 22, 1183–1198.

Ricker WE (1975) Computation and interpretation of biological statistics of fish populations. Bulletin 191, Department of Environment, Fisheries and Marine Service, Ottawa.

Scheffer, M. et al. 2001. Catastrophic Shifts in Ecosystems. Nature 413, October 11, 2001: 591-596

Stephens, D. W., and Krebs, J. P. (1986). *Foraging Theory.* Princeton, NJ: Princeton University Press.

Walker, B. and D. Salt. (2006) *Resilience Thinking: Sustaining Ecosystems and People in a Changing World.* Washington, DC: Island Press.

Walker, B. et al. *Resilience, Adaptability and Transformability in Social-ecological Systems*. Ecology & Society (2004) vol. 9 (2) pp. 5-14

APPENDIX A: PARAMETER ESTIMATES

Variable Name	Attribute of System	Estimate	Units	Citation
Algae	Percentage of seafloor covered by algae when algae are in season (during 1/3 of year).	0.06	Dimensionless	Torre-Cosio 2002; Basurto 2008 cited in Bueno and Basurto 2009; 143
Fecundity Rate	This variable represents the number of individuals (baby mollusks) produced by a female mollusk over her lifetime	20	Dimensionless	Bueno & Basurto 2009 144
Average organism per person per day	Number of organisms caught per fisher per day.	0.54	Thousand mollusks/person/day	Bueno & Basurto 2009; 144
Average Seri Boats	Average number of Seri boats at start of model run, changed at year 5 for scenario testing.	15	boats/year	Basurto 2010 personal communication
Average number of organisms caught per boat per day	Average number of organisms caught per boat per day	2,160	Thousand mollusks/boat/day	Bueno & Basurto 2009
Carrying capacity CDH	AT & PR compete for food and space, and the system has a single carrying capacity for the two species.	24500	Thousand mollusks	Bueno and Basurto 2009; 144
delay	Delay in fishers' response to changes to relative abundance. 0.083 years = 1 month.	0.083	year	Basurto unpublished data.
eelgrass	Percentage of seafloor covered by eelgrass when eelgrass is in season (during 2/3 of the year).	0.22	Dimensionless	Torre-Cosio 2002; Basurto 2008 cited in Bueno and Basurto 2009
Fishing effort	Percentage of days fished per year	0.5	year	Bueno & Basurto 2009
fishing luck distribution	Probability distribution function with a mean of 1 and standard deviation of 0.4.	RANDOM NORMAL (0, 2, 1, 0.4, 1)	Dimensionless	Basurto unpublished harvest data.
Initial CDH population	Initial CDH population. 90% of these are mature individuals.	22,050	Thousand mollusks	Bueno and Basurto 2009
Initial proportion PR	Percentage of CDH population composed of PR	2/3	Dimensionless	Basurto unpublished data

Initial immature AT population	Initial immature AT population	735	Thousand mollusks	
Initial immature PR population	Initial immature PR population	1,470	Thousand mollusks	
Initial mature AT population	Initial mature AT population	6,615	Thousand mollusks	
Initial mature PR population	Initial mature PR population	13,230	Thousand mollusks	
Mature lifespan distribution AT	Prob. Dist. Function representing the range of natural lifetimes for AT if not harvested, once maturitry is reached. Average of 9 years, StDev of 2.	RANDOM NORMAL (1,13,9,2,0)	year	
mature lifespan distribution PR	Prob. Dist. Function representing the range of natural lifetimes for PR if not harvested, once maturity is reached.. Average of 12, StDev of 3.	RANDOM NORMAL(0,20,12,3,0)	year	
Number of immature AT per kg	Used to convert immature AT harvest numbers, measured in thousand mollusks/year, into metric tons/year	60	Thousand mollusks/ton. (=Mollusks/kg)	Basurto 2006 193 & unpublished data
Number of immature PR per kg	Used to convert immature PR harvest numbers, measured in thousand mollusks/year, into metric tons/year	40	Thousand mollusks/tone. (=Mollusks/kg)	Basurto 2006 193 & unpublished data
Number of mature AT per kg	Used to convert mature AT harvest numbers, measured in thousand mollusks/year, into metric tons/year	30	Thousand mollusks/ton. (=Mollusks/kg)	Basurto 2006 193 & unpublished data
Number of mature PR per kg	Used to convert mature PR harvest numbers, measured in thousand mollusks/year, into metric tons/year	20	Thousand mollusks/ton. (=Mollusks/kg)	Basurto 2006 193 & unpublished data
Number of people/boat	Crew of one boat, usually contains only one diver plus three other crewmembers.	4	people/boat	Bueno & Basurto 2009
Rule 1 days fished	Percentage of year fished.	0.5	Year	Bueno & Basurto 2009

