Restoration of the Catarina Scallop in the Ensenada de La Paz, Mexico

A group project submitted in partial satisfaction of the requirements for the degree Master of Environmental Science & Management

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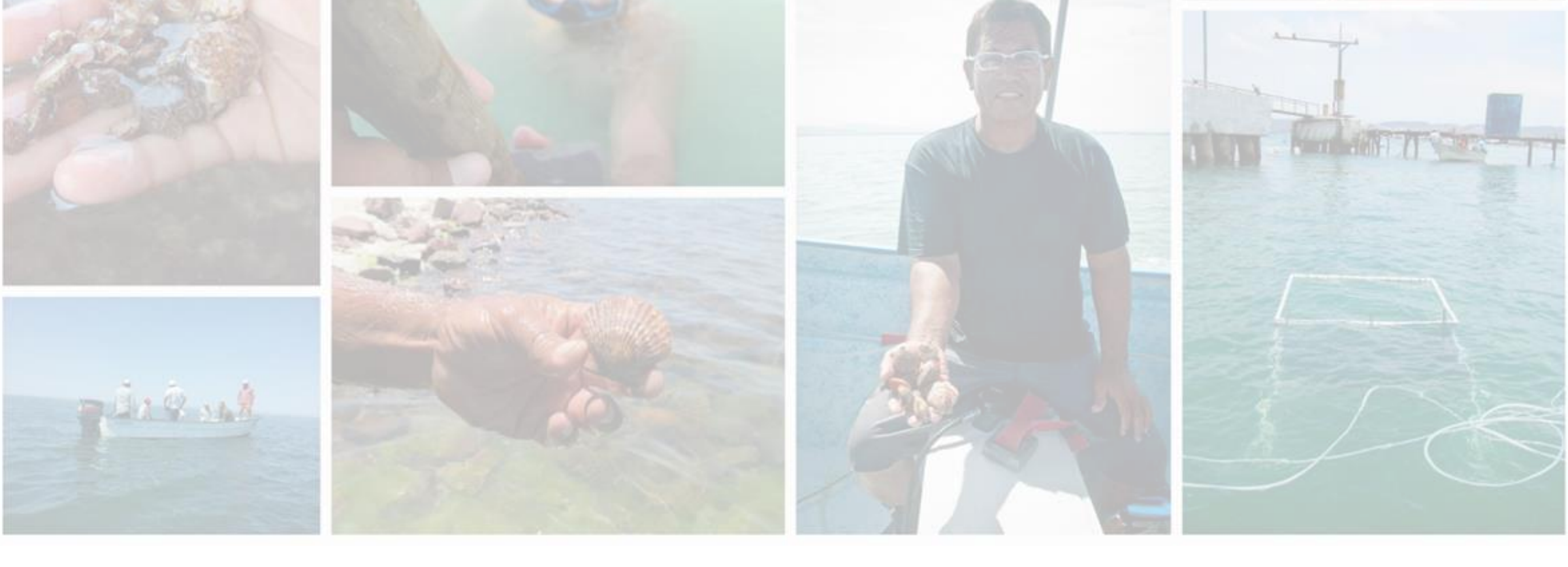
Noroeste Sustentable and the Fishermen of El Manglito

March 2014



Signature Page

The mission of the Bren School is to play a leading role in researching environmental issues, identifying and solving environmental problems, and research scientists and environmental management professionals.

Group Project: Establishing feasibility metrics and evaluating the potential for Catarina scallop (*Argopecten circularis/ventricosus*) restoration and aquaculture in the Ensenada de La Paz.

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The Group Project is required of all students in the Master's of Environmental Science and Management (MESM) Program. It is a three-quarter activity in which small groups of students conduct focused, interdisciplinary research on the scientific, management, and policy dimensions of a specific environmental issue.

This Final Group Project Report is authored by above MESM students and has been reviewed and approved by:

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Abstract

The population of the Catarina scallop, a high value species for artisanal fishers in Baja California Sur, collapsed in 1978 in the Ensenada de La Paz and has never recovered. Habitat degradation and overfishing are some of issues preventing scallop recovery. Noroeste Sustentable (NOS), a non-governmental organization focused on community development, is working with the El Manglito fishing community in La Paz to repopulate the Ensenada with Catarina scallops, and eventually reopen the fishery. Our team developed different scenarios for the restoration effort, focusing on major population bottlenecks for recovery, including the lack of lagoon habitat, illegal fishing, and population enhancement through aquaculture. We tested the cost-benefits of each scenario using a bioeconomic model that we created to simulate conditions influencing scallops in the lagoon. To better parameterize the model, we conducted a field experiment to assess the survival rate of the scallops on the Ensenada seafloor in different habitat types. We compared a total of 15 restoration scenarios, each a unique combination of different levels of habitat restoration, aquaculture intensity, surveillance, and seeding. The results indicate that habitat and its restoration has the greatest influence on the population biomass of scallops. The results also suggest that aquaculture is not economically feasible. We thus recommend that NOS focus their efforts on carrying out a pilot habitat restoration project in the historical fishing grounds. Restoration efforts would also benefit from continued surveillance to discourage illegal fishing and scallop seeding from aquaculture production for a minimum of 3 years, preferably at a higher quantity of scallops per year than 340,000. Future research should evaluate the current level of the suitable habitat, and the feasibility of different habitat restoration methodologies.

Executive Summary

Our project focuses on the Catarina scallop, *Argopecten ventricosus*, a species with high cultural and commercial value in Baja California Sur, Mexico. The importance of this species is reflected by its presence in the Baja California Sur flag. Historically abundant in the wild, the fishery today is nearly depleted. The restoration of the Catarina fishery in the Ensenada is expected to strengthen the property rights of local fishers, to restore this native species to its historical range, to support the recovery of other species, such as the pen shell clam, and to generate jobs. In this way, fishermen and the local community stand to gain from a restored native fishery and a sustainable aquaculture industry in the Ensenada.

The objective of this project is to identify restoration strategies to restore the Catarina scallop population to a sustainable level in the Ensenada de La Paz, which could ultimate contribute to bringing economic benefits to the community of El Manglito. In order to achieve these objectives, we must take a look at the life cycle and history of the Catarina scallop in Baja California Sur.

The Catarina scallop, *Argopecten ventricosus*, is a bay scallop found in near shore shallow lagoons. Reaching sexual maturity around 6 months, each scallop produces up to 2-3 million eggs and ultimately settles on shell hash, seagrass, and algal turf. The scallop reaches an adult size of 56 mm in approximately 1 year. The life span of the Catarina scallop is 2-3 years and can reach a height of 80mm. Sensitive to sedimentation, water quality, and illegal fishing, the Catarina is vulnerable to environmental perturbations. Ranging from Northern Peru to Northern Mexico, the Catarina scallop is heavily fished, which over time has led to local extinctions in Panama and several locations in Baja California Sur. Our research focuses on the Catarina scallop in the Ensenada de La Paz, in Baja California Sur, Mexico. The Ensenada was once the main fishing ground for the Catarina scallop in Baja California Sur, until the population collapsed in 1979. Habitat degradation and overfishing are some of issues preventing scallop recovery.

Noroeste Sustentable (NOS), a non-governmental organization focused on community development, is located in the fishing community of El Manglito, just outside the city center of La Paz. NOS and El Manglito fishermen are working together to restore and repopulate the lagoon with Catarina scallops to levels high enough to reopen the fishery. Together they have developed a repopulation model in which the fishermen receive Catarina scallop seeds and raise the seed in a nursery until they reach a size of roughly 10 mm. The juveniles are transferred into corrals until they reach a size of 30 mm. when they are collected and released in the Ensenada. The goal is to seed enough mature scallops to reproduce and repopulate the Ensenada with Catarina scallops. Some of the challenges to the restoration effort are community engagement and illegal fishing. It is estimated that illegal fishing makes up for 40% for scallops fisheries. This event, along with the illegal fishing of the Pen Shell scallop, led to the development of a surveillance team of local fishermen.

Since our study aims to identify restoration strategies that would repopulate the Ensenada to a sustainable level, we identified major population bottlenecks that may inhibit recovery and also mechanisms that may enhance the recovery. The lack of settlement habitat in the Ensenada may pose a threat to recovery by not providing enough substrate for Catarina recruits to settle. Illegal fishing continues to occur, despite enforcement, resulting in the poaching of seeded scallops. We would also like to investigate increasing the length and quantity of scallops seeded into the wild as a manner in

which to speed up the restoration. Finally, we would like to explore the idea that aquaculture could generate a source of income for the fishermen during the restoration effort.

In order to analyze these effects, we created a bioeconomic model to simulate conditions influencing the Catarina scallop population in the lagoon. We used life-cycle parameters and relationships to develop an age-structured population model. This population model builds upon the Von Bertalanffy growth function, the Beverton-Holt stock-recruitment relationship, length-weight relationship, fecundity, maturity, natural mortality, fishing mortality, and illegal fishing mortality. We assume that the starting population is zero and use a total of 4 age classes (0-3 years). Each time interval in the model represents 1 year, and the population was simulated through 100 years.

Within the model we tested 15 restoration scenarios, each a unique combination of different levels of habitat restoration, aquaculture intensity, surveillance and seeding. The costs and benefits were analyzed for each restoration scenario. Since illegal harvest continues to occur in the Ensenada, we can expect that illegal fishing will occur at every stage of the project and continue to occur when the fishery opens. We assume that the intensity of illegal fishing would depend on the level of surveillance and its effectiveness and thus we modeled 3 levels of illegal fishing: 40%, 20% and 5%. We use recruitment as a proxy for habitat availability. Since there is a lack of historical landing data, we used the estimated quantity of scallops during the final year the fishery was open as a reference for historical abundance. We consider this baseline to be conservative. For our analysis, we assume that current available habitat represents 30% of the habitat available in the final year the fishery was open. We varied the habitat availability at 30%, 60% and 100% to represent current levels of habitat. To model the intensity of aquaculture operation in the bioeconomic model we designed three levels of aquaculture intensity at 0, 580,000, and 2,320,000. In both these aquaculture levels, the scallops would be matured in the cages to the 56 mm legal size and then harvested for sale. To model the effect of seeding on the Catarina population recovery in the bioeconomic model we designed four levels of seeding. Level 1 assumes an annual quantity of 340,000 for one year, level 2 assumes 340,000 scallops per year, for three years, level 3 assumes 680,000 scallops per year, for three years, and Level 4 assumes 680,000 scallops per year, for 6 years.

The 15 scenarios produced outputs of population biomass (B/B0), average catch value, fishery net present value (NPVw), aquaculture net present value (NPVaq), restoration investment, fishery net present value (NPVw)/fishery NPVmax, Years to carrying capacity (K), and years to 25% population biomass (B/B0). A sensitivity analysis was used to test the sensitivity of our model to changes in input values known to have high uncertainty and in order to incorporate the effect of environmental stochasticity into the population biomass, we conducted a Monte Carlo simulation to reflect this stochasticity through natural mortality in the model.

According to our model, the scallop population is expected to recover from depletion, but at different rates and achieving different population sizes depending on the restoration strategy used. The biomass varies between 0.19 and 0.96. The highest population biomass (>90%) is reached by only 5 scenarios, all of which have in common that scallop habitat is restored up to 100% of the historical levels. Alternatively, low-performing scenarios have usually lower levels of suitable habitat, relative to historical levels. We found that the strategies that achieve smaller population sizes reach a stable level faster, and bigger ones take more time to reach their carrying capacity, however, with significant variability. The fishery was modeled to open after the population grows over a threshold of 25% of theoretical virgin conditions. Our analysis shows that when the fishery opens, all scenarios that open are able to maintain a population size above the threshold, with the exception of one scenario. However, five restoration strategies are never able to reach a population size above the threshold, which have in common low levels of suitable habitat. Not surprisingly, restoration strategies that attain a higher biomass while the fishery remains closed are able to maintain a bigger population that is subject of both legal and illegal fishing. How soon the fishery opens can affect how the population recovers. However, eventually in all cases the population stabilizes at around 20 years assuming a legal fishing rate of 60%.

With an average local market price of US$0.63/K of whole scallops with shell, and a legal fishing level of 60% of the scallops over the legal size limit (56 mm), fishermen would obtain in average between US$39,801 and US$124,333 per year from selling the scallop harvest. Fishery NPV ranges from (-6,747,399.46) to $175,291.54 and fishery income NPV ranges from (-$242,302.57) to $1,769,984.47. Scenarios with a negative fishery income are scenarios in which the fishery never opens and do not invest in habitat restoration. The scenarios with the highest fishery income NPV have high restoration investments, restoring the habitat to either 60% or 100%. NPV Ratios over 0.5 involve habitat restoration of 100%. Aquaculture NPV ranged from (-$11,340,280.19) to $0.00. The Aquaculture NPV is directly correlated with the quantity of scallops produced in aquaculture. The scenarios with a negative NPV fail to reach a B/B_0 of 0.25, thus, the fisheries in these scenarios do not open, resulting in an investment in restoration, with no returns on investment. In contrast, the scenarios with the highest NPV maintain a high B/B_0, even after the fishery opens. Habitat restoration investment values range from $0 to $7,584,351.93 while mean catch value per year ranges from $0 to $207,221.68. Lastly, our analysis shows a relationship between mean catch value and habitat restoration investment.

Our results indicate that habitat area appears to be the most important factor in restoring the scallop population across the different strategies. However, we assume that the current suitable habitat is at 30% of the 100% historical pre-collapse level. This is an assumption with high uncertainty given that we currently have no evidence to back our assumption that habitat is indeed at 30%. We also find that Illegal fishing has more of an observed effect on population recovery than seeding and aquaculture, but its effects on either population size or rate of recovery seems to be moderated by other restoration variables and by habitat. We found that seeding of juveniles into the wild is extremely important for the recovery of the scallop population in the Ensenada. Once past the initial seeding, our results indicate that after 3 years, seeding has less of an observed effect on population recovery than habitat and surveillance, and a similar effect to that of aquaculture. The negative values of Aquaculture NPV demonstrate that, under the current costs of production, aquaculture does not provide a profit for the fishermen. Doubling the density or doubling the percentage of aquaculture area may allow fishermen to make a profit, however, the complexities of transitioning livelihoods from fishing to aquaculture farming should also be considered.

Our study concludes that habitat restoration is necessary for the fishery to generate profit. According to our client, the fishery must generate at least $443,077 in revenue per year to sustain the livelihood of the El Manglito fishing community. Among our scenarios, the maximum mean catch value per year is $207,221.68, which is less than half the target value. Although the Catarina fishery can potentially generate profits, it is not sufficient enough for the fishermen to depend only on Catarina scallops. The limitations of our analysis are that we assume that biomass is limited to that of the final year when the fishery was open. The scenarios with negative NPVs are also limited by the assumption that in our model the fishery will open when the biomass arrives at 0.25. Additionally, our sensitivity analysis reveals that reductions in price per kilogram are expected to have a larger impact on the NPV of the fishery. Ultimately, the Catarina fishery has the potential to become economically feasible, especially if restored simultaneously with the Pen Shell clam. According to our results, the biggest obstacle in achieving economic feasibility is the capital to complete habitat restoration.

We recommend restoring the Catarina habitat in the historical fishing grounds and to conduct further research to assess the best strategy to restore habitat. This can be done through the partnerships that NOS has developed with the Bren School, the Massachusetts Institute of Technology, or the Universidad Autonoma de Baja California Sur. Additionally we recommend that the fishermen continue the surveillance program in the Ensenada. Additionally, the efforts by NOS and some of the local fishers to raise awareness among the community about the restoration of the Ensenada should continue as they help support the surveillance program. Since our sensitivity analysis shows that natural mortality is more important than illegal fishing, we recommend continuing the seeding effort and increasing the quantity seeded by more than 340,000. Continuing to plant scallops at a size of 30 mm will contribute to lower mortality. In addition, maturing the scallops inside cages over restored substrate may help decrease predation, and increase survival as more larvae are able to recruit to the next generation. Lastly, we recommend that NOS continue to establish or further develop partnerships with the private sector and with the academic sector. Community engagement, in the vision of restoring the Ensenada and the Catarina population, is paramount in making restoration efforts successful in the long term. Nevertheless, we must also continue to recognize that working with community members to create new job sources through the diversification of the use of marine resources is essential in ensuring a successful and long lasting restoration.

