California Sea Grant
Final Project Progress Report

R/F-198

Using Matrix Models to Evaluate Abalone Conservation and Fishery Management Strategies: A Prospective Elasticity Analysis

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Project Hypotheses

Using size structured matrix models we tested the following hypotheses:

Red H1) The size limit for the recreational fishery of 7 inches (178mm) does not protect the size classes that contribute most to the population growth rate in the model. This would be the case if the summed elasticity values of fecundity, growth, and survival of red abalone larger than the legal size limit was greatest. In this scenario, it is the large individuals (> 178 mm) in the population that are most important to sustaining population growth, implying managers could establish size limits to protect individuals in large size classes.

Red H2) The size limit for the recreational fishery of 8 inches (203 mm) does not protect the individuals in the size classes that contribute most to the population growth rate. In this situation, the summed elasticity value of fecundity, growth, and survival of individuals would be greatest for abalone larger than 203 mm. It would be advisable to increase the size limit for the fishery to protect individuals that contribute most to the population growth rate.

Red H3) The size limit for the recreational fishery of 6 inches (153 mm) does not protect the individuals in the size classes that contribute most to the population growth rate. In this situation, the greatest elasticity values of fecundity, growth, and survival of individuals would be for abalone larger than 153 mm which would support the management decision of the current 178mm resulting in no changes to the size limits.

Red H4) Mortality from `bar-cuts' on sub-legal abalone (100-150mm) does not influence population growth rate. In this situation summed elasticity values of growth, survival, and fecundity of abalone < 178 mm is greatest. Bar-cuts on "sublegal" abalone are a form of incidental mortality in the recreational fishery that may be significant in some populations. If this null hypothesis is rejected managers would be advised to allocate resources to outreach and education to reduce incidental mortality from bar cuts in the recreational fishery.

Red H5) Reproductive senescence in the largest individuals is not the most important factor influencing population growth rate. In this case, the elasticity values for fecundity in the largest size classes would be greatest. If the null hypothesis is rejected, managers would be advised that Marine Protected Areas should be established to protect old large females. If the null is supported fishing reproductively senescent (necrotic eggs) old large females would have little impact on the fishery.

For white abalone:
White H1) `Seeding' or outplanting newly settled juveniles in large numbers will not cause the greatest increase in the population growth rate in the model. This conservation strategy, in which newly settled juveniles raised in an aquaculture facility, would be the strategy of choice if the sum of the elasticity values for growth and survival of small juveniles had the greatest effect on population growth rates. Maximization of the elasticity of this size class of individuals would result from reduced mortality for the smallest individuals in the matrix model.

White H2) "Seeding and headstarting" large white abalone at 50% of their maximum size will not result in the greatest increase in population growth rates. This enhancement strategy would be recommended if the summed elasticity values for growth and survival of median-size abalone had the greatest effect on population growth. Because of the large mortality of newly settled and small individuals in many marine invertebrate populations it may be found that population growth is maximized by reducing juvenile mortality and maximizing growth.

White H3) Aggregating wild mature adults, thereby minimizing Allee effects, will not result in the greatest increase in population growth rates. Researchers have speculated that low densities of spawning individuals may lead to low interactions of egg and sperm causing a reduction of progeny in broadcast spawning invertebrates (Ebert 1998). This conservation strategy would utilize divers to aggregate individuals found as singletons in the wild and would be recommended if the summed elasticity values of fecundity for each size class were greatest.

Project Goals and Objectives
The objectives of the project were to create practical quantitative tools to address applied fishery management and marine conservation problems for California's abalone populations. We accomplished both goals during this project.

(1) The first was to develop a size-based matrix population model of red abalone in northern California to evaluate management options. To do this, we brought together a diverse array of biological information on size specific vital rates from previously conducted tag -recapture studies and reproduction studies. These data were incorporated into a size structured matrix population model. Using this model we evaluated various management strategies which were either currently in place (e.g. size limits) or proposed (e.g. Marine Protected Areas within the context of the Marine Life Protection Act process).