Rule 2 AT immature harvest	Lack of any enforced limitation on the harvesting of immature AT	1	Dimensionless (percentage)	Bueno & Basurto 2009
Rule 2 PR immature harvest	Allowed take of immature PR, realistically enforced	0.1	Dimensionless (percentage)	Basurto unpublished data.
Rule 3 proportion of fishing effort for AT	Proportion of fishing effort devoted to AT	1- OFT function in terms of PR(perceived relative abundance PR)		
Rule 3 proportion of fishing effort for AT	Proportion of fishing effort devoted to AT	OFT function in terms of PR(perceived relative abundance PR)		
OFT function in terms of PR	Type III functional response curve for distributing fishing effort for PR and AT based on perceived proportion of PR in the underwater CDH. Effort for AT is 1 minus the output of this function.	[(0,0)-(1,1)],(0,0.05),(0.05,0.05),(0.3,0.05),(0.4,0.05),(0.5,0.122807),(0.538226,0.451754),(0.568807,0.578947),(0.6,0.697368),(0.66,0.798246),(0.75,0.85),(1,0.85)	Dimensionless (percentage)	
rule 4 for supply decision for AT (element of)	threshold of price of AT	165 (~=$15 USD)	MXN Pesos (USD)	Basurto 2008 p32 for dynamic, Basurto personal communication for threshold
Survival rate function	A smoothed Beverton-Holt equation function of the survival rate of newly born CDH based on the total CDH population / carrying capacity	[(0,0)-(1.5,0.6)],(0,0.5),(0.1,0.49),(0.2,0.48),(0.4,0.46),(0.6,0.42),(0.8,0.34),(0.9,0.25),(0.95,0.15),(1,0),(1.5,0),(2,0)	Dimensionless	Bueno and Basurto 2009, modified
time to mature AT	length of time for AT to reach reproductive age	1	year	Bueno and Basurto 2009; Basurto 2008