Project significance

This project focuses on the recovery of a collapsed marine resource and associated artisanal fishery. Although focused on the population of one marine species, the Catarina scallop *Argopecten circularis/ventricosus*, its recovery has larger implications for the coastal lagoon ecosystem and the fishing community who have lived around and depended on it for generations. Populations of this species have collapsed in the Las Perlas Archipelago in Panama (Medina et al., 2007), and in the Ensenada de La Paz, in Baja California Sur, Mexico (Baqueiro et al., 1981); in the case of the Ensenada the population has not yet recovered. As a result, the Catarina fishery and the socioeconomic benefits derived from it disappeared as the community observed the deterioration of the Ensenada marine ecosystem, and local fishermen migrated to other areas to fish. During the last few years some of these fishermen and their families have formed alliances with the local non-government organization Noroeste Sustentable (NOS), and have started an aquaculture project to repopulate the Ensenada with Catarina scallops. Quantitatively analyzing the outcomes of recovery, under different circumstances and using different strategies, will assist these stakeholders in optimizing the recovery of the Catarina population.

This analysis is of particular significance to fishermen and businesses whose income depends on the commercialization of benthic resources such as the Catarina scallop, and to the federal and state fisheries agencies that seek to balance the conservation of marine resources with job generation. This analysis is also of particular significance to non-profit organizations that seek to partner with fishermen and local communities to rebuild collapsed or depleted benthic species of commercial importance using aquaculture.

Our evaluation of different restoration strategies through a bioeconomic model will help optimize current and future efforts to recover the Catarina population. The recovery of the Catarina scallop will be a significant step in increasing social capital and collaboration, and in getting closer to achieving the goal of restoring the marine ecosystem of the Ensenada de La Paz. As an organization focused on enhancing ecosystem health and social cohesion, NOS is responsible for catalyzing the restoration efforts by engaging the local community in aquaculture and surveillance efforts, and by encouraging communication among fishermen who were previously adversaries. By identifying the optimal combination of restoration strategies, our project deliverables will allow NOS to generate results sooner and thus increase the willingness of the local community to continue their efforts to restore the

Ensenada as a whole. As one of many locations in Northwestern Mexico characterized by dwindling marine resources, the Ensenada will serve as a source of inspiration for other communities who seek to bring these resources back.

Objectives

The goal of this project is to develop and evaluate alternative restoration strategies, and provide recommendations that: 1) optimize the recovery of the Catarina scallop population and 2) maximize economic benefits to the local community brought about by the expected recovery. This assessment will provide our client with a tool to prioritize restoration initiatives and resources. More specifically we focus on the following objectives:

- Identify the existing biological, economic and social bottlenecks affecting the restoration and aquaculture of *Argopecten ventricosus*.
- Determine indicators of biological and economic feasibility for the restoration of the scallop population.
- Evaluate the current conditions of different habitat types in the Ensenada to support the growth and survival of the scallop.
- Simulate the dynamics of a Catarina scallop population using life-cycle parameters for the species.
- Develop and evaluate different restoration scenarios or strategies that reflect the array of possibilities for the restoration project.
- Identify and provide recommendations on the most important factors or actions for the successful recovery and sustainable management of its fishery.

Background

Small-scale fisheries

The ocean provides us with a variety of goods and services, some of which include employment and food. Seafood is the main source of protein for more than one billion people and accounts for 20% of global protein consumption (Gaines, 2014). To date, roughly 300 million people fish for an income, 90% of which fish in small-scale fisheries (Kalikoski, 2012). As the human population steadily rises, global demand for fish protein will only increase, leaving fisheries vulnerable to depletion. Small-scale fisheries are especially susceptible due to lack of resources for effective management, leading to fishery failures, which can have a strong social and economic impact on fishermen livelihoods.

Fisheries managers attempt to mitigate decline by maintaining target species abundance, establishing quotas, employing territorial use rights fisheries (TURFs), and implementing Marine Protected Areas (MPAs). However, these methods may not be sufficient to recover a collapsed population. In these cases, restoration may be necessary. When considering restoration, some questions may include:

- Has the ecosystem changed so much that the population cannot recover?
- What cultural or institutional obstacles might exist?
- Do we know enough about the life cycle of the species?
- Is there funding and support for a recovery effort?

About the Species

The Catarina scallop, Argopecten ventricosus, is a bay scallop that is found in near shore shallow lagoons (Figure 1B). Reaching sexual maturity around 6 months, each scallop produces up to 2-3 million eggs during each spawn (Blue Ocean Institute, 2012). The Catarina scallop has a larval duration in the water column for 12-30 days until it ultimately settles on shell hash, seagrass, and algal turf (Maeda-Martinez et al., 1993). The scallop reaches a recruitment size of 30 mm in 60-75 days and ultimately reaches an adult size of 56 mm in 1 year. The life span of the Catarina scallop is 2-3 years and can reach a height of 80 mm (Felix-Pico, 1994).

Figure B1. Juvenile Catarina scallops. Photo Credit: Nicole Corpuz.

Sensitive to sedimentation, water quality, and illegal fishing, the Catarina is vulnerable to environmental perturbations (Felix-Pico, 1994). Ranging from Northern Peru to Northern Mexico, the Catarina scallop is heavily fished, which over time has led to local extinctions in Panama and several locations in Baja California Sur (Leon-Carballo et al., 1991). Our research focuses on the Catarina scallop in the Ensenada de La Paz, located with the Bay of La Paz, in Baja California Sur, Mexico. The Ensenada was once the main fishing ground for the Catarina scallop in Baja California Sur, until the population collapsed in 1979 (Baqueiro et al., 1981).

The Catarina Scallop Fishery

The Catarina scallop fishery in Baja California Sur runs on a basin-specific total allowable catch system (TAC) with a minimum catch size in the Ensenada de La Paz of 56 mm. When the fishery is open, the Regional Fisheries Research Centers allow 60% of the total Catarina biomass at or above the commercial size to be fished in a given area (SAGARPA). The Catarina scallop is hand caught by divers, resulting in minimal to no bycatch and negligible environmental impact to the seafloor given the type of substrate on which it is generally found (Blue Ocean Institute, 2012). The Catarina scallop was one of the most important fished species of mollusk for the fishermen of El Manglito, a small community of fishermen in La Paz, from its peak in the 1950's until its ultimate depletion in 1978, when the density declined to zero organisms per square meter (Baqueiro et al., 1981). After the fishery closed in 1979 in the Ensenada de La Paz, the fishery migrated to other parts of Baja California Sur and continued to deplete Catarina resources in Bahia Concepcion, Ojo de Libre Lagoon, San Ignacio Lagoon, and Bahia Magdalena. Today, the Catarina scallop fishery remains closed in the Ensenada de La Paz.

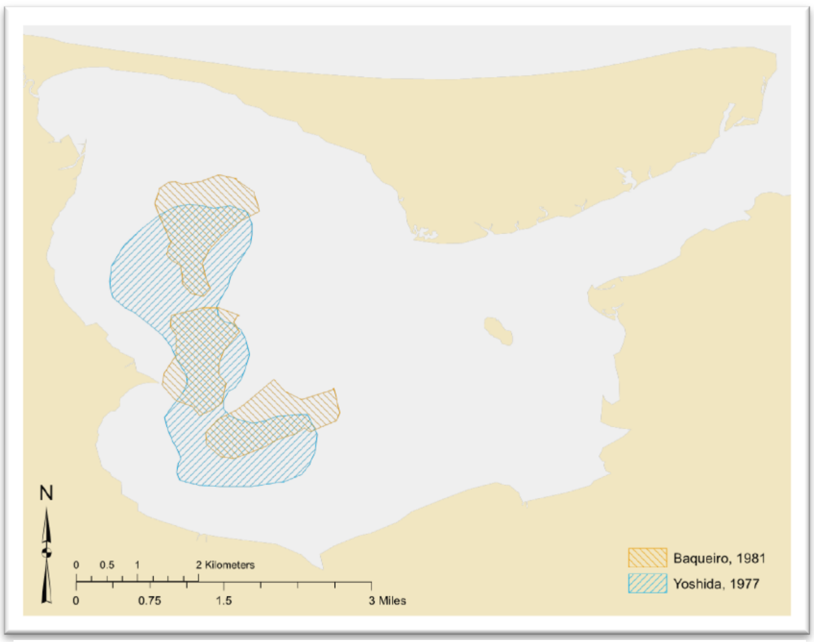

Figure B2. Historical Catarina Fishing grounds according to Baqueiro et al. (1981) and Yoshida (1977).

Causes of Collapse

Hurricane Liza

Hurricane Liza, rated as a Category 4, passed near the town of La Paz in October 1976. News sources report that hurricane Liza produced an 8-foot storm surge, flooding the city and causing the dike of the El Cajoncito creek to overflow and burst (Figure 2B). 20,000 people were left homeless, mudslides killed hundreds of people and lots of sediment was dumped into the Ensenada (Yates, 1976). According to local fishermen, this sudden deposit of sediment would have severely modified the habitat for scallops, making it not hospitable for the population anymore (Mendez, 2013).

Figure B3. Hurricane Liza broke the El Cajoncito dam, causing widespread flooding throughout La Paz. Photo courtesy of Harry Merrick.

Overfishing

Although a total allowable catch (TAC) was implemented and permission was required to fish for the Catarina scallop, records show that reported landing data was not accurate in estimating exactly how much Catarina was extracted from fishing grounds. The scallop was fished without permission, lacked accurate reports on the actual amount of Catarina landed, and fished while the fishery is closed. Many academics and government officials believe this is the reason for the depletion in, and inability of the Catarina scallop to repopulate the Ensenada de La Paz. (Baqueiro, et al. 1981)

Pollution

There is a lack of published literature on this topic, but it is worth noting that many fishermen and other stakeholders mention that historically, raw sewage from the local sanitation plant was released directly into the Ensenada. Today, a wastewater treatment plant exists; however the fishermen we interviewed believe that during seasons of high rainfall, the wastewater storage facility overflows and untreated water runoff flows into the Ensenada.

It is possible that a combination of Hurricane Liza, overfishing and water pollution ultimately caused the local extinction of the Catarina Scallop in the Ensenada. With a combination of abrupt changes in the substrate, changes in water temperature, and poorly regulated fishing, it is easy to see how the substrate could have changed to become an inhospitable environment for the settlement of Catarina recruits. With the hurricane event in 1976 and the Catarina's ultimate depletion in 1978, it is likely that the scallop was not able to successfully reproduce before the adult population died.

The Restoration of the Ensenada de La Paz

Stakeholders

Noroeste Sustentable (NOS)

Noroeste Sustentable is a non-governmental organization focused on sustainable community development for fishing communities in the northwestern part of Mexico. Located in the fishing community of El Manglito, NOS has been working in the Ensenada for the past ten years. NOS and fishermen are working together to restore and repopulate the lagoon not only with Catarina scallops but also other benthic resources to levels high enough to reopen the fishery.

The restoration of the Catarina scallop in the Ensenada is an initiative of high importance to NOS, and was conceived through participative and collective reflections with fishermen. These stakeholders see the restoration as an intervention that can create systemic change in the fishery system of Bay of La Paz. NOS aims to ensure that fishermen proposals, such as the restoration of the Catarina fishery, materialize and improve through collective learning. As this process moves forward the community is expected to develop a greater ownership over their resources.

NOS staff includes managers, scientists and fishermen who hold fishing concessions in the Ensenada. The staff collectively has deep environmental, socioeconomic, and legal knowledge about local conditions. In addition, NOS has close ties to Mexican government institutions, such as the Center for Biological Investigation in the Northwest (CIBNOR), the Interdisciplinary Center for Marine Science (CICIMAR) and the Universidad Autonoma de Baja California Sur (UABCS). These institutions have resources dedicated to aquaculture and fisheries research and continue to contribute valuable information and skills to this project.

El Mangle Center

Other stakeholders include El Mangle Center, a recently established campus dedicated to providing space and resources to engage civil society in restoring natural environments to promote economic and civil wellbeing. Funded by the Walton Foundation, El Mangle partnered in 2012 with NOS and 80 local fishermen on a large-scale project to clean the Ensenada.

El Manglito Fishermen

With over 100 fishermen with close family ties, El Manglito is a small community located just outside the city center of La Paz. While one hundred and seven of these fishermen are members of one of the twelve cooperatives of El Manglito, many others are not (Noroeste-Sustentable, 2014). The restoration of the Catarina fishery in the Ensenada is expected to strengthen the property rights of local fishers, to support the recovery of other species, such as the pen shell clam, and to generate jobs. In this way, fishermen and the local community stand to gain from a restored native fishery and a sustainable aquaculture industry in the Ensenada. The Catarina scallop fishery has therefore been an important part of the regional economy for more than half a century and part of the local cultural heritage for much longer.

How does the restoration work?

NOS and the fishermen use a special exploratory aquaculture permit (EAP) issued by CONAPESCA to restore the native fishery. Aquaculture can be used as a legal tool to enforce property rights and reduce illegal harvest of Catarina scallop. An EAP allows the fishermen to raise Catarina scallops in an aquaculture environment for the end goal of repopulation. Although this permit also allows the fishermen to sell the scallops, CONAPESCA collects 5% of the profit to invest in the development of research activates (FAO, 2014).

The purpose of the restoration of the Catarina scallop is two-fold: to bring community engagement to the El Manglito fishing community, and to restore the population so that the Catarina can help reduce fishing pressure on the pen shell scallop. There are several species of Pen Shell scallops: *Atrina maura*, *Pinna rugosa*, *Pinna tuberculosa*, and for none of which aquaculture methods are available. With a higher commercial value than the Catarina scallop, the Pen Shell scallops also have declining populations in the Ensenada (Noroeste-Sustentable, 2014).

The Cooperative Mangle Cenizo has an exploratory aquaculture permit valid from December 2011 to December 2016 for aquaculture within the Ensenada. Of the fisher members of the Mangle Cenizo, NOS was able to gain the support of community leaders Guillermo Mendez Camacho and Hubbert Mendez Camacho. In collaboration with NOS and the El Mangle Center, Hubbert and Guillermo piloted the first attempt to restore the Catarina scallop in 2012. Catarina scallops were grown in the Robles Aquaculture facility to juvenile size and were donated to the restoration effort.

Since that time, NOS and the fishermen have developed a different repopulation model. The fishermen now receive Catarina scallop seeds from Robles Aquaculture. These scallop seeds are raised in a nursery in the El Mangle Center, where the seeds are grown in mesh bags inside Nestier trays until they reach a size of roughly 10 mm. The juveniles are transferred into corrals until they reach a size of 30 mm. The scallops are then collected and released in the Ensenada. The goal is to seed enough mature scallops to reproduce and repopulate the Ensenada with Catarina scallops.

Challenges to the effort

Community Engagement

Running the nursery is an intensive effort and many knowledgeable hands are needed. One of the greatest challenges to the restoration effort is community engagement. NOS, Hubbert and Guillermo were able to engage 12 additional fishermen from El Manglito to join the effort. These fishermen design, build and clean cages, manage scallop densities within the nursery and corrals, and release scallops into the wild.

Surveillance and Illegal fishing

One of the biggest threats to the success of the repopulation effort is illegal fishing. In Mexico, it is estimated that illegal fishing makes up for 20% of the catch in commercial fisheries. The number is higher for scallops at 40%(Agnew et al., 2009). Illegal activity has directly impacted the Catarina restoration effort. In 2012, during the first attempt at repopulation, the nursery corral located in the Mangle Cenizo development aquaculture concession was broken into and all the scallops were taken. This event, along with the illegal fishing of the Pen Shell scallop, led to the development of a surveillance team of local fishermen. These fishermen patrol the Ensenada for illegal fishermen, locally known as *patitos*. *Patitos* typically swim from shore with snorkel, mask, fins, and extraction tools and collect scallops and clams from the Ensenada.

The controversy with *patitos* is delicate given that the definition of illegal is not very clear. Some *patitos* belong to a cooperative, however, they are fishing a resource for which the fishery is closed, or for which they do not have a fishing permit. Other *patitos* do not belong to a cooperative and are fishing for sustenance or for a small profit. To add to the complication, some *patitos* are relatives of the fishermen involved in the restoration effort. That is why it is important that the patrolman approach the illegal fishermen in a non-threatening way.

Mitigation

NOS and the fishermen collaborate to come up with mitigation techniques against these factors. After the first nursery robbery, the nursery was moved to a beachfront concession constantly under 24-hour surveillance. As of 2014, the scallop grow-out corrals were also placed in this beachfront concession in order to reduce fuel costs. In order to monitor the effectiveness of the patrolmen, each patrolmen is equipped with a GPS and has check in times and locations throughout the day.

Methods

Bioeconomic model

In order to test the impacts of different restoration strategies, we identified major population bottlenecks that would inhibit recovery. These bottlenecks (Figure M1) include the lack of settlement habitat, illegal fishing pressure, and population enhancement through seeding. We tested the costs and benefits of each restoration scenario by creating a bioeconomic model to simulate conditions influencing the Catarina scallop population in the lagoon. We tested 15 restoration scenarios, each a unique combination of different levels of habitat restoration, aquaculture intensity, surveillance and seeding.

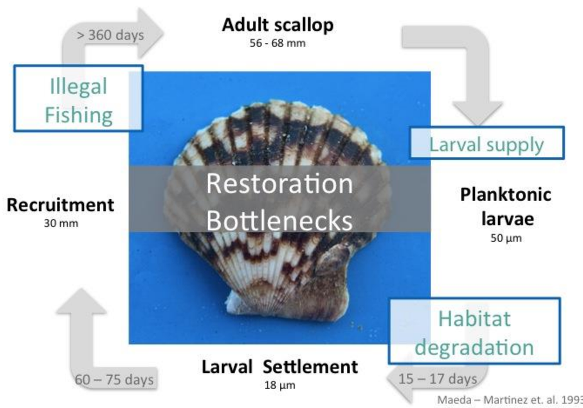

Figure M1. Life cycle and limited larval supply, lack of settlement habitat, and illegal fishing pressure may be factors limiting the success of recovery.

Hydrological Isolation

We assume that the Catarina scallop population in the Ensenada is hydrologically isolated from other populations in the Gulf of California. Although the fishery closed in the Ensenada after the collapse, the Catarina population has failed to recover. The larval duration of the Catarina scallop, which lasts from 12 to 30 days (Maeda-Martinez et al., 1993), and the oceanographic conditions of the Ensenada may have isolated this population from others in the Gulf of California. Simultaneously, overfishing in the Ensenada and in the adjacent Bay of La Paz may have eliminated any possibility of local self-repopulation. Studies in Florida indicate that the larval transport of the bay scallop *Argopecten irradians* from source sites is unlikely, given a larval duration of 20 days (Arnold et al., 1998). In addition, the mollusk *Littoria littorea*, which like Catarina has a veliger larval stage and period of about 30 days, has a realized (mean) dispersal distance of 40-42 km (Shanks et al., 2003). The area of the Ensenada is 42 km^2.

Life Cycle

In order to reflect the dynamics of a Catarina scallop population we used life-cycle parameters and relationships to develop an age-structured population model. This population model builds upon individual growth and stock-recruitment relationships, and other life history parameters. The population is modeled as a single entity, with no interaction with external populations. We assume that the starting population is zero, given the persistent absence of individuals of the species in the Ensenada after the collapse of the fishery in 1979 (Baqueiro et al., 1981). We used a total of 4 age classes (0-3 years), given that this species has an average lifespan of 2-3 years(Felix-Pico, 1994). Each time interval in the model represents 1 year, and the population was simulated through 100 years.

Von Bertalanffy Growth Function

The Von Bertalanffy growth function (VBGF) has been widely used to model individual growth in exploited fish populations (Von-Bertalanffy, 1957). Moreover, the VBGF has been reported to be an accurate descriptor of growth in scallops (MacDonald and Thompson, 1985) as well as other bivalves (Bachelet, 1980; Ceccherelli and Rossi, 1984; Griffiths, 1981). The average length at each age class was calculated as follows:

$$L_t = L_\infty \cdot (1 - e^{-k(t-t_0)})$$

Where L_t is the length at age t, L_{inf} is the asymptotic length, k is the growth coefficient and t_0 is the theoretical age at size zero. Input parameters of *A. ventricosus* were taken from(Felix-Pico, 1994), with the exception of t_0, which was found to provide unrealistic growth projections. Thus, this parameter was calculated using the equation developed by Pauly (1979), which uses VBGF parameters:

$$log(-t_0) = -0.3922 - 0.2752 \cdot \log(L_\infty) - 1.038 \cdot \log(k)$$

Length-weight

Weight (kg) at any given age class (W_i) was calculated from the length parameter using a simple exponential relationship and the mean length estimated by the VBGF (L_i). The coefficients (*a, b*) for the length-weight equation were taken from Felix-Pico *et al.* (1997) (Felix-Pico et al., 1997):

$$W_i = a \times L_i{}^b$$

Fecundity

The average number of eggs generated by individual scallops at each age class (f_i), was also estimated through an exponential relationship. Fecundity parameters for *A.* ventricosus (Villalejo-Fuerte and Ochoa-Baez, 2006) were used for the coefficient and exponent inputs, *a* and *b*, as well as the mean length at each age class (L_i):

$$f_i = a \times L_i{}^b$$

Maturity

We used the following log-growth equation to calculate maturity-at-length (m_i), which is used to estimate the reproductive output of the population. Parameters for the size at which 50% and 95% of individuals are mature, m_{50} and m_{95}, were obtained from Villalejo-Fuerte and Ochoa Baez (Villalejo-Fuerte and Ochoa-Baez, 2006):

$$m_i = \frac{1}{1 + e^{\left(\frac{(-log(100)\times(L_i - m_{50}))}{m_{95} - m_{50}}\right)}}$$

Total egg production (eggs/yr) for each year (E_t) was calculated as the multiplication between the number of individuals at each age class in that year (N_{it}) with its age-specific fecundity (f_i) and maturity (m_i):

$$E_t = \sum f_i \cdot m_i \cdot N_{it}$$

Stock-recruitment

To understand how a population reproduces and grows in time, it is fundamental to identify how the mature individuals of the population (i.e. spawning stock) and their reproductive output (i.e. eggs), translate into new young that will be added to the population. This represents nature's regulation of a population size, independent of whether or not the populations are being exploited (Sparre and Venema, 1998). This is important, assuming that the scallop population is expected to suffer from illegal and legal fishing once the fishery opens. We modeled recruitment with the function developed by (Beverton and Holt,1957):

$$R_t = \frac{E_{t-1}}{(\alpha - \beta \cdot E_{t-1})}$$

Where R_t is the numbers of recruits in year t, E_{t-1} is the number of eggs from year *t-1*, and α – β are parameters of the relationship. These 2 parameters were estimated as follows:

$$\alpha = E_0 \cdot \frac{1 - S}{4 \cdot S \cdot R_0}$$

$$\beta = \frac{5 \cdot (S - 1)}{4 \cdot S \cdot R_0}$$

Where E_0 is maximum egg production, R_0 is maximum recruitment and S is steepness. Since virgin recruitment and egg production parameters are not available for this species, we estimated maximum egg production (E_0) and recruitment (R_0) by using historical landings reported for the final year the fishery was open in the Ensenada (Baqueiro et al., 1981). We used conservative value of steepness of 0.7, which along with our E_0 and R_0 estimates, would reduce the likelihood that our population projections would be overestimated.

Natural mortality

The survival of the population from each year to the next was determined by natural mortality (M_w) as well as legal (uL) and illegal fishing mortalities (uI) to each cohort of the current population. Since natural mortality was not available in the literature for this species, we estimated this parameter using the equation developed by Froese and Pauly (2000) (Froese and Pauly, 2000) and the L_{inf} and K parameters from the VBGF:

$$M_W = 10^{(0.566 - 0.718 \cdot \log(L_\infty) + 0.02T)}$$

Where T is the mean annual water temperature (24.65°C). Although this equation was developed for marine fishes, we found our estimate of M_W to be similar to the mortality of other species of scallops in the wild (Bricelj et al., 1987; Gwyther and McShane, 1988; Summerson and Peterson, 1990; Wolff et al., 2007).

Fishing

One of the main goals of the restoration project is to reopen the fishery of the Catarina scallop, which is expected to significantly contribute to the livelihoods of the local fishing community. We approached this aspect of the system by including legal and illegal fishing levels into the model.

Illegal fishing

According to our interviews with fishermen and stakeholders, illegal harvest continues to occur in the Ensenada, even while fishing has been banned for many resources. With this knowledge, we can expect that illegal fishing will occur at every stage of the project and continue to occur when the fishery opens. However, the intensity of illegal fishing would depend on the level of surveillance and its effectiveness. We modeled 3 levels of illegal fishing: 40%, 20% and 5%. We assume that in the absence of surveillance, illegal fishing would have a high impact by removing 40% of the vulnerable population (Noroeste-Sustentable, 2014), which is still below recent estimates for Mexico. If the surveillance were partial (e.g. 6 hours a day, 5 days a week), then illegal fishing would be controlled to a level of 20% of the vulnerable population, which is close to global estimates of illegal fishing for scallops(Agnew et al., 2009). If the surveillance were highly effective and with high levels of fisher engagement (e.g. twelve hours of surveillance, every day), then we expect that illegal fishing would be reduced to 5%. Even though these estimates are rough, recent evidence has shown that even low surveillance can have as significant impact in decreasing illegal fishing and poaching (Davis et al., 2004).

Fishing mortality (u)

The number of scallops removed every year by legal and illegal fishing ($F_{t,i}$) was determined by multiplying the number of scallops at each age class with size selectivity of fishing (s_L) and the level of legal fishing (u_L). The same relationship was used to calculate the removal of individuals by illegal fishing, but instead using illegal selectivity (s_I) and illegal fishing level (u_I). Both fishing mortalities were calculated in the following equation:

$$F_{t+1,i} = N_{t,i} \cdot (u_L \cdot s_L) \cdot (u_I \cdot s_I)$$

Finally, when all sources of mortality are accounted, the number of individuals for all cohorts surviving to the next year ($N_{t+1,i}$) is:

$$N_{t+1} = \sum N_{t,i} \cdot (1 - M_W) \cdot (1 - s_L \cdot u_L) \cdot (1 - s_I \cdot u_I)$$

Fishery Economics

Fishery profits are expected only during the years when the fishery is open. Since the decision to open a fishery is heavily influenced by political factors, we made the assumption that the Catarina scallop fishery would open when the population reached 25% of virgin biomass (B_0); which is a common reference limit used in the US and Canada (Hillborn et al., 2003). According to a recent report by the Centro Regional de Investigacion Pesquera (CRIP), the current regulation for the Catarina scallop fishery allows for a total quota of 60% of the individuals at and above the minimum legal size of 56 mm available for harvest in a fishing bank in the Ensenada de La Paz (Leon-Carballo et al., 1991).

Fishing revenues were calculated by using the local market price estimate (see Market Price) and the given catch at the selected fishing mortality. Illegal fishing revenues were not included in this model. In order to estimate the projected monetary value of fishing, we estimated the Net Present Value of the fishery (NPV_F) by summing discounted fishery profits (P_F) after 20 years, and using 2 discount rates: one at 3%, assuming that the restoration would be performed by the non-profit organization NOS (Libecap, 2013); and one at 14%, which is a discount rate typically applied to a for-profit business. The NPV_F was calculated as follows:

$$NPV_F = \sum \frac{P_F}{(1+r)^i}$$

Market price

We used a price of US$ 0.63 per kg of whole scallops (with shell), based on local estimates of US$5.38 per kilogram of scallop meat (no shell) and a ratio of 0.12 of scallop meat over total scallop weight. This ratio used our length-weight relationship for a scallop of 56 mm, and mean scallop meat weight for the species (Baqueiro et al., 1981; Felix-Pico et al., 1989).

Habitat

Through an extensive literature review, we found that both settlement and adult survival rely on appropriate habitat for many similar scallop species. Catarina larvae seek out shell for settlement and adults require more complex algal or seagrass refuges from predators (Arnold, 1995; Brumbaugh et al., 2006; Eckman, 1987; Thayer and Stuart, 1974). Historically, Catarina scallops were found in muddy portions of the Ensenada that contained a layer of shell hash as well as various species of algal turf, suggesting that this species follows the same trends defined for the similar scallop species in the reported studies (Baqueiro et al., 1981; Yoshida and Alva, 1977). Through informal interviews, fishermen suggest that habitat quality in the Ensenada has declined. In order to account for this factor in our model, we used habitat availability as a proxy for recruitment. Since Catarina scallops are aggregate settlers, we assume recruitment is limited by the level of suitable habitat. To quantify this in our model, we look at historical landing records to estimate past population size and level of recruitment.

Habitat Parameters

Since landings data is limited for Catarina scallops in the Ensenada, we used the estimated quantity of scallops landed in 1978, the final year the fishery was open, as a reference for historical abundance (H_0). We consider this baseline to be conservative since the population in 1978 was heavily exploited. According to Baqueiro et al. (1981), the population of Catarina over the legal catch size in 1978 was of approximately 19,000,000 scallops. In order to produce this quantity of adult scallops, our model estimated recruitment to be 24,000,000. Thus, our value for Virgin Recruitment (R_0) is 24,000,000, which amounted to a population size of 41,847,000 scallops. We transformed this value to Biomass using our length-weight relationship, and obtained estimate a proxy for Virgin Biomass (B_0) equal to 760,011 Kg. Using these values, we calculated current recruitment by reducing virgin recruitment (R_0) by the relative availability of habitat. For our analysis, we assume that current suitable habitat (H_1) represents 30% of the habitat available in the final year the fishery was open, thereby reducing recruitment from 24,000,000 to 7,200,000.

For our model we varied the habitat availability at 30%, 60% and 100% to represent current levels of habitat, and potential availability with moderate and intense habitat restoration, respectively. We consider 'habitat' to include both shell hash and algal turfs. With this assumption we presume that habitat that supports recruits may also provide refuge for adults, resulting in a constant natural mortality for scallops that settle in both existing and restored habitats.

Costs

In order to estimate habitat restoration costs, we assume that habitat restoration would require enhancing the substrate with shell hash to which algal turf would colonize naturally. Based on reported values for oyster restoration, which require similar practices, sources cited costs for restoration at roughly $2,500USD per hectare (Environmental Law Institute, 2011).

It is possible that other factors, such as changes in water quality, could result in recruitment limitation, however, due to the lack of data and literature on this topic we were unable to include such elements in the model.

Aquaculture

Aquaculture involves the cultivation and harvest of marine species under controlled conditions. In scallop aquaculture, the scallops are confined in cages, thus, reducing the mortality rate by providing protection from scallop predators. The government has granted exploratory aquaculture concessions to fishermen who are interested in repopulating the Ensenada coastal lagoon with Catarina. This type of aquaculture has the potential to provide greater property rights to exploratory aquaculture concession permit holders. This is especially beneficial in the Ensenada, where illegal fishing poses a significant threat to marine species of commercial value, such as the Catarina scallop.

In addition, our client NOS is currently conducting basic aquaculture operations, such as growing Catarina from seed to juvenile size in a nursery, and growing scallops to a mature size in aquaculture cages. Aquaculture offers the potential to generate revenue independent of the wild scallop fishery. This revenue could be used as an alternative source of income while wild population recovers. Scallops in aquaculture also have the potential to reproduce and release larvae outside the cages to the rest of the Ensenada. Because of these benefits, we chose to evaluate the benefits of scaling up aquaculture.

Aquaculture Parameters

The aquaculture operation involves 2 stages: the nursery stage and the aquaculture stage. Within the nursery, scallops are grown from seed of approximately 5 mm in size to juveniles of 30 mm (length of the longest rib). The nursery operation is set up in an exploratory aquaculture concession close to shore, where fishermen can easily access with snorkeling gear. In the nursery, the scallops are contained inside mesh bags stored in floating plastic trays, called Nestier cages. These Nestier cages are stacked and covered with mesh. A buoy and weight are attached to allow the setup to remain in the water column.

Once the scallops reach a size of approximately 30 mm they are transferred to exploratory aquaculture concessions where they are placed directly on the ocean seafloor, covered with a cage, and grown to or above the legal adult size of 56 mm. The cages have a PVC frame and mesh walls attached to the frame with fishing rope. The size and shape of these cages are variable. Although few, some fishers go as far as building in a mesh bottom, lifting the cages off the seafloor, and supporting them with wooden structures. When modeling the scenarios we used the lowest mortality rate equal to 0.175, which we derived from our summer experiment, to calculate scallop mortality in the aquaculture cages.