time to mature PR	length of time for PR to reach reproductive age	2	year

Appendix B: Model Equations

```
actual proportion PR in current harvest=
           IF THEN ELSE((thousand AT harvested per year+thousand PR
harvested per year
      )>0, thousand PR harvested per year/(thousand PR harvested per
year+thousand AT harvested per year
      ), 0)
      Units: Dmnl

algae=
      0.06+0.06*PULSE( 10, duration ) *-decrease
Units: Dmnl
Percentage of seafloor covered by algae when algae is in season.

annual total CDH harvested in tons=
      tons AT harvested per year+tons PR harvested per year
Units: tons/Year

"Average organism per person/day"=
      0.54
Units: thousand mollusks/person/day
2.16 thousand organisms harvested per boat per day in the
           original model. This was then converted to average
organisms per
           person per day by dividing 2,160 by 4.

births AT=
      Mature AT Population*female percent*(fecundity rate AT/mature
lifespan distribution AT
)*effect of the population increase
Units: thousand mollusks/Year

births PR=
      Mature PR Population*female percent*(fecundity rate PR/mature
lifespan distribution PR
)*effect of the population increase
Units: thousand mollusks/Year

carrying capacity CDH=
      24500
Units: thousand mollusks
AT & PR compete for food and space, and the system has a single
           carrying capacity for the two species.

days per year=
      365
Units: days/Year

decrease=
      1
Units: Dmnl [0,1,0.25]

default delay=
      0.083
```

```
Units: Year
Delay for feedback loops. When smaller than 0.33, it is the
           smallest time increment in the model, and the TIME STEP
should
           be delay/2. If larger than 1/3 the TIME STEP should be 1/6.

duration=
      200
Units: years

eelgrass=
      0.22+0.22*PULSE( 10, duration )*-decrease
Units: Dmnl
percentage of seafloor covered by eelgrass when eelgrass is in
           season. comercial Seri fishers do not fish in the eelgrass.

effect of the population increase=
      surviving rate function (Total CDH Population/carrying capacity
CDH)
Units: Dmnl

fecundity rate AT=
      20{2.2}{1.3}
Units: Dmnl

fecundity rate PR=
      20
Units: Dmnl

female percent=
      0.5
Units: Dmnl

fisher delay for AT price=
      SMOOTH(price of AT, default delay)
Units: MXN/kg

fishing luck distribution=
      {1} RANDOM NORMAL(0, 2, 1, 0.4, 0)
Units: Dmnl
Sometimes fishers are more or less lucky, due to factors other
           than density of the CDH population that time-step. the
           stochastic fishing luck is meant to indicate the luck of
the
           draw due to other factors such as weather, skill of crew,
           turbidity of water, luck in choosing good fishing site(s),
etc.
           0.4 is set as StDev based on unpublished harvest data by
           Basurto, showing a Standard Deviation in harvest catch per
boat
           of 40%. If anything 40% might in the higher end of the
range,
           given that the model does not take into account many other
           mechanisms available to fishers to diminish their
probability of
           "bad luck".
```

```
immature AT density=
      Immature AT Population/carrying capacity CDH
Units: Dmnl

immature AT harvested=
      ((outsider harvest rate of AT+Seri harvest rate of AT)*immature
AT density
*fishing luck distribution*(1-Percentage of Seagrass Coverage
      ))*rule 2 AT immature harvest
Units: thousand mollusks/Year

Immature AT Population= INTEG (
      births AT-maturation rate AT-immature AT harvested,
            {460} initial CDH population*(1-Initial Proportion PR)*0.1)
Units: thousand mollusks

immature PR density=
      Immature PR Population/carrying capacity CDH
Units: Dmnl

immature PR harvested=
      ((outsider harvest rate of PR+Seri harvest rate of PR)*fishing
luck distribution
*immature PR density*(1-Percentage of Seagrass Coverage
      ))*rule 2 PR immature harvest
Units: thousand mollusks/Year

Immature PR Population= INTEG (
      births PR-maturation rate PR-immature PR harvested,
            {1841} initial CDH population*Initial Proportion PR*0.1)
Units: thousand mollusks

initial AT harvested=
      23
Units: tons/Year

initial boats=
      15
Units: boats/Year [0,80,1]

initial CDH population=
      22050
Units: thousand mollusks
Should be 90% of carying capacity. Using this value, and the
            Initial ratios of 2:1 for PR:AT, and 9:1 for
Mature:Immature,
            the initial values for each of the four population stocks
is