The local fishermen have been granted 116,000 m^2 of exploratory aquaculture concessions. Following other examples of aquaculture in Chile, we assume that only 10% of this area would be covered with cages and called this situation high intensity aquaculture. The remaining space would be used as corridors where divers can access the cages. Assuming an optimal aquaculture density of 200 scallops per m^2, the maximum number of scallops that can be grown in the current aquaculture area is 2,320,000 scallops.

To model the intensity of aquaculture operation in the bioeconomic model we designed 3 levels of aquaculture intensity.

- The no-aquaculture level represents a situation in which all scallops produced in the nursery would be used to seed the wild population. The costs of operating the nursery would therefore be internalized by the wild fishery operation since it directly benefits from seeding.
- The low-intensity aquaculture level represents a situation where 580,000 scallops, 25% of the maximum number of 2.32 million, would be matured in cages to the 56 mm legal size and then harvested for sale.
- The high intensity aquaculture scenario represents a situation where 2,320,000 scallops would be matured in the cages to the 56 mm legal size and then harvested for sale. For both the low and high aquaculture intensity scenarios, the nursery would be expected to produce the corresponding number of scallops, and the cost of production would be assumed by the aquaculture operation.

Aquaculture Assumptions

One important aquaculture assumption of our bioeconomic model is that scallop in aquaculture cages would reproduce before harvest. A percentage of the larvae would recruit to the wild scallop population, while a portion of the larvae would settle within the aquaculture cage or settle in seed collection bags in the water column. We also assumed that the cages would contain a fixed density of

200 scallops/m^2 at any given time; the optimal stocking density according to Maeda-Martinez et al. (2000) (Maeda-Martinez et al., 2000).

Aquaculture Costs

Labor for the aquaculture operation is provided by 14 fishermen who work 6 hours a day, 5 days a week. The salary per day is USD$ 26.53. In 2013, the first year of the nursery, the fishermen produced 340,000 scallops to a size of 30 mm. We used this value as the baseline productivity for the aquaculture operation. We assumed that the associated costs of producing the 340,000 scallops would increase linearly with aquaculture size (see Scenarios section). The cost to produce 340,000 scallops at a size of 30 mm is USD$91,577 (Plascencia, 2014). In order to account for aquaculture production cost for the low or high intensity number of scallops, we created a correction factor dividing the desired aquaculture scallop quantity, by the base production scallop quantity.

$$Low\ intensity\ aquaculture\ level: \$91{,}577 * \left(\frac{580{,}000\ scallops}{340{,}000\ scallops}\right) = \$156{,}219.59$$

$$High\ intensity\ aquaculture\ level: \$91{,}577 * \left(\frac{2{,}320{,}000\ scallops}{340{,}000\ scallops}\right) = \$624{,}878.35$$

We accounted for labor costs on an annual basis, while material replacement was incurred every 5 and 10 years. Revenues were calculated by multiplying the quantity of scallops at harvest size by the market price, which fluctuated between \$5.38 and \$7.69 USD per kilogram of adductor muscle. Profits were calculated by subtracting nursery costs and labor and materials from the revenue. The net present value per year was also calculated (see NPV sections). Detailed baseline production costs are listed in Table M1.

Table M1. Costs of scallop aquaculture operation in 2013

Aquaculture	Cost (US$)	Frequency (yr)
Nursery		
Material and gear	$2,346.15	5
Salaries	$89,169.23	1
Deadweights	$61.54	10
Farming		
Materials and gear	$4,153.85	5
Maintenance	$32,500.00	1
Fuel	$492.31	1

Seeding

Since the Catarina scallop population in the Ensenada de La Paz would be hydrologically isolated from other populations in Baja California Sur, we conclude that population enhancement is necessary to restart the local reproduction and recruitment processes. In addition, our client NOS has been conducting seeding operations when we started working on the restoration project. For this reason, we varied seeding lengths in years as well as quantities of scallops seeded.

Seeding Parameters

The seeding operation involves growing scallops from a spat size of 5 mm to juveniles at 30 mm in length inside Nestier cages and corrals (Figure M2). The nursery operation is set up in an exploratory aquaculture concession close to the shore, which fishermen can easily access with snorkeling gear. At the nursery the scallops are contained inside floating Nestier cages stacks, and cages made with mesh and PVC tubes, both of which are fixed with nylon ropes and concrete deadweights to the bottom, and to buoys at the surface. Once the scallops reach a size of approximately 30 mm they are transferred to different areas of the Ensenada, and placed directly on the

Figure M2. Fishermen holding Nestier tray containing juvenile scallops, which are grown in the nursery up to 30 mm. Photo credits: Daniella Rojas.

ocean seafloor. The areas where the 30 mm scallops are seeded would be considered open access once the fishery reopens.

To model the effect of seeding on the Catarina population recovery in the bioeconomic model we designed 4 levels of seeding.

- Level 1: The Ensenada seafloor is seeded with **340,000 scallops for 1 year**. Since NOS has already seeded 340,000 scallops, this would be the equivalent of NOS discontinuing seeding the seafloor with additional scallops.
- Level 2: The Ensenada seafloor is seeded with **340,000 scallops per year, for 3 years**. Since NOS has already seeded 340,000 scallops this would be the equivalent of NOS seeding the seafloor for **2 more years** with **340,000 scallops per year**.
- Level 3: The Ensenada seafloor receives **680,000 scallops per year, for 3 years**. Since NOS has already seeded 340,000 scallops this would be the equivalent of NOS seeding the seafloor for **2 more years** with **680,000 scallops per year**.
- Level 4: The Ensenada seafloor receives **680,000 scallops per year, for 6 years**. Since NOS has already seeded 340,000 scallops this would be the equivalent of NOS seeding the seafloor **for 5 more years** with **680,000 scallops per year**.

One important assumption is that NOS and the fishers can only obtain funding for seeding for a maximum of 6 years. Therefore, we limit seeding to 6 years.

Seeding Costs

Labor is provided by 14 fishermen, who work 6 hours a day for five days a week. The salary per day is USD$ 26.53. In 2013, the first year of the nursery, the fishermen produced 340,000 scallops to a size of 30 mm. We used this value as the baseline productivity for the seeding operation. We assumed that the associated costs of producing the 340,000 scallops would increase linearly with the seeding quantity (see Scenarios section). The cost to produce and seed 340,000, 30 mm scallops in the nursery is $108,073 (NOS financial report). To account for the nursery cost of producing each of the four seeding levels we created a correction factor dividing the desired seeding scallop quantity, by the base production scallop quantity. For the 1st and 2nd, and for the 3rd and 4th seeding levels the only things that varies is the number of years, and the cost of seeding is assigned per year.

$$1st\ \&\ 2nd\ seeding\ levels: \$108{,}073 * \left(\frac{340{,}000\ scallops}{340{,}000\ scallops}\right) = \$108{,}073$$

$$3rd\ \&\ 4th\ seeding\ levels: \$108{,}073 * \left(\frac{680{,}000\ scallops}{340{,}000\ scallops}\right) = \$216{,}146$$

We accounted for labor costs on an annual basis, while material replacement was incurred every 5 and 10 years. These costs were assumed by the wild fishery since it would receive the most direct benefit from seeding (see Wild Fishery section). Detailed baseline production costs are listed in Table M2.

Table M2. Costs of scallop seeding operation in 2013

Seeding	Cost (US$)	Frequency (yr)
Nursery		
Material and gear	$2,346.15	5
Salaries	$89,169.23	1
Deadweights	$61.54	10
Transport, nursery to seafloor		
Fuel & oil	$246.15	1

Recovery Scenarios

Of all possible scenario combinations we selected 15 as the most realistic ones and most likely to occur. We then modeled the recovery of the population under each of these 15 scenarios over 100 years.

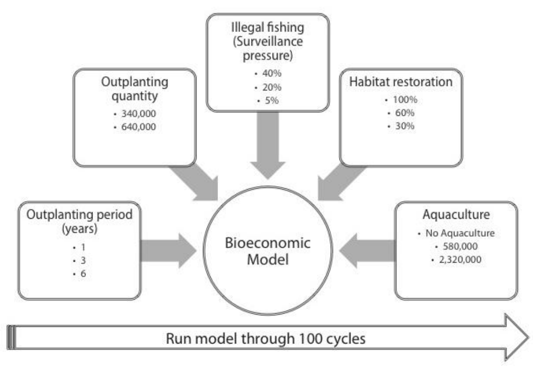

Figure M3. Recovery variables and their corresponding values.

Scenario 1: During the 100 year period, all of the scallops grown in the nursery are matured in an aquaculture system that supports 2,320,000 scallops per year. The base number of 340,000 scallops is seeded during the first year, and larval input during the next 99 years comes from the scallops inside the aquaculture cages and from the seeded scallops. The surveillance level is high resulting in 5% illegal fishing removing scallops from the wild population, not from aquaculture. Catarina habitat is not restored and remains at its current 30% level.

Scenario 2: During the 100 year period there is no aquaculture. The base number of 340,000 scallops is seeded during the first year, and larval input during the next 99 years comes from the seeded scallops. The surveillance level is high resulting in 5% illegal fishing removing scallops from the wild population. Catarina habitat is restored to the historical level of 100%.

Scenario 3: During the 100 year period there is no aquaculture. The base number of 340,000 scallops is seeded during the first year, and larval input during the next 99 years comes from the seeded scallops. The surveillance level is medium resulting in illegal fishing of 20% illegal fishing removing scallops from the wild population. Catarina habitat is not restored and remains at its current 30% level.

Scenario 4: During the 100 year period there is no aquaculture. The base number of 340,000 scallops is seeded during the first year, and larval input during the next 99 years comes from the seeded scallops. The surveillance level is medium resulting in illegal fishing of 20% illegal fishing removing scallops from the wild population. Catarina habitat is restored to the historical level of 100%.

Scenario 5: During the 100 year period, the base number of 340,000 scallops is seeded during the first year, after that all of the scallops grown in the nursery are matured in an aquaculture system that supports 580,000 scallops per year. Larval input during the next 99 years comes from the scallops inside the aquaculture cages and from the seeded scallops. The surveillance level is low resulting in 40% illegal fishing removing scallops from the wild population, not from aquaculture. Catarina habitat is not restored and remains at its current 30% level.

Scenario 6: During the 100 year period, the base number of 340,000 scallops is seeded during the first year, after that all scallops grown in the nursery are matured in an aquaculture system that supports 2,320,000 scallops per year. Larval input during the next 99 years comes from the caged scallops and from the seeded scallops in the first year. The surveillance level is low resulting in 40% illegal fishing removing scallops from the wild population, not from aquaculture. Catarina habitat is not restored and remains at its current 30% level.

Scenario 7: During the 100 year period there is no aquaculture, and 340,000 scallops are grown in the nursery and seeded every year for a maximum of 3 years. Larval input during the next 97 years comes from the scallops seeded during the first 3 years. The surveillance level is high resulting in 5% illegal fishing removing scallops from the wild population. Catarina habitat is restored to the intermediate level of 60%.

Scenario 8: During the 100 year period, there is no aquaculture and 340,000 are grown in the nursery and seeded at 30 mm every year for a maximum of 3 years. Larval input during the next 97 years comes from the scallops seeded during the first 3 years. The surveillance level is medium resulting in 20% illegal fishing removing scallops from the wild population. Catarina habitat is not restored and remains at its current 30% level.

Scenario 9: During the 100 year period, 340,000 scallops are grown every year in the nursery and seeded at 30 mm every year for a maximum of 3 years. The nursery also provides 30 mm scallops which are later matured in an aquaculture system that supports 580,000 scallops per year. Larval input during the next 97 years comes from the scallops seeded during the first 3 years and from the scallops inside the aquaculture cages. The surveillance level is medium resulting in 20% illegal fishing removing scallops from the wild population. Catarina habitat is restored to the intermediate level of 60%.

Scenario 10: During the 100 year period there is no aquaculture, and 680,000 scallops are grown every year in the nursery and seeded at 30 mm every year for a maximum of 3 years. Larval input during the next 97 years comes from the scallops seeded during the first 3 years. The surveillance level is high resulting in 5% illegal fishing removing scallops from the wild population. Catarina habitat is restored to the historical level of 100%.

Scenario 11: During the 100 year period, 680,000 scallops are grown every year in the nursery and seeded at 30 mm every year for a maximum of 3 years. The nursery also provides 30 mm scallops which are later matured in an aquaculture system that supports 2,320,000 scallops per year. Larval input during the next 97 years comes from the scallops seeded during the first 3 years and from the scallops inside the aquaculture cages. The surveillance level is high resulting in 5% illegal fishing removing scallops from the wild population. Catarina habitat is restored to the historical level of 100%.

Scenario 12: During the 100 year period, 680,000 scallops are grown every year in the nursery and seeded at 30 mm every year for a maximum of 3 years. The nursery also provides 30 mm scallops which are later matured in an aquaculture system that supports 580,000 scallops per year. Larval input during the next 97 years comes from the scallops seeded during the first 3 years and from the scallops inside the aquaculture cages. The surveillance level is medium resulting in 20% illegal fishing removing scallops from the wild population. Catarina habitat is restored to the intermediate level of 60%.

Scenario 13: During the 100 year period there is no aquaculture, and 680,000 scallops are grown every year in the nursery and seeded at 30 mm every year for a maximum of 6 years. Larval input during the next 97 years comes from the scallops seeded during the first 6 years. The surveillance level is high resulting in 5% illegal fishing removing scallops from the wild population. Catarina habitat is restored to the intermediate level of 60%.

Scenario 14: During the 100 year period there is no aquaculture, and 680,000 scallops are grown every year in the nursery and seeded at 30 mm every year for a maximum of 6 years. The nursery also provides 30 mm scallops, which are later matured in an aquaculture system that supports 580,000 scallops per year. Larval input during the next 97 years comes from the scallops seeded during the first 6 years and from the scallops inside the aquaculture cages. The surveillance level is high resulting in 5% illegal fishing removing scallops from the wild population. Catarina habitat is restored to the historical level of 100%.

Scenario 15: During the 100 year period there is no aquaculture, and 680,000 scallops are grown every year in the nursery and seeded at 30 mm every year for a maximum of 6 years. Larval input during the next 97 years comes from the scallops seeded during the first 6 years. The surveillance level is low resulting in 40% illegal fishing removing scallops from the wild population. Catarina habitat is not restored and remains at its current 30% level.

Table M3. Fifteen restoration scenarios varying seeding period, seeding quantity, illegal fishing pressure, virgin habitat area, and aquaculture intensity .

Restoration Scenarios

Scenario	Description	Outplanting period (years)	Outplanting quantity	Illegal fishing pressure	Virgin habitat area	Aquaculture intensity
1	Heavy aquaculture and heavy surveillance	1	340,000	0.05	0.3	3
2	Heavy surveillance and heavy habitat restoration	1	340,000	0.05	1	1
3	Mild surveillance	1	340,000	0.2	0.3	1
4	Mild surveillance and heavy habitat restoration	1	340,000	0.2	1	1
5	Mild aquaculture; no surveillance or habitat restoration	1	340,000	0.4	0.3	2
6	Heavy aquaculture	1	340,000	0.4	0.3	3
7	Heavy surveillance, mild habitat restoration	3	340,000	0.05	0.6	1
8	Mild surveillance	3	340,000	0.2	0.3	1
9	Mild surveillance, mild habitat restoration, mild aquaculture	3	340,000	0.2	0.6	2
10	Heavy surveillance and heavy habitat restoration	3	680,000	0.05	1	1
11	Heavy surveillance, heavy habitat restoration and heavy aquaculture	3	680,000	0.05	1	3
12	Mild surveillance, mild habitat restoration and mild aquaculture	3	680,000	0.2	0.6	2
13	Heavy surveillance, heavy habitat restoration	6	680,000	0.05	1	1
14	Heavy surveillance, heavy habitat restoration, and mild aquaculture	6	680,000	0.05	1	2
15	Heavy outplanting only	6	680,000	0.4	0.3	1

Model analysis

Outputs

Population Biomass (B/B_0)

In order to identify the success of each restoration scenario, we compare the biomass (B) at any given year to a baseline biomass (B_0). We define the baseline biomass (B_0) as the Virgin Biomass, from the total population of scallops during the final year the fishery was open. This gives us the ratio B/ B_0. We display the population in ratio form because our goal is to compare restoration strategies, not to provide precise values of population biomass or economic returns. By graphing the B/B_0 of each scenario for each year, we are able to track the population growth over time.

Average Catch Value

Average Catch Value is calculated by taking the average revenue of the annual catches from the wild fishery over the course of 50 years. This value allows us to identify the amount each scenario could possibly generate.

Fishery Net Present Value (NPVw)

The fishery Net Present Value is the sum of the profits derived from wild caught scallops over 20 years, discounted at a rate of 3%. NPVw is used to determine the worth of the wild fishery in a given scenario.

Aquaculture Net Present Value (NPVaq)

The Aquaculture Net Present Value is the sum of the profits derived from the sale of scallops raised in aquaculture, discounted at a rate of 3%. NPVaq is used to determine the worth of the aquaculture operation in a given scenario.

Restoration Investment

We assume restoration would only occur in the historical fishing grounds because the highest scallop densities have been found there in the past (Yoshida and Alva, 1977). The cost to restore the historical fishing grounds in the Ensenada is USD$10,834,788.48. In any given scenario, the restoration costs can vary from USD$0 for scenarios without restoration, or USD$ $3,250,436.54 for scenarios restored to 60% virgin habitat, to $10,834,788.48 for scenarios with 100%. These values represent the amount of restoration investment that must be made to recover the habitat to either 60% or 100% of the condition in 1978 prior to the collapse of the Catarina fishery.

Fishery NPV/Fishery NPVmax

In order to compare the value of the wild fishery for each scenario, we compare the NPVw of a given scenario against the NPVw of the scenario with the highest value. This approach allows us to analyze how productive each scenario could be in relation to the productivity of the most productive scenario.

Years to Carrying Capacity (K)

Carrying Capacity (K) is defined as the maximum number of individuals a population size can sustain. This value is defined by identifying the year in which the population stabilizes for a given scenario. This value allows us to know how long it would take to reach 100% recovery.

Years to 25% Population Biomass (B/B_0)

For our analysis, we assume that the fishery will open when the population reaches 25% of Virgin Biomass. This value is defined by identifying which year the population reaches 25% of the biomass ratio B/B_0.

Sensitivity Analysis

A sensitivity analysis was used to test the sensitivity of our model to changes in input values known to have high uncertainty. We ran 2 sensitivity analyses: 1) by varying the range of values of Illegal fishing against a range of values for natural mortality, and 2) by varying the range of values for scallop price against the values for costs of habitat restoration. The analysis identified which parameters affect the output of our model the most, and also which parameters have the greatest impact on recovery.

Monte Carlo simulation

In order to incorporate the effect of environmental stochasticity into the population biomass, we conducted a Monte Carlo simulation to reflect this stochasticity through natural mortality in the model. We chose natural mortality because the sensitivity analysis identified our model to be most sensitive to this parameter. We tested different levels of stochasticity to analyze the effect of lower and higher frequency and intensity of common climatic impacts occurring in the region, such as hurricanes.

Results

Habitat Experiment

We found that scallops can survive and grow on various types of habitat and substrate in the Ensenada. The survival rate varied from 85% near the historical fishing grounds to 6.25% in the aquaculture concession site (**Figure R1, Annex 1**). The Deep site showed a survival rate of 0%, where no scallops were found in the cages or in the vicinities. Scallop growth showed lower variation, with growth rates that ranged between 1.7 to 2.2 mm/week in shell length, with the highest being in the concession site near to the beach. Interestingly, higher survival and growth rates were associated with habitats composed mainly by shell and seagrass and/or algal turf cover.

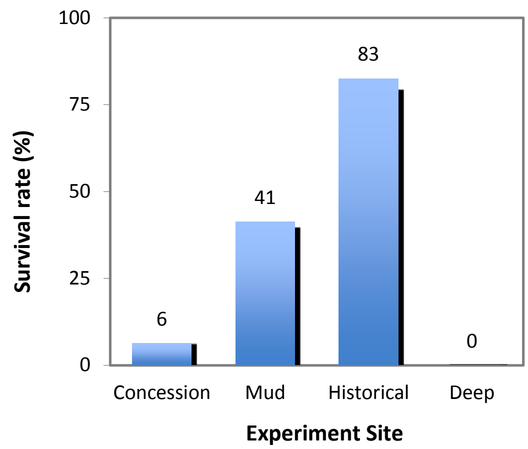

FIgure R1. Survival of scallops after 4 weeks at the four experimental sites in the Ensenada.

Scallop recovery

Population Growth

According to our model, the scallop population is expected to recover from depletion, but at different rates and achieving different population sizes depending on the restoration strategy used. **Figure R2** displays the relative biomass curve (i.e. Biomass ratio, B/B_{max}) of each scenario over time, when the population remains 'unfished'. This means that legal fishing was not allowed (i.e. fishery remains closed), but illegal fishing does occur. When comparing the performance of all

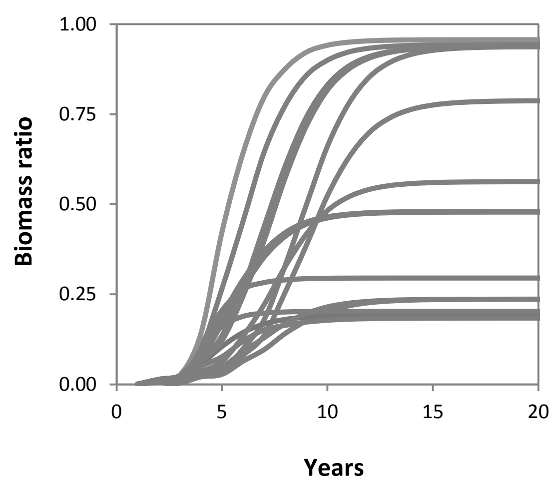

Figure R2. Scallop biomass growth in time for all restoration strategies (N=15), with "no fishing". This simulation considers the fishery remains closed, though illegal fishing does occur at different levels for the different strategies.

scenarios, they show large differences in their relative biomass, which vary between 0.19 and 0.96. This analysis considers that a Biomass ratio of 1 represents the maximum biomass a scallop population could reach in the Ensenada, in relation to historical landings data (see Methods).

Under all scenarios, the population ultimately recovers and stabilizes at carrying capacity, which was different for every scenario (**Table R1**). Given the conditions we established in our scenarios, the catarina scallop population would take between 7 and 18 years to recover, with a median of 13 years. The high performing scenarios also take a relatively longer time to achieve. In general, we found that the strategies that achieve smaller population sizes reach a stable level faster, and bigger ones take more time to reach their carrying capacity (**Figure R4**). However, there is significant variability, with some high-biomass. Also, the highest population biomass (>90%) are reached by only 5 scenarios (2, 10, 11, 13, 14), all of which have in common that scallop habitat was increased up to the same level of the historical habitat. On the other hand, low-performing scenarios usually lower levels of available habitat, relative to historical levels. However, there is inter-scenario variability that would not be explained by the amount of available habitat.

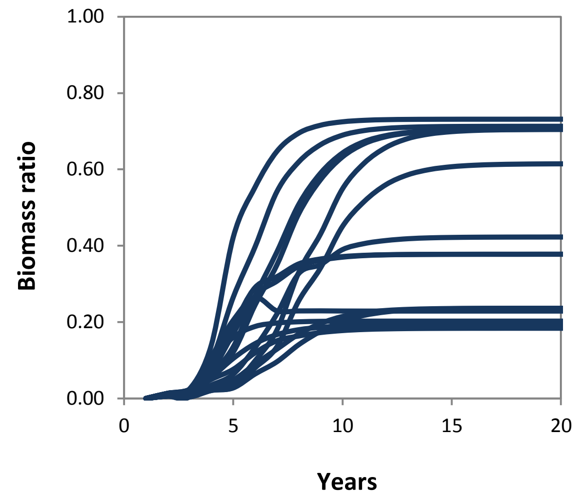

Figure R3. Scallop biomass growth in time for all restoration strategies (N=15), with fishing. In this simulation, both illegal (at different levels) and legal fishing (0.6) are occurring.

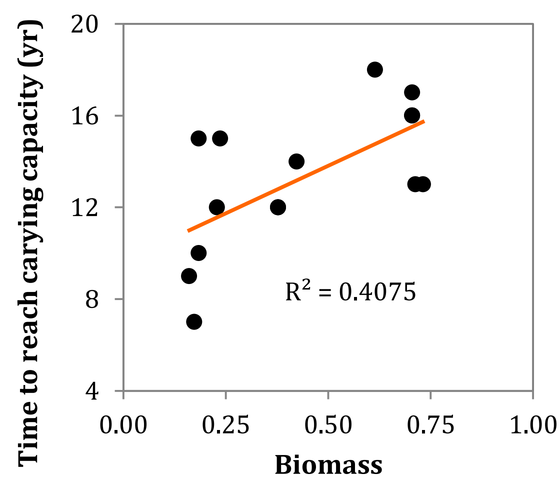

Figure R4. Relationship between relative biomass and the time it takes to each population to reach carrying capacity.

Table R1. Relative biomass for each restoration strategy. The 'unfished' biomass considers the legal fishery to be closed, while for the 'fished' biomass the population is subject to both types of fishing.

Scenario	%Historical habitat	Biomass 'unfished'	Biomass 'fished'	Years to K
1	30%	0.30	0.23	12
2	100%	0.94	0.70	17
3	30%	0.24	0.24	15
4	100%	0.79	0.61	18
5	30%	0.19	0.19	9
6	30%	0.20	0.20	7
7	60%	0.56	0.42	14
8	30%	0.24	0.24	15
9	60%	0.48	0.38	12
10	100%	0.94	0.70	16
11	100%	0.96	0.73	13
12	60%	0.48	0.38	12
13	100%	0.94	0.70	16
14	100%	0.94	0.71	13
15	30%	0.18	0.18	10

Fishery

The fishery was modeled to open after the population grows over a safe threshold ($B/B_{MAX} > 0.25$), which was used as a reference point for overfishing (FAO 1996). If the population is subject to both types of fishing, their effect is readily apparent on the population growth curves (**Figure R3**). There, the biomass reaches a relatively lower stable point due to the fishing pressure removing significant portions of the population every year. With the fishery open, all scenarios are able to maintain a population size above the threshold, with the exception of scenario 2 (**Table R1**). However, many restoration strategies (33%) are never able to reach a population size above the

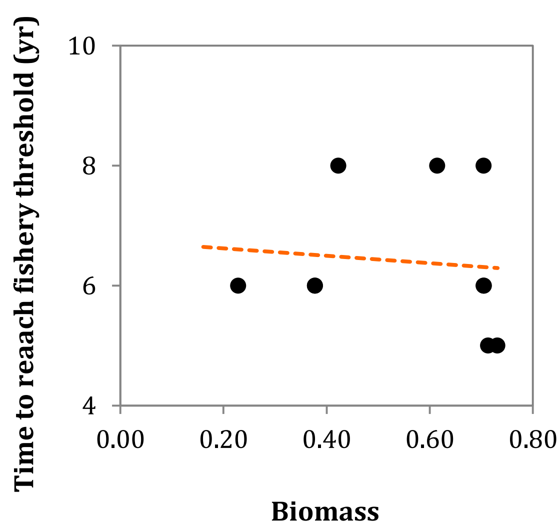

Figure R5. Relationship between relative biomass and the time it takes for scenarios to reach a population biomass over the fishery threshold. In some cases the fishery never opens.

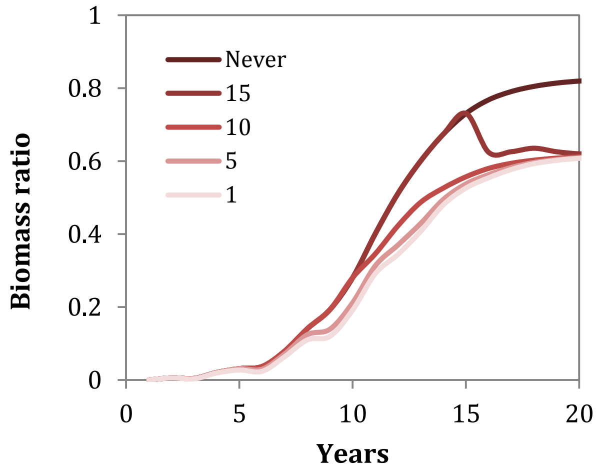

FIgure R6. Relative biomass in time for one scenario (#2), with the fishery opening at different years (1, 5, 10, 15 or never opening at all). Here, the fishery threshold does not apply.

threshold (i.e. scenarios 3, 5, 6, 8, 15), which have in common low habitat availability (30% of historical levels). When habitat is restored at 100% or at 60%, it allows the population to reach the 0.25 fishery threshold in six years.

Not surprisingly, restoration strategies that attain a higher biomass while the fishery remains closed are also the same that are able to maintain a bigger population that is the subject of both legal and illegal fishing. How soon the fishery opens can affect how the population recovers. If the fishery threshold is no longer considered, and the population is modeled to open at different points in time arbitrarily, then the recovery paths of the population vary (**Figure R6**). Only when the fishery remains closed for 15 years there is an apparent effect over the population. However, eventually in all cases the population stabilizes with fishing at around 20 years.

Economic feasibility

Catch value

Higher population sizes would render higher catch value for fishermen if the fishery opens. With an average local market price of US$0.63/K of whole scallops with shell, and a fishing level of 60% of the scallops over the legal size limit (56 mm), fishermen would obtain in average between US$39,801 and US$124,333 per year by the sell of the scallop catch (**Table R2**). However, the selling price of the scallops would significantly affect the

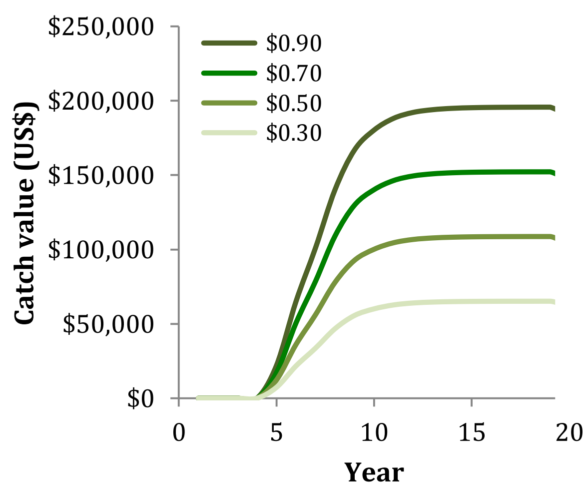

Figure R7. Annual value of the scallop catch at different selling prices. Catch is assumed to be fixed at 60% of the expected economic returns from the fishery. When price is varied, the revenues from selling the scallops can be almost four times greater when the price is high ($0.90/k), when compared to a low end price ($0.30/K) (Figure R7).

When looking at how the fishery of the catarina scallop could provide for the local fishing communities, we compared our scenarios to our client's target. In order to provide income by fishing only in the Ensenada for the 80 fishers that live in the community, fishing profits must generate at least USD$443,077 in revenue per year (Personal communication, Alejandro Robles). The highest performing scenario would only provide income to support 22 fishermen, which represents about 28% of NOS' target (**Figure R9**).

Table R2. Mean value of the catch of catarina scallops for the first 20 years, at a fishing level of 60% of the vulnerable biomass (length>56 mm). Also, the number of years it takes to open the fishery. *N* = fishery never opens.

Scenario	Mean Catch	Fishery opens (yr)
1	$39,801.52	6
2	$110,521.80	8
3	$0.00	*N*
4	$92,472.99	8
5	$0.00	*N*
6	$0.00	*N*
7	$68,270.96	8
8	$0.00	*N*
9	$61,440.27	6
10	$113,945.07	6
11	$124,333.01	5
12	$61,725.41	6
13	$114,915.92	6
14	$119,088.06	5
15	$0.00	*N*

Fishery

The Net Present Value of the fishery (NPV_F) exhibits high variability under different scenarios, ranging from -$6,747,399.46 to $175,291.54 (**Table R3**). Negative NPV_F are expected given that the fishery includes all the costs associated with the restoration and repopulation of the scallop. Scenario 1 is the only to achieve a non-negative value, which might be due to a lack of investment in

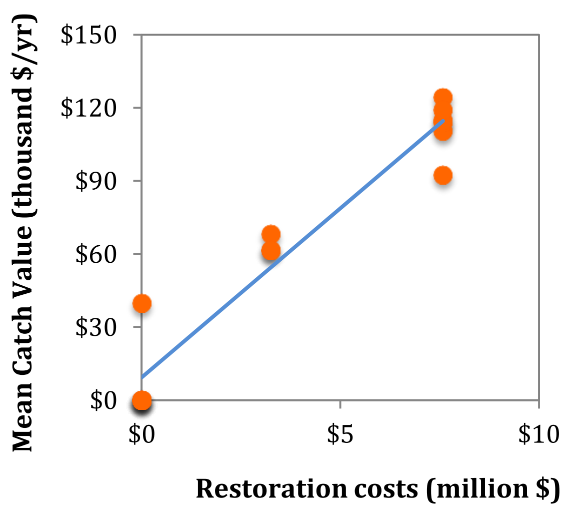

Figure R8. Mean catch value per year in reference to the amount invested in habitat restoration in habitat restoration and from surveillance reducing illegal fishing up to 5%.