            computed at the start of the model run. This is done
primarily
            to decrease the number of auxilary variables while
retaining
            flexibility. The 9:1 Mature:Immature ratio is hard-coded.

initial PR harvested=
      14
Units: tons/Year
```

```
Initial Proportion PR=
      2/3
Units: Dmnl
Anecdotal evidence from Basurto (unpublished) suggests a PR:AT
           ratio of 2:1.

maturation rate AT=
      Immature AT Population/time to mature AT

      {DELAY CONVEYOR(births AT, 1,rule 2 harvest immature*harvest rate
of AT*(1-Percentage of Seagrass Coverage), initprofile , 800 {2800}
{initial immature population}, 1)}
Units: thousand mollusks/Year

maturation rate PR=
      Immature PR Population/time to mature PR

      {DELAY CONVEYOR(births PR, 1, rule 2 harvest immature*harvest
rate of PR*(1-Percentage of Seagrass Coverage), initprofile , 3000
{1900} {initial immature population}, 1)}
Units: thousand mollusks/Year

mature AT density=
      Mature AT Population/(carrying capacity CDH)
Units: Dmnl

mature AT harvested=
      (outsider harvest rate of AT+Seri harvest rate of AT)*fishing
luck distribution
*mature AT density*(1-Percentage of Seagrass Coverage
      )
Units: thousand mollusks/Year

Mature AT Population= INTEG (
      maturation rate AT-natural deaths AT-mature AT harvested,
           {4139} initial CDH population*(1-Initial Proportion
PR)*0.9)
Units: thousand mollusks

mature lifespan distribution AT=
      {9} RANDOM NORMAL(0,13,9,2,0)
Units: years

mature lifespan distribution PR=
      {13} RANDOM NORMAL(0,20,13,3,0)
Units: years
seed value of 0 calls the model-wide noise seed constant, which
           is controlled by the NOISE STREAM variable

mature PR density=
      Mature PR Population/(carrying capacity CDH)
Units: Dmnl
Based on the idea that the density = 1 when the population is at
           carrying capacity

mature PR harvested=
```

```
      (outsider harvest rate of PR+Seri harvest rate of PR)*fishing
luck distribution
*mature PR density*(1-Percentage of Seagrass Coverage
      )
Units: thousand mollusks/Year

Mature PR Population= INTEG (
      maturation rate PR-natural deaths PR-mature PR harvested,
           {16577} initial CDH population*Initial Proportion PR*0.9)
Units: thousand mollusks

more boats=
      0
Units: boats/Year [-15,30,1]

natural deaths AT=
      Mature AT Population / mature lifespan distribution AT
Units: thousand mollusks/Year

natural deaths PR=
      Mature PR Population / mature lifespan distribution PR
Units: thousand mollusks/Year

NOISE SEED=
      71
Units: Dmnl [0,1000]

number of immature AT per kg=
      RANDOM NORMAL (0,2,1.75,0.2,0)*30
Units: thousand mollusks/tons
thousand mollusks/tons = mollusks/kg. A range of between 1.5 and
           2 (average 1.75) times as many immature as mature
individuals as
           immature individuals.

number of immature PR per kg=
      RANDOM NORMAL (1,2,1.75,0.2,0)*20
Units: thousand mollusks/tons
A range of between 1.5 and 2 (average 1.75) times as many
           immature as mature individuals as immature individuals.

number of mature AT per kg=
      30
Units: thousand mollusks/tons
thousand mollusks/tons = mollusks/kg. AT are smaller than PR,
           meaning there are 50% more of them per tonne, and this
           contributes to their greater per ton cost.

number of mature PR per kg=
      20
Units: thousand mollusks/tons

number of organisms caught per boat per day=
      2.16
Units: thousand mollusks/boat/day
2,160 number of organisms harvested per boat per day in the
```

```
           original model. This is simpler than caclualting organisms
per
           person and then people per boat. The number of fishers per
boat
           varies from 3.1 to 4.3, for an average crew size of 3.7.
"The
           configurations you see most often are either one diver and
one
           or two crew members. Or two divers and two or three crew
           members."

"number of people/boat"=
     4
Units: person/boat
Crew of one boat. Default in Seri community is 4; one diver plus
           three other crew members.

OFT function in terms of PR(
     [(0,0)-
(1,1)],(0,0.05),(0.05,0.05),(0.3,0.05),(0.4,0.05),(0.5,0.122807),(0.53
8226
,0.451754),(0.568807,0.578947),(0.6,0.697368),(0.66,0.798246),(0.75,0.
85),(
1,0.85))
Units: Dmnl
[(0,0)-(1,1)],(0,0.05),(0.05,0.05),(0.3,0.1),(0.4,0.15),(0.5,0.45
           ),(0.6,0.6),(0.66,0.7),(0.7,0.75),(0.75,0.85),(1,0.85)

outsider average boats=
     initial boats*outsider boat percentage+PULSE( 5 , 200 )*(more