Fishermen NPV (NPV_{FM}) on the other hand, which only considers the costs of surveillance, ranged from -$242,302.57 to $1,769,984.47.

Scenarios with a negative NPV_{FM} are those in which the fishery never opens and do not invest in habitat restoration. The scenarios with the highest NPV_{FM} have high restoration investments, increasing the available scallop habitat to either 60% or 100%, increasing the chances for the fishery to open. Once again, scenario 11 attains the highest NPV for fishermen, and so was used as the maximum attainable

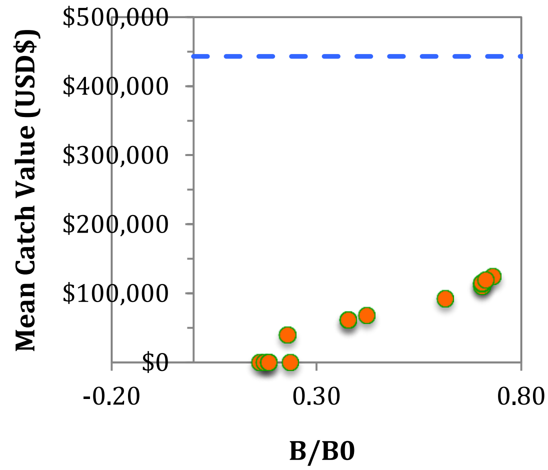

Figure R9. Mean catch value per year in relation to biomass of the wild population. According to Alejandro Robles (NOS), in order to sustain the livelihoods of all the local fishermen (N=80) they would require USD$443,077.

Table R3. Economic feasibility indicators of a potential catarina scallop fishery in the Ensenada. Fishery NPV includes all costs of restoration, nursery, seeding and surveillance, and would represent the view of a funding organization. Fishing NPV only includes the costs of surveillance and would represent the view of local fishermen cooperatives.

Scenario	Fishery NPV ($)	Fishing NPV ($)	Fisher NPV Ratio	Restoration investment ($)
1	$175,291.54	$280,216.86	0.16	$0.00
2	-$5,963,507.25	$1,082,174.49	0.61	$7,584,351.93
3	-$347,227.88	-$242,302.57	-0.14	$0.00
4	-$6,006,388.70	$1,039,293.03	0.59	$7,584,351.93
5	-$226,076.60	-$121,151.28	-0.07	$0.00
6	-$226,076.60	-$121,151.28	-0.07	$0.00
7	-$2,703,005.27	$577,301.36	0.33	$3,250,436.54
8	-$547,999.30	-$242,302.57	-0.14	$0.00
9	-$2,438,029.79	$842,276.84	0.48	$3,250,436.54
10	-$6,252,685.76	$1,299,464.12	0.73	$7,584,351.93
11	-$5,782,165.41	$1,769,984.47	1.00	$7,584,351.93
12	-$2,724,630.92	$861,372.44	0.49	$3,250,436.54
13	-$6,747,399.46	$1,364,262.05	0.77	$7,584,351.93
14	-$6,538,445.13	$1,573,216.38	0.89	$7,584,351.93
15	-$1,292,056.38	-$121,151.28	-0.07	$0.00

value in the NPV Ratio. NPV Ratios over 0.5 involve habitat restoration of 100%. NPV Ratios that range from 0-0.49 involve habitat restoration to 60%. Finally, NPV Ratios below 0 do not invest in habitat restoration.

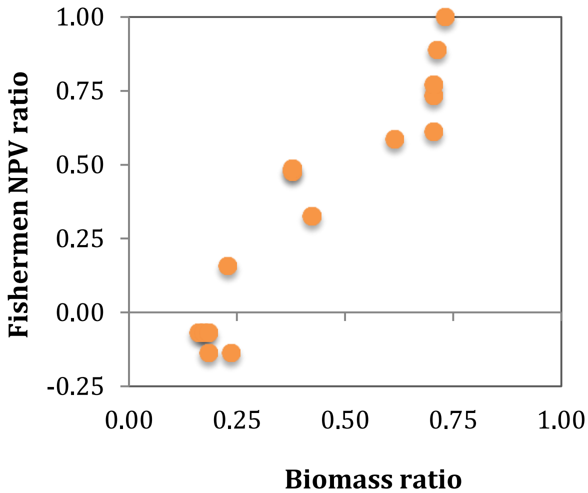

Figure R10. Tradeoff Analysis of the scallop fishery. In the conservation axis is the Biomass ratio and in the economic axis the NPV_{FM} ratio.

Aquaculture

The mean current cost to produce 2,320,000 scallops is $855,959, and to produce 580,000 scallops it is $213,990. At a market price fluctuating between $5.38 and $7.69 per kilogram of adductor muscle revenues were $13,255 for 580,000 scallops and $53,020 for 2,320,000 scallops; the corresponding NPVs at a 3% discount rate for 100 years were -$2,835,070 and -$11,340,280 respectively.

Currently it costs $128,662 to produce 340,000 scallops. In order for aquaculture to break even under the current costs, approximately 4,119,709 scallops need to be produced. This quantity is close to double the current maximum aquaculture potential. This break-even quantity can potentially be achieved by doubling the cage density from 200 to 400 scallops/m2, or by doubling the percentage of aquaculture area occupied by cages from 10% to 20%.

Table R4. Aquaculture Net Present Value for all restoration scenarios.

Scenario	Farmed scallops (Quantity/year)	Aquaculture NPV (US$)
1	2,320,000	-$11,340,280.19
2	0	$0.00
3	0	$0.00
4	0	$0.00
5	580,000	-$2,835,070.05
6	2,320,000	-$11,340,280.19
7	0	$0.00
8	0	$0.00
9	580,000	-$2,835,070.05
10	0	$0.00
11	2,320,000	-$11,340,280.19
12	580,000	-$2,835,070.05
13	0	$0.00
14	580,000	-$2,835,070.05
15	0	$0.00

Habitat restoration

In order to determine the benefits from habitat restoration, we looked at the revenue that fishermen could generate in relation to habitat restoration investment. Habitat restoration investment values range from $0 to $7,584,351.93 while mean catch value per year ranges from $0 to $207,221.68. In **Figure R8** it's readily apparent the positive relationship between mean catch value and habitat restoration investment. In one case, it is possible to generate $66,335.86 without investing in habitat restoration. In this scenario, only 5% of wild catch is lost to illegal fishing, while all other scenarios that do not invest in habitat restoration, have 20% or 40% of wild catch lost to illegal fishing.

Surveillance costs

Surveillance to maintain illegal fishing at 5, 20 and 40% was estimated to cost $32,573, $16,289, and $8,143 respectively. The surveillance cost along with the habitat restoration cost (when applicable) was subtracted from wild fishery revenues. As a result, those scenarios with lower illegal fishing were more costly than those with higher illegal fishing.

Tradeoff analysis

We performed a fishery trade off analysis by comparing the fishermen net present value of the wild fishery with the biomass of the wild population. In our model, we assume the total allowable catch (TAC) to be 60% and the B/Bo of a fishery must reach 0.25 for the wild fishery to open. The scenarios with a negative NPV fail to reach the fishery threshold, and so no benefits from fishing can be captured (**Figure R10).** In these cases, a high investment in restoration translates not many ecological or economic returns. In contrast, the scenarios that recover the population to a higher biomass are able to obtain a higher economic return and help to offsets their initial investment.

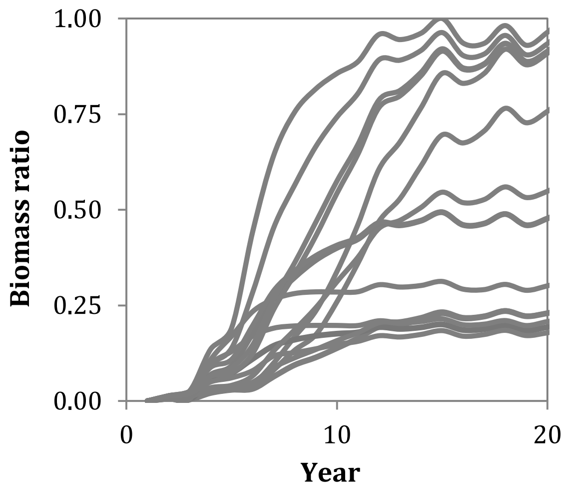

Figure R11. Mean biomass ratio for all 15 scenarios, after 100 iterations of montecarlo simulations

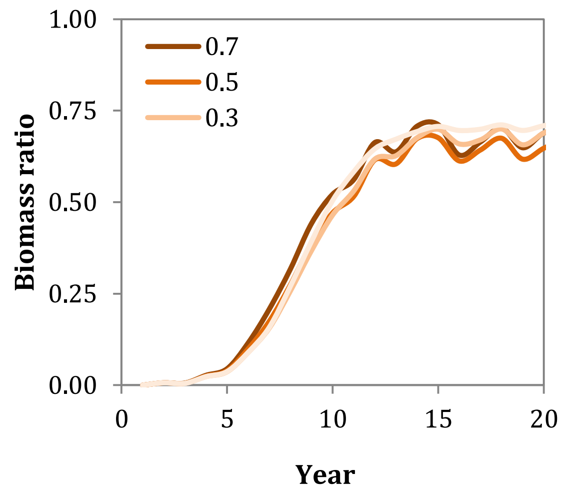

Figure R12. Mean biomass ratio of one scenario (#2) of 100 iterations of montecarlo simulations , at different levels of stochasticity.

Environmental variability

The use of Montecarlo Simulations (MS) allowed us to introduce environmental variability into our model. Since the sensitivity analysis identified our model to be sensitive to changes in the natural mortality of the scallop (see Annex 2), we used MS to introduce stochasticity through this parameter. For all scenarios, we used the same variability matrix in order to make the results of our different scenarios comparable. Under all scenarios, stochasticity increases the overall variability of the population (**Figure R11**). The intensity of this variability depends on the level of stochasticity introduced. However, the mean of this variation does not appear to significantly change the scallop biomass at different levels of stochasticity (**Figure R12**).

Restoration factors

Habitat

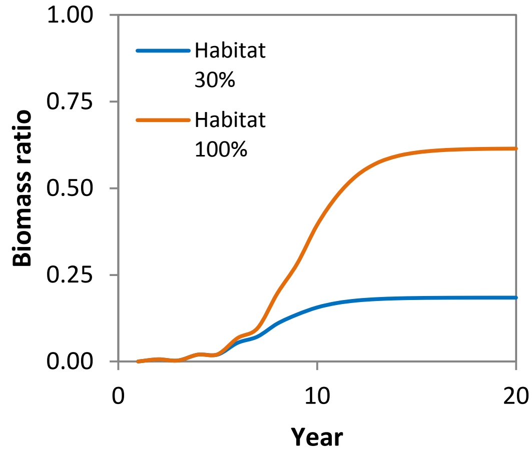

Figure R13. Effect of habitat over biomass. The blue line represents habitat at 30% of its historical potential, and the orange line habitat at 100% of its historical potential.

The effect of habitat on recovery was tested by selecting two scenarios where habitat was varied and all other variables were held constant (scenarios 3 and 4); other variables, however, are at play. In both scenarios illegal fishing is removing 20% and legal fishing 60% of the population per year. Seeding only occurs once and at an intensity of 340,000 as opposed to 3 or 6 years. In addition, given that the aquaculture intensity is zero, larvae from scallops in aquaculture cages are not contributing wild population recruitment. These factors prevent the population from reaching a biomass of 1.00. The population with 100% habitat reaches a higher biomass ratio at a slower rate, while the one with 30% habitat reaches a lower biomass ratio at a faster rate (**Figure R13**). However, the high biomass scenario only takes 3 more years in reaching its carrying capacity. The difference between these two biomass ratios after 20 years is 43%.

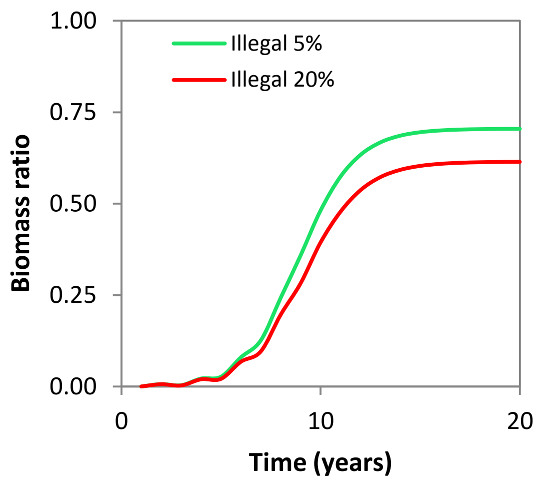

Figure R14. Effect of illegal fishing on scallop biomass.

Surveillance

We tested the effect of surveillance on recovery by comparing scenarios where illegal fishing was varied to account for different levels of surveillance. We found that illegal fishing has more of an effect on population recovery than seeding and aquaculture, but less than habitat recovery (**Figure R14**). Unlike

habitat, the effect of illegal fishing pressure on either population size or rate of recovery seems to be moderated by the other variables. When illegal fishing is at 40%, the population does not reach the 0.25

fishery threshold in 100 years. The effect of illegal fishing at 5 or 20% is more difficult to discern; given that we observe scenarios that reach 0.25 in the fewest number of years but others like scenario one do not reach it at all. In the group of scenarios in the 0.6 to 0.8 biomass range, populations subject to 5% fishing pressure always recovered faster than those subject to higher levels of illegal fishing. Scenarios with habitat availability lower than 100% do not follow this pattern, given that some with 20% fishing pressure actually recovering faster than some with 5% illegal fishing. Similarly at 30% of historical habitat availability, scenarios with 40% fishing pressure recover at about the same rate as those with 5% fishing pressure, and consistently faster than the intermediate fishing pressure of 20%.

Aquaculture

We isolated the effect of aquaculture intensity on recovery by selecting two scenarios where aquaculture intensity was varied and all other variables were held constant (**Figure R15**). High intensity aquaculture (HIA) results in the biomass recovering at a faster rate than at low intensity aquaculture (LIA). However, after both populations stabilize the HIA scenario grows to be only 1% higher than the LIA scenario. Although the scenario that reaches the highest biomass (i.e. 11) assumes larval input from HIA, of the other scenarios that reach a biomass ratio in the 0.6 to 0.8 range only scenario 14 assumes LAI, while scenarios 13, 10, 2 and 4 assume no aquaculture. Similar aquaculture intensity does not seem to have an effect on the population reaching the 0.25 biomass ratio (Tables R2, R4). Scenarios with HIA can either reach the 0.25BR in the fewest number of years (#11) or not in 100 years (#1, 6).

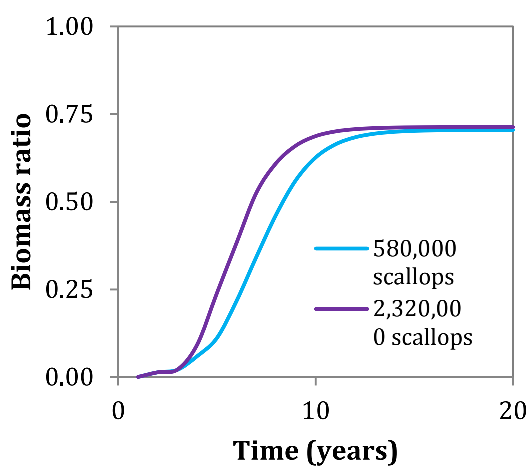

Figure R15. Scenarios comparing the effect of aquaculture intensity on the population biomass.

Seeding

We assume that doubling the seeding amount is possible if the productivity of the nursery is increased. Higher seeding quantity results in a slightly faster recovery time, however, seeding at 340,000 and 680,000 scallops ultimately result in the same population size when the restoration stabilizes (**Figure R16**). Also, a longer seeding period, in this case three years, results in the population reaching a higher biomass ratio in a shorter period of time (**Figure R17**). After a 20 year period, however, both the one and three year seeding periods result in the same biomass ratio.

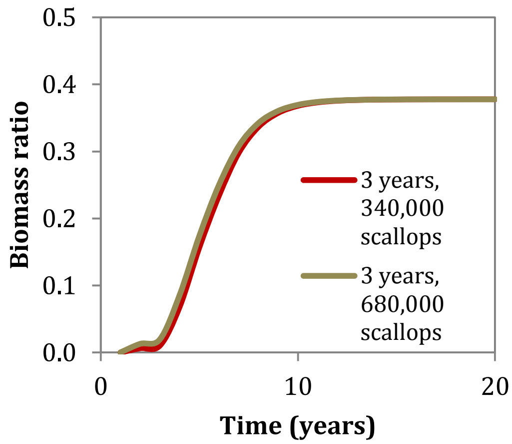

Figure R16. Scenarios comparing the effect of the scallop quantity seeded on the Catarina biomass ratio.

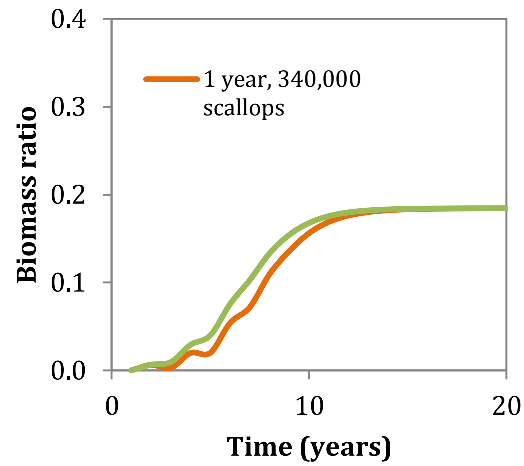

Figure R17. Scenarios comparing the effect of number of seeding years on the Catarina biomass ratio.

Discussion

Habitat

Habitat area appears to be the most important factor in restoring the scallop population across the different strategies. It can drive biomass close to historical level in 1978 if it is restored up to 100% of the historical distribution of fishing grounds in the Ensenada. Therefore, the high impact that habitat restoration may have on biomass makes this aspect of the project highly relevant. Scallops have shown to be gregarious settlers in some species (Harvey et al., 1993).
Also, similar restoration projects targeting other species of bivalves have shown that providing shell as bottom substrata can promote the recovery of overexploited populations (Lenihan, 1999), or other habitat features such as seagrass (Peterson et al. 1995) can enhance the recovery of overexploited or depleted populations.

Correspondingly, in our model we multiplied recruitment (R_0) by the suitable habitat in a particular scenario to account for the cumulative effects of habitat restoration on the scallop population. The assumption that recruitment is limited by suitable habitat, however, should be further tested in this particular context. For example, if scallops are dependent on algal turf cover for predation protection, then the scallop population recovery would be tied to algal turf recruitment and survival in the new shell bottom. This would mean that recruitment is not only limited by the amount of shell hash cover and type (e.g. Catarina shells as opposed to Bay scallop shells), but also by the algal cover over the restored shell hash substrate.

In addition, we also assumed that the current suitable habitat was at 30% of the 100% historical pre-collapse level. This is an assumption with high uncertainty given that we currently have no evidence to corroborate habitat is indeed at 30%. Provided that our assumption is correct, and that suitable habitat in fact is lower than its historical potential of 100% just prior to the collapse of the Catarina fishery, a successful habitat restoration effort should potentially increase suitable habitat to 100%. In fact, all the recovery scenarios in the 0.6 to 0.8 biomass range assume that habitat can be restored to pre-collapse 100%. Conversely, if habitat were already at 100% and other bottlenecks were preventing recovery, or in the case it cannot be restored to 100%, then the next best scenarios become those in the 0.30 to 0.50 biomass range (Figure R3).

Illegal Fishing

Illegal fishing has more of an observable effect on population recovery than seeding and aquaculture, but its effects on either population size or rate of recovery seems to be moderated by these variables and by habitat. In addition to 100% habitat, the top scenarios in the high biomass range all assume 5% illegal fishing; with the exception of scenario four which assumes 20%. These results indicate that the inability to decrease illegal fishing from either 40 or 20 to 5%, is expected to shift these top scenarios to slower recovery at lower biomass ratios as illustrated by scenario 4.

In addition, illegal fishing mortality has a bigger relative effect over biomass than legal fishing, which may be due to the fact that illegal fishermen tend to have a lower selectivity and will take scallops as small as 30mm, when the legal size is 56 mm(Noroeste-Sustentable, 2014). This can be an important consideration if our client seeks to open the Catarina fishery sooner, given that at 40% illegal fishing no scenarios reach 0.25BR.

Our assumption that changes in the level of illegal fishing are only driven by the level of surveillance, allowed us to account for changes and results in a measurable way. However, in addition to surveillance NOS is using other approaches to control illegal fishing such as raising awareness over fisheries declines and involving the community in the restoration effort to increase stewardship over the Ensenada resources. One of our assumptions was that the percent of illegal fishing in a scenario would result in an equivalent take of scallops from the wild fishery; for example 20% illegal fishing would mean illegal removal of 20% of the scallops in the wild population of sizes at or above 30mm. Although it may be difficult to discern what portion of the change in illegal fishing is due to surveillance, and what portion is due to "softer" approaches, the net change can be measured by the surveillance team and targeted to reduce the illegal take of scallops from the wild population.

Seeding

Growth in aquaculture and transplantation of juveniles into the wild has been observed to have a significant effect on increasing the density of an overexploited population of the clam *Mercenaria mercenaria* (Peterson et al., 1995). Moreover, when adult individuals of the scallop *A. irradians* were transplanted to recruitment limited areas from where a scallop population had previously been decimated after a red algal bloom, it increased the density from <1 to 15 scallops per m^2. In our study, we found that seeding of juveniles into the wild is extremely important for the recovery of the scallop population in the Ensenada. The initial seeding of 340,000 scallops completed by NOS in 2013 was essential in restarting the process of repopulation, given that the Catarina population collapsed from a density of 6 scallops per m^2 to 0 scallops per m^2 in 1979; the scallop continued to be missing many years after depletion (Lango-Reynoso, 1994). This fallow period along with information on the limited larval dispersal of the related species *A. irradians*, lead us to believe that without the initial seeding by NOS habitat restoration or surveillance may have not been enough to bring back the Catarina scallop to the Ensenada. Once past the initial seeding, our results indicate that after 3 years, seeding has less of an observed effect on population recovery than habitat and surveillance, and a similar effect to that of aquaculture.

Once the initial seeding has taken place, seeding quantity followed by seeding period have less of an observed effect on population recovery than habitat, and surveillance, and a similar effect to that of aquaculture. Higher seeding quantity and longer seeding period tend to lead to the population reaching a 0.25BR in fewer years, but the trend is not absolute. Shorter seeding period does result in a population reaching the 0.25BR in more years or not reaching it at all in the 100 year modeling period. This is an important finding given that our client is currently investing in producing more larvae to continue the seeding effort. Longer seeding periods and at a higher quantity, although more costly for our client, generate more jobs or extend the job period for local fishers. It is expected that by working on the repopulation effort these fishers also develop a higher ownership over the resource as they return the Catarina scallops that they or their ancestors took form the Ensenada.

Aquaculture

The negative values of Aquaculture NPV demonstrate that, under the current costs of production, does not provide a profit for the fishermen. The high costs associated with labor makes aquaculture prohibitive under all scenarios, assuming the current production efficiency. Doubling the density from 200 to 400 scallops per m^2, or doubling the percentage of aquaculture area occupied by cages from 10% to 20% may allow fishermen to make a profit, assuming that the costs remain close to the current production costs. The complexities of transitioning livelihoods from fishing to aquaculture farming should also be considered.

Although aquaculture for profit is not feasible, aquaculture has high potential to serve as a source for spawning stock. Scallops in aquaculture would be protected from predation, fishing mortality, and provide a consistent supply of larvae to the wild population. However, a study on temperature and predator influence on growth, survival and energy allocation for reproduction on the Catarina scallop (Guerra et al. 2011) found that scallops may not be driven to reproduce in the absence of predators, since the presence of predators allocates energy to growth rather than gonad production. As a result, survivorship is prioritized and spawning is delayed. Although survivorship in aquaculture has the potential to provide a large amount of seed to the natural population, the spawning potential may be significantly reduced if the scallops are in a protective structure.

Economic Feasibility

In assessing the economic feasibility of the Catarina scallop restoration project as a whole, we find that fishery profits from Catarina are highly dependent on habitat restoration, the market price for Catarina and restoration investment.

Habitat Restoration

Our study concludes that habitat restoration is necessary for the fishery to generate profit. Although Figure R3 demonstrates that reducing illegal fishing to 5% may allow the fishery to generate revenue without investing in habitat restoration, according to our analysis, the greater the investment made into habitat restoration, the higher mean catch value possible.

As mentioned in the results section, the fishery must generate at least $443,077 in revenue per year to sustain the livelihood of the El Manglito fishing community. Among our scenarios, the maximum mean catch value per year is $207,221.68, which is less than half the target value. Although the Catarina fishery can potentially generate profits, it is not sufficient enough for the fishermen to depend only on Catarina scallops.

When price is varied, the revenues from selling the scallops can be almost four times greater when the price is high ($0.90/k), when compared to a low end price ($0.30/K) (Figure R7). Thus is important to consider the effect that the market could have towards achieving the goals of the restoration project. Increasing the profits of the fishery by changing how the product is sold or aiming for more valuable markets (i.e. sustainable certification) would have a significant effect over the expected returns of fishermen.

Model Limitations

Although our model takes into account the major factors affecting restoration, it is not without limits. In our model we assume that biomass is limited to that of the final year when the fishery was open. It is possible, however, that biomass could have been greater before the final year the fishery was open. In situ, the biomass value may be elastic, therefore, depending on the amount of habitat restored, the Ensenada may be able to sustain a greater amount of biomass than our model allows.

The scenarios with negative NPVs are limited by the assumption of our model that the fishery will open when the biomass arrives at 0.25. In practice, the biomass in which the fishery may open is determined by the government agency CRIP. If the fishery were to open at 15%, all the scenarios that currently have a negative NPV would likely have a positive NPV, however, the value would likely be low due to the low biomass.

Our model is also limited by analyzing only the Catarina scallop. The Ensenada provides other species of value, such as the Pen Shell clam. NOS is simultaneously working with the fishermen to recover the Pen Shell clam population. Many El Manglito fishermen have agreed to stop fishing for the Pen Shell clam, and work as patrolmen to discourage any prospective poachers. The Pen Shell has benefited from this surveillance, and Pen Shell stock has recovered over the past 3 years (Noroeste-Sustentable, 2014). Pen Shell clams sell for a higher price than the Catarina scallop. If the Catarina and Pen Shell species are recovered simultaneously, both species may be able to generate enough revenue to sustain the livelihood of the El Manglito Fishing community.

Catarina Market Price

As mentioned previously in the results section, our sensitivity analysis reveals that reductions in price per kilogram are expected to have a larger impact on the NPV of the fishery. For example, a price of $0.30 would cause the NPVw to be lower than the restoration costs of all analyzed scenarios. This indicates that if the Catarina were to become a species of lower market value, there would be less incentive to restore the Catarina habitat if the market price is too low.

Ultimately, the Catarina fishery has the potential to become economically feasible, especially if restored simultaneously with the Pen Shell clam. According to our results, the biggest obstacle in achieving economic feasibility is the capital to complete habitat restoration. In comparison, similar restoration projects have shown higher overall costs than profits and have depended heavily on governmental funds to support habitat restoration efforts(Lenihan, 1999). These resources may not be readily available in Mexico. Thus, is important to properly assess the potential costs of scallop habitat restoration in the Ensenada, but also to evaluate local and external market prices into the future.

Environmental

Scallop population biomass is most sensitive to changes in natural mortality (M_{wild}), and Monte Carlo simulation is a useful tool to address the uncertainty of this parameter in our results.

The negative relationship between NPV_f and temperature can provide a glance at how increases in future mean temperatures could significantly affect the scallop population. Given that the natural mortality equation is in a part a function of mean water temperature, the true effect of increased temperature over Catarina scallops should be further tested. However, there is evidence that the optimum range for scallop growth and feeding in the Ensenada between is 19 and 22 degrees Celsius, and that a mean lethal temperature is reached at 29 Celsius.

Climatic events, such as hurricanes are one of the more destructive forces to shallow-water marine environments. Hurricanes of high intensity have been reported to have a huge impact over shellfish populations and the economic activities that depend on fishing them. Under future projections of climate change, it is expected that the frequency of intense climatic events will be significantly higher in the next decades (Bender et al. 2010)

General

The habitat features in the site with highest survival (shell and seagrass and/or algal turf cover) are described by the literature as the main components of the catarina scallop habitat before the population disappeared from the Ensenada (Baqueiro et al., 1981). This would be an important factor to consider for the placement of seed and where to focus restoration efforts. In this sense, it would be important to use the experience from other restoration projects to guide the next steps for the restoration.

The high performing scenarios were found take a relatively longer time to achieve. This is important for restoration planning, because associated with the higher investment of better performing strategies, there would probably be higher expectations of the restoration project between stakeholders. These expectations would demand faster and better results, and should be taken into account in future decision-making.

Achieving a higher biomass and faster population growth would ultimately provide benefits from the fishery. This could be important in the future planning and management of this population, as a higher biomass could potentially achieve higher population resilience when confronted to severe environmental changes. However, given that genetic diversity and population complexity promotes resilience for sustainable management of fisheries (Hillborn et al., 2003), it is important that the seed production comes from a diverse genetic pool.

Predation, mainly by crabs, snails and some species of fish, has been reported to have a significant impact over catarina scallops in the wild, and to be a threat to bottom aquaculture scallops as well (Lango-Reynoso, 1994). Given its potential effect over the first years of recovery, current predation intensity of catarina scallops should be assessed and density of the main predators estimated. This information could be used to advise the restoration project on when to increase seeding or take other actions to avoid another collapse, especially during the period before reaching carrying capacity.

When considering livelihoods, the highest performing scenario provides income to support 22 fishermen, which represents about 28% of NOS' target (**Figure R9**). It is important then to look at how the recovery of other fishing resources, many of them more valuable than the Catarina scallop (i.e. Pen shell) could contribute to reach this target.

Recommendations

The bioeconomic model generated scenarios under which the Catarina scallop population in the Ensenada recovered at faster or slower rates and at higher and lower levels of B/B_0. It is important, however, to highlight that each of these scenarios is a combination of different variables and that caution must be taken when teasing them apart. We believe the model results were useful in indicating specific values per variable under which recovery is fastest and more economically feasible.

It is also worth noting that the system that our client NOS is dealing is with extremely variable and requires quick adaptation to new opportunities and challenges. For example, the Ensenada is located in an area prone to hurricanes. If a hurricane where to threaten the area during the restoration of the Catarina population, habitat restoration and seeding may become priorities to reverse damage to the Catarina habitat.

On the other hand, increases in the efficiency to mature scallops in aquaculture may significantly reduce the cost of aquaculture and make it a more attractive option to repopulate and employ more of the local fishers. This could potentially happen through a partnership with a company that has a well-established aquaculture technique and knowledge on the subject.

The primary goal of the Catarina restoration is to rebuild the Catarina scallop population in the Ensenada at the fastest rate and lowest cost. With this primary objective in mind we proceed to make the following recommendations:

Restore the Catarina habitat in the historical fishing grounds

Our model results indicate that habitat restoration has the most observable positive effect over the increase of the wild population over time. Habitat is currently limiting the total carrying capacity that the system of the Ensenada can reach, and the total recruitment that the population can achieve. Habitat restoration efforts (Lenihan, 1999) have succeeded at restoring the habitat for oysters. In the case of the Catarina in the Ensenada restoration may be as simple as purchasing Catarina shells from the region and placing them in the area where the historical fishing banks were located. Yet care must be taken to prevent disease outbreaks from introduced pathogens through the shells. We recommend that research is conducted to assess the best strategy to restore habitat. This can be done through the partnerships that NOS has developed with the Bren School, the Massachusetts Institute of Technology, or the Universidad Autonoma de Baja California Sur.