boats*outsider boat percentage
)+PULSE( 25 ,100 )*0
Units: boat/Year
Number of outsider boats in fishery, with pulse at 25 years of
           more outsider boats

outsider boat percentage=
     0
Units: Dmnl [0,1,0.025]
percentage of overall average boats that are outsider boats

outsider fishing effort=
     Seri fishing effort
Units: Year
Percentage of days per year fished by outsiders. Mainly
           determined by Seri institutional rules. Ought to be a
function
           of their opportunity costs, among other factors, as well
but
           that may be too complicated to model

Outsider harvest capacity=
     (outsider fishing effort*days per year*number of organisms caught
per boat per day
*outsider average boats)
Units: thousand mollusks/Year
Maximum annual harvest capacity for all outsider boats in
```

```
           fishery.

outsider harvest rate of AT=
     Outsider harvest capacity
Units: thousand mollusks/Year
Outsider rate of harvest, by default ignores seagrass and both
           market and abudence feedbacks

outsider harvest rate of PR=
     Outsider harvest capacity
Units: thousand mollusks/Year

perceived relative abundance PR=
     SMOOTH(relative abundance PR,default delay)
Units: Dmnl

Percentage of Seagrass Coverage=
     PULSE TRAIN(0, 0.67, 1 , 200 )*eelgrass+PULSE TRAIN(0.67 , 0.33 ,
1 ,200 )
*algae
Units: Dmnl
Field research by Torre-Cosio (2002) and Basurto (2008) reported
           that, during roughly 8 months of the year, the eelgrass
Zostera
           marina covers 22% of the Infiernillo Channel's sea bottom,
and
          in the remaining months of the year, the algae Caulerpa spp.
           covers about 6%.

price function(
     [(-2,0)-
(300,400)],(0,340),(7,290),(25,220),(44,165),(55,130),(68.5015,100
),(80,77),(100,47),(150,20),(175,10),(200,7),(300,2))
Units: MXN/kg
-0.36*buyer delay for AT supply+36 {-0.14*buyer delay for AT
           supply+36}

price of AT=
     price function(tons AT harvested per year)
Units: MXN/kg
USD ($)--but should be MXN Pessos!

proportion AT of harvest=
     IF THEN ELSE(annual total CDH harvested in tons>0, tons AT
harvested per year
/annual total CDH harvested in tons, 0)
Units: Dmnl

proportion immature in current AT harvest=
     IF THEN ELSE(thousand AT harvested per year>0,immature AT
harvested/thousand AT harvested per year
,0)
Units: Dmnl

proportion immature in current PR harvest=
     IF THEN ELSE(thousand PR harvested per year>0,immature PR
harvested/thousand PR harvested per year
```

```
,0)
Units: Dmnl

proportion of PR of harvest=
      IF THEN ELSE(annual total CDH harvested in tons>0, tons PR
harvested per year
/annual total CDH harvested in tons, 0)
Units: Dmnl

regrowth rate AT=
      births AT - natural deaths AT - mature AT harvested
Units: thousand mollusks/Year

regrowth rate CDH=
      (births PR+births AT)-(natural deaths PR+natural deaths AT)-
(mature AT harvested
+mature PR harvested)
Units: thousand mollusks/Year

regrowth rate PR=
      births PR-natural deaths PR-mature PR harvested
Units: thousand mollusks/Year

relative abundance AT=
      1-relative abundance PR
Units: Dmnl

relative abundance PR=
      Total CDH PR/Total CDH Population
Units: Dmnl

rule 1 days fished=
      1*Seri fishing effort
Units: years

rule 2 AT immature harvest=
      1
Units: Dmnl
There is no rule preventing the catch of immatures, but for the
            most part, divers catch very little numbers of immatures
because
            they cannot see them! With no feedbacks or forcing rules,
the
            percentage of immatures caught is equal to their percentage
in
            the overal population, which varies between 20% and 30%.
This
            seems about right; 30% is an upper bound.

rule 2 PR immature harvest=
      1{0}
Units: Dmnl [0,1,0.25]

rule 3 proportion of fishing effort for AT=
      1-OFT function in terms of PR(perceived relative abundance PR)
{IF THEN ELSE( (1-perceived relative abundance PR) < 0.25, 0.15, 1)}
Units: Dmnl
```

```
If fishers percieve the proporation of AT relative to PR to be
           less than a threshold, they will cut their harvest of AT by
85%.
           {IF THEN ELSE(target proportion PR in current harvest=0, 1,
           (1-target proportion PR in current harvest)/Current
Proportion
           AT in water)}

rule 3 proportion of fishing effort for PR=
      OFT function in terms of PR(perceived relative abundance PR) {IF
THEN ELSE(perceived relative abundance PR<0.4, 0.05, 1)}
Units: Dmnl