Continue to the surveillance program in the Ensenada

Our model results indicate that high illegal fishing has a highly negative observed effect on the recovery of the Catarina scallop. Although not part of this Group Project or analyzed in our model, other overfished benthic species such as the Pen Shell scallop are benefiting from such program (Noroeste-Sustentable, 2014). In addition, the efforts by NOS and some of the local fishers to raise awareness among the community about the restoration of the Ensenada should continue as they help support the surveillance program.

The sensitivity analysis also shows that natural mortality is more important than illegal fishing. Continuing to plant scallops at a size of 30 mm will contribute to lower mortality. In addition, maturing the scallops inside cages over restored substrate may help 1) decrease predation, and 2) increase survival as more larvae are able to recruit to the next generation.

Increase the quantity of scallops seeded

Although seeding was a necessary step to bring back the Catarina scallop to the Ensenada, it is also costly. Our model suggest that it may not be necessary to continue seeding for more than three years if seeding occurs at 680,000 and is supported by other variables such as an increase in Catarina suitable habitat, and higher compliance to reduce illegal fishing to 5%(as observed in the results of scenario 10). Even one year of seeding at 340,000 seems to be enough to recover the population of Catarina faster and at higher biomass if surveillance is high and the Catarina suitable habitat in the fishing areas is restored to 100%.

Establish or further develop partnerships with the private sector and with the academic sector

Community engagement, in the vision of restoring the Ensenada and the Catarina population, is paramount in making restoration efforts successful in the long term. Nevertheless, we must also continue to recognize that working with community members to create new job sources through the diversification of the use of marine resources is essential in ensuring a successful and long lasting restoration.

Our model results suggest that scaling up the aquaculture of the Catarina scallop to commercial levels is too costly given the current production costs. Nevertheless, if partnerships are developed with sustainable aquaculture enterprises who are knowledgeable on the subject, stakeholders may be able to increase the aquaculture production efficiency and significantly reduce costs.

The price of the Catarina scallop, in addition to production efficiency, is another reason why the value of the wild fishery and aquaculture generate relatively low profits. Increases in price though new markets and partnerships can significantly support the restoration, as funds from scallop sales serve to partially offset the costs of habitat restoration, surveillance and seeding.

Conclusion

The Catarina scallop is a species of high value to artisanal fishers in Baja California Sur. In 1978, the fishery collapsed in the Ensenada de La Paz, forcing fishermen to find alternative products to fish, sometimes in faraway locations. Although there are no studies on the reason for the collapse, theories include habitat degradation, climatic variation and overfishing. Nevertheless the species has not naturally recovered even after 30 years of the fishery being closed. Noroeste Sustentable and the fishermen of El Manglito are working in collaboration to repopulate the Ensenada with Catarina scallops in hopes to reopen the fishery. Over the last year, the fishermen have grown Catarina scallops from seed to juvenile size in a nursery until a size of 30 mm. The scallops are then released into the wild, in hopes that they grow to spawning size and release larvae into the water column.

The Bren School designed an experiment and confirmed that the Catarina scallops could actually survive on the seafloor of the Ensenada de La Paz. We then created a bioeconomic model that included biological, ecological, social, political and economic input parameters. Fifteen restoration scenarios were created that focused on variable levels of suitable habitat availability, aquaculture intensity, illegal fishing pressure, and seeding quantities and time periods. We ran the 15 scenarios through the bioeconomic model and found that habitat restoration has the greatest influence on the Catarina recovery. The model also shows that although aquaculture can generate revenue, the nursery and aquaculture costs are too high to make a profit.

Our recommendations to NOS and the fishermen of El Manglito are to restore the Catarina habitat in historical fishing area, to continue the surveillance program in the Ensenada, to increase the quantity of scallops seeded, and to continue to establish and develop relationships with the academic and private sector to ensure sounds strategies that maximize the ecologic and economic sustainability of the Catarina scallop in the long term.

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Annex 1

Testing Catarina Survivorship on the Substrate of the Ensenada

Methods

A total of 320 juvenile scallops with a mean length of 30mm were selected from the scallop nursery. We used scallops of this size to allow for an easier recognition during measurements. We placed an equal amount of scallops (N=40) inside cages in 4 different habitat types, which are refered as the following: 1) Historical, 2) Concession, 3) Deep, 4) Mud (Table A).

Table A1. Experimental sites

	Historical	Concession	Deep	Mud
Habitat composition	Sand Shell Seagrass Algae	Shell hash Algae	Shell hash Sand Mud Algae	Mud
Habitat quality	Good	Intermediate	Intermediate	Poor
Current Speed	Low	High	High	Low
Other features	Described by experts as ideal site for the Catarina scallop to survive.	Protected from illegal fishing.	Protected from abrupt temperature changes (6 m).	Near water treatment plan, expected to be unsuitable for the scallop to grow, with very low productivity

Eight cages were built with a PVC frame and mesh walls. Each cage was 1-by-1 m surface, and a height of 0.5 m. Two cages were randomly placed in each of the four sites. This is to account for a replicate case, and also to have a backup cage in case of theft. The cages were anchored down to the seafloor by hammering down the legs of the frames into the seafloor. The scallops were transported to the sites in a large plastic tub, with fresh water replacement every few minutes. Forty scallops were placed in each cage, because according to fishermen this is the amount of scallops that would naturally live together in a 1-m^2 area. The scallops were placed directly on the bottom of the ocean floor. This allows the scallops to be exposed to the same conditions of substrate and water quality, but with protection to predators. After placement, scallops were counted and cages were cleaned approximately every two weeks for 45 days. Cages were scrubbed with a brush to ensure a flow of water through the mesh walls. During cleaning, a visual survey was performed around the cages to see if any scallops escaped. During each resampling event, the diver opened the cage and felt the bottom for scallops and scallop shells. Living scallops were picked up and counted out in another bag. Dead and empty shells were brought up to the surface and kept as samples. Scallop size, namely length and height were measured at the beginning and at the end of the experiment to find the mean growth at different sites. During the final survey, the scallops from each cage were collected and measured. The survival experiment team consisted of Nicole Corpuz, Mary Luna, Raul Cosio (UABCS), Margarita Gutierrez (UABCS), expert diver Guillermo Mendez Camacho, and ¨panga¨ captain Hubert Mendez Camacho.

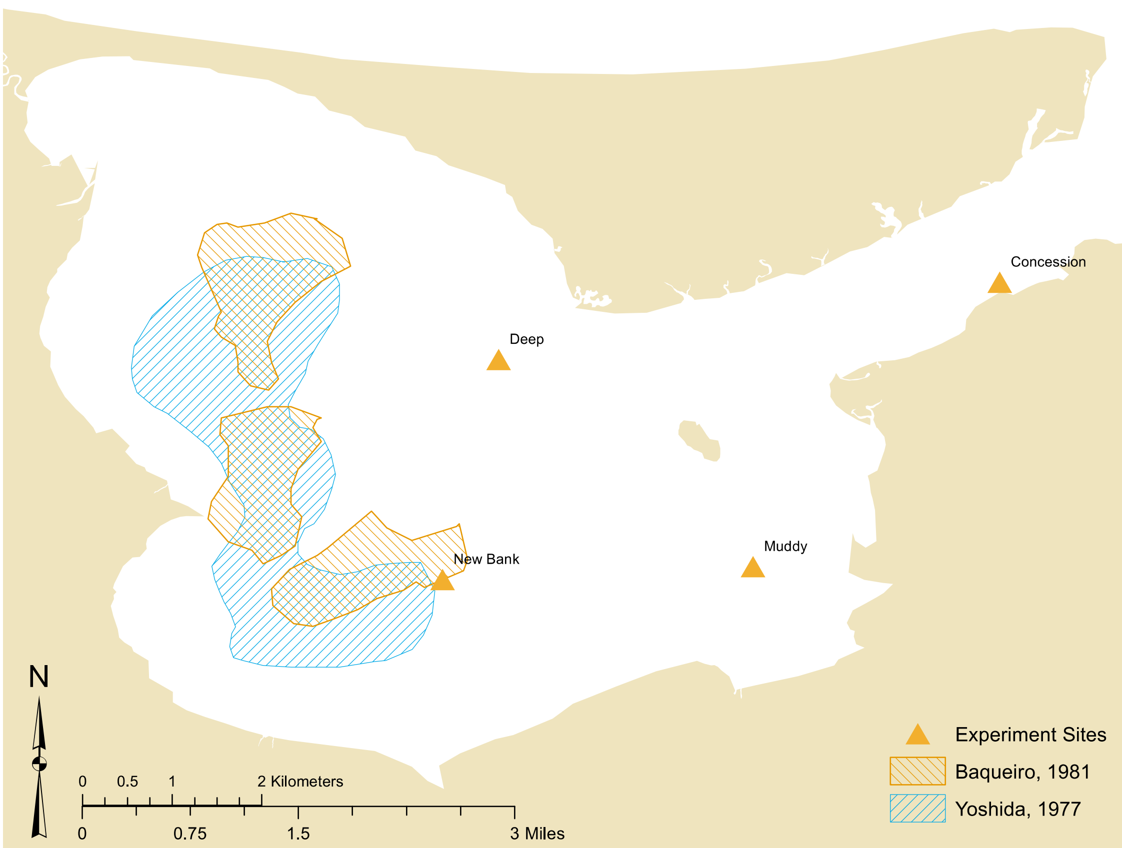

Figure A1. Map of Experiment sites and Historical fishing ground, according to Baqueiro and Yoshida.

Results

Each site was sampled at least four times, with the exception of the cages in the deep site. Consistent resampling was difficult due to harsh environmental conditions, such as strong currents and poor visibility, and also due to the inability to secure a ride to each site. The Historical site is located in an area with low current speed, less than one meter visibility, and sand, shell and sea grass and algae substrate. A total of 66 scallops out of 80 survived at the end of the experiment, resulting in a survivorship rate of 82.5%. The average daily growth rate was 0.25 mm/d. The concession site is located in the channel of the Ensenada, has a high current speed, and two-meter visibility. The habitat is characterized by sand, shell and some sea grass and algae cover. A total of 5 scallops survived, resulting in a survivorship rate of 6.25%. The average daily growth rate was 0.32 mm/d.

Table A2. Table of survivorship for each experiment site.

Site	Historical site		Concession		Deep		Muddy	
Cage#	1	2	1	2	1	2	1	2
7/10/13	40	40	40	40	40	40	40	40
7/25/13	31	39	35	38	1	5	22	22
8/9/13		20	0	19				
8/14/13							11	22
8/16/13	34	32						
8/20/13			0	5				
Final	**34**	**32**	**0**	**5**	**0**	**0**	**11**	**22**

Discussion

Survivorship

The Historical site had the highest survival (82.5%). The visibility at this site was low, and the substrate was dense, with a lot of plant matter, sand, mud, and shell. Because of this, it was difficult to discern whether the missing scallops were victim to predation, died naturally, got lost in the substrate, or, least likely, escaped the cage.

The concession site had the lowest average survivorship rate of 12.5%. This site had fairly good visibility in which it is possible to see the substrate from the top of the cage. It was located in a sandy site, with minimum shell and plant cover. No empty shells were found, however, deep channels were formed under the cages. We believe that the strong current created these channels, providing a manner for the scallops to escape with the force of the current.

Table A3. Experiment duration, survivorship, ending height, ending length, and growth rate per day.

Average	Historical Site	Concession	Deep	Muddy
Duration of Experiment (days)	37	31	35	16
Quantity Survived	33	5	3	16
Percent Survived	82.5	12.5	N/A	41.25
Height (mm)	39.5	43.6	N/A	37.9
Length (mm)	41.5	45.8	N/A	39.1
Growth rate/day (mm)	0.25	0.32	N/A	0.24

We were unable to calculate the survivorship rate for the deep site because deep channels were found beneath both cages, allowing the scallops to escape, possibly with the current. No empty shells were found in or around the cages. Divers scanned the area around the cages, and no scallops were found, indicating that the current likely moved the scallops, since scallops do not typically move long distances. We decided to terminate the experiment early because of the low survivorship rate, the inability to repair damaged cages, and also the possibility that the scallops would be lost ,.

The average survivorship at the muddy site was 41.25%. This site had extremely poor visibility, warmer temperatures than the other sites, and the substrate was fine mud. Empty unbroken shells were found inside the cage, indicating the scallops died of natural mortality or suffocation. The fishermen believe that the surviving scallops survived by attaching themselves to the mesh walls of the cages.

Growth

The average shell size was highest at the concession site, with average height of 43.6mm and length of 45.8mm. The growth rate at this site was 0.32mm per day. The average size and growth rate may be biased because it was a mean taken from only five individuals. However, the flow of water was colder, faster and had frequent exchange of water from the Bay of La Paz, so

Figure A2. Growth Rate in mm per day for each site.

those factors may have also played a role in the high average shell size.

The average size and growth rate was lowest at the muddy site, with an average height of 37.9mm and length of 39.1mm. The growth rate was 0.24mm per day. This low size and rate may be due to the poor water quality in the area, low water exchange from the Bay of La Paz, and the unfavorable muddy substrate.

The historical site had an average shell height of 39.5mm and length of 41.5mm. This site had the highest surviving individuals, indicating that among all the sites, the historical site has the lowest standard error.

Conclusion

This experiment has shown that the Catarina scallops can survive in the Ensenada; however, current speed, substrate and temperature may play an important factor in determining survival rates. Based on this experiment, the Catarina scallops can survive on various types of substrates, with or without plant cover, and areas of various temperatures. However, the type of substrate cover and temperature play a significant role in the growth rate of the scallops. Further tests need to be done with more cages and temperature gauges to conduct a more scientific analysis.

Annex 2

Sensitivity analysis

The biomass ratio in our model was found to be most sensitive to changes in the natural mortality. We compared natural mortality (M_{wild}) to legal and illegal fishing, growth parameters and virgin recruitment found that natural mortality is consistently the strongest driver of B_{100}/B_0 (Figure **A**, appendix **SA**). We assess this effect further in the direct relationship between temperature (an input to mortality) and fishery profits, below.

Natural Mortality

Illegal Fishing

	0.4	0.45	0.5	0.55	0.6	0.65
0.4	0.793	0.705	0.620	0.539	0.461	0.386
0.5	0.773	0.688	0.606	0.527	0.451	0.378
0.6	0.754	0.671	0.591	0.515	0.441	0.369
0.7	0.734	0.655	0.577	0.502	0.430	0.361
0.8	0.716	0.638	0.563	0.491	0.420	0.353
0.9	0.697	0.622	0.549	0.479	0.411	0.345

Worse

Better

Table AA1. Sensitivity analysis heat map of natural mortality against illegal fishing level. Here, we show how these parameters affect changes in biomass ratio over 100 years, The colorbar shows whether the biomass is high or low under each combination.

Illegal fishing was also compared against legal fishing and had a larger influence on B_{100}/B_0 (appendix **SA**). We also vary illegal fishing pressure in our scenarios to account for this significance and the unpredictability of this parameter (see Scenario Biomass Outputs).

Total profits from the wild Catarina fishery were compared over a range of costs for habitat restoration per hectare of recovered benthos and prices per kilogram of scallops. Each factor was assessed over a realistic range of values and total net present value (NPV) across 100 years of fishing was calculated (Table **#B**). Both of these parameters affect total NPV, but price per kilogram of scallops is the stronger indicator. The direct relationship between price and NPV is further assessed below.

Table AA2: Sensitivity output of cost of habitat restoration (USD $ per hectare, horizontal) against price of scallops (USD $/kg scallops, vertical). Changes in in NVP of 100 years of fishing are reported. Values do vary based on costs or restoration but price per kg of scallops is the stronger indicator. Black line indicates zero profit limit.

	5000	6000	7000	8000	9000	10000
0.3	-1409365	-2189956	-2970547	-3751137	-4531728	-5312319
0.4	-267696	-1048287	-1828877	-2609468	-3390059	-4170649
0.5	873974	93383	-687208	-1467798	-2248389	-3028980
0.6	2015643	1235052	454462	-326129	-1106720	-1887310
0.7	3157312	2376722	1596131	815540	34950	-745641
0.8	4298982	3518391	2737800	1957210	1176619	396028
0.9	5440651	4660060	3879470	3098879	2318288	1537698
1	6582320	5801730	5021139	4240548	3459958	2679367