If fishers percieve the relative population of PR relative to AT
           to be less than a given threshold, they will cut their
harvest
           of PR by 95%. (Because PR is less valuable than AT.) {IF
THEN
           ELSE(target proportion PR in current harvest=0, 1, (target
           proportion PR in current harvest/Current Proportion PR in
           water))}

rule 4 supply decision for AT=
      IF THEN ELSE(fisher delay for AT price < 165, 0.15 , 1 )
Units: Dmnl
If the price is less than 165 pesos, the fishers will cut their
           harvest of AT by 90% in order to reduce supply and drive
the
           price up again.

Seri average boats=
      initial boats*(1-outsider boat percentage)+PULSE( 5 , 200 )*(more
boats*(1
-outsider boat percentage))+PULSE( 25 ,100 )
      *0 {15+PULSE( 5 , 200 )*more Seri boats+PULSE( 25 ,100 )*0{(-more
boats)}}
Units: boat/Year
Average number of boats at start of model run; pulse at year 5
           with more Seri boats for scenario testing

Seri fishing effort=
      0.5
Units: Year
Percentage of days fished per year. "To clarify: in Bueno and
           Basurto we used 0.5, which is considered by fishers roughly
the
           average for the region and because my 2000 data for the
Seri was
           not available at the time. Now that there is data available
for
           2000-1 (141 days) & 2009 (281) days, they result in an
average
           of 211 worked days, that is 0.57. Having said that, not all
           boats go out all days, and there surely there is variation
           between years. So if you are estimating a fixed number of
boats
           per day, then the fishing effort would be overestimated. In
that
```

```
          case I still think 0.5 is a reasonable proxy to continue to
use."

Seri harvest capacity=
     (rule 1 days fished*days per year*number of organisms caught per
boat per day
*Seri average boats)
Units: thousand mollusks/Year
Maximum annual harvest for all Seri boats in the fishery.

Seri harvest rate of AT=
     Seri harvest capacity*rule 3 proportion of fishing effort for AT
Units: thousand mollusks/Year

Seri harvest rate of PR=
     Seri harvest capacity*rule 3 proportion of fishing effort for PR
Units: thousand mollusks/Year

surviving rate function(
     [(0,0)-
(1.5,0.6)],(0,0.5),(0.1,0.49),(0.2,0.48),(0.4,0.46),(0.6,0.42),(0.8
,0.34),(0.9,0.25),(0.95,0.15),(1,0),(1.5,0),(2,0))
Units: Dmnl
given by the Beverton-Holt equation; smoothed. Original:
          [(0,0)-
(2,0.6)],(0,0.5),(0.1,0.48),(0.8,0.36),(1,0),(1.5,0),(2,0)
           Alt Smooth Version:
          [(0,0)-
(1.5,0.6)],(0,0.5),(0.1,0.49),(0.2,0.48),(0.4,0.43),(0.573

     394,0.37),(0.756881,0.28),(0.866973,0.2),(0.944954,0.1),(1,0),(1.
          5,0),(2,0) Smoothed version:
          [(0,0)-
(1.5,0.6)],(0,0.5),(0.1,0.49),(0.2,0.48),(0.4,0.46),(0.6,0
          .42),(0.8,0.34),(0.9,0.25),(0.95,0.15),(1,0),(1.5,0),(2,0)
          Highly Nonlinear:
          [(0,0)-
(1.5,0.6)],(0.00917431,0.0236842),(0.137615,0.239474),(0.2

     11009,0.347368),(0.284404,0.410526),(0.40367,0.434211),(0.6,0.42)
          ,(0.8,0.34),(0.9,0.25),(0.95,0.15),(1,0),(1.5,0),(2,0)
Linear:
          [(0,0)-(1.5,1)],(0,1),(1,0),(1.5,0),(2,0)

thousand AT harvested per year=
     immature AT harvested + mature AT harvested
Units: thousand mollusks/Year

thousand PR harvested per year=
     mature PR harvested + immature PR harvested
Units: thousand mollusks/Year

TIME STEP = 0.04
     Units: Year
     The time step for the simulation.

time to mature AT=
```

```
     1
Units: Year

time to mature PR=
     2
Units: Year

tons AT harvested per year=
     DELAY1I( ((immature AT harvested/number of immature AT per
kg)+(mature AT harvested
/number of mature AT per kg)), default delay, initial AT harvested)
Units: tons/Year

tons PR harvested per year=
     DELAY1I( ((immature PR harvested/number of immature PR per
kg)+(mature PR harvested
/number of mature PR per kg)), default delay, initial PR harvested)
Units: tons/Year

Total CDH AT=
     Immature AT Population+Mature AT Population
Units: thousand mollusks

Total CDH Population=
     Total CDH AT + Total CDH PR
Units: thousand mollusks

"Total CDH Population/Carrying Capacity"=
     Total CDH Population/carrying capacity CDH
Units: Dmnl

Total CDH PR=
     Immature PR Population+Mature PR Population
Units: thousand mollusks

total immature CDH=
     Immature AT Population+Immature PR Population
Units: thousand mollusks

total mature CDH=
     Mature AT Population+Mature PR Population
Units: thousand mollusks
```