(2) The second goal was to construct a matrix population model for white abalone using data gleaned from the literature and other conspecifics to rank proposed conservation actions.
(2a) The NOAA White Abalone Recovery Team has outlined a wide array of potential conservation actions in the draft recovery plan including seeding small white abalone, seeding large adults, aggregating wild adults, and no recovery action. This model has been used to help prioritize which size class and vital rates might have the most impact on population growth.
(2b) A quantitative approach to threats assessments is also needed in the recovery planning process in order to evaluate which threats may have the largest impact on population growth. Sensitivity analyses of these matrices helped evaluate which of these recovery options and threats will have the most influence on population growth rate in the model.
Finally, publication of these models in the peer reviewed literature will contribute to our understanding of how quantitative modeling methods can aid marine fishery management and conservation of endangered species.

Briefly describe project methodology
We constructed size-based matrix models and examined their associated elasticity values for red and white abalone, to test hypotheses regarding the efficacy of a range of management and conservation strategies. We assumed a pre-breeding, birth-pulse population. Growth transition probabilities were multiplied by annual survivorship, as derived by the Jolly-Seber algorithm, to derive the matrix elements of survival within a size class and growth and survival to subsequent size classes. In the first row observed mean fecundities for females in each size class were

multiplied by Po (survival from fertilization to year 1). Each element of the size transition matrix was multiplied by the probability of annual survivorship as determined by Jolly-Seber. We assumed that there were three distinct size classes (small, medium and large) with unique annual survivorship. The value of P0 was calculated by iteration since no experimental results exist for first year survivals P0 nor are estimates available from the literature. The maximum eigenvalue, referred to as the "dominant eigenvalue" of a projection matrix is equal to the population growth rate. Fecundity values of reproductive females are found in the first row of the matrix and are multiplied by P0. Assuming that the population growth rate, •, is 1, (meaning the population is neither growing nor shrinking) the value of P0 can be solved for by iteration until the dominant eigenvalue of the projection matrix is equal to 1.0.

An understanding of the relative importance of these matrix elements to population growth rate (•) can aid in effective management and conservation by providing a quantitative tool to evaluate management and conservation alternatives. Proportional changes in (•) will result from changes in vital rates such as growth, survivorship, and fecundity. A prospective elasticity analysis evaluates the functional dependence of population growth rate, (•), on proportional changes in individual vital rates. This type of analysis can be used to ask questions such as, is population growth most sensitive to changes in growth and survivorship of small abalone, or the reproductive output of large abalone? How will protection of the largest females in Marine Protected Areas impact population growth? If the largest females have many senescent eggs will the populations benefit from MPAs? Is the existing size limit of 7 inches in northern California protecting (decreasing mortality) the size class that has the most impact on population growth or is their quantitative evidence from the modeling work that this size limit should be adjusted upward or downward?

Describe progress and accomplishments toward meeting goals and objectives

We have made tremendous progress with the proposed work completing both the creation of a red and a white abalone matrix model. This entailed developing parameters for each size class in both the red and the white abalone model from experimental work (in the case of red abalone fecundity) or from searching the literature to mine variables from previous work (in the case of the white abalone). Now that these models have been created we can use them to ask questions about current management questions, such as the validity of the existing size limit as well as use it to forecast which future perturbations (e.g.

ocean acidification) might have the most impact on population growth. We can do this by changing the values of any of the parameters and seeing how this impacts populations' growth (elasticity analysis of the model).

The results of this work have been published in the journal *Ecological Applications.*

During the course of working on this project we encountered a common problem faced by researchers working with endangered species - not enough size specific growth data, and no way to get more. Due to the scarcity of the species today tagging and recapturing white abalone that live at deep depths to get more of the growth data we needed for the creation of the model was not feasible. For our first paper we used the data we had and included the caveat that more growth data would be better for creating the white abalone growth matrix. This inspired a solution to our problem, which worked into a more general paper and published this solution in the journal *Ecological Modelling*. This solution uses a semi-empirical treatment blending a sparse data set with a theoretical growth model (curve) to generate the parameters for a matrix model. This solution can be used for any organism one wishes to work with and so we feel will be generally applicable for endangered species.

These two major accomplishments represent the successful completion of this grant.

Along with these two deliverables we have made significant progress on two other additional areas thanks to the hard work of our Sea Grant Trainee Cynthia Button. She has worked with our research group to generate fecundity estimates for Wavy Turban Snails now the target of an emerging fishery in California. These size specific fecundity estimates will allow use to create a size based matrix model for this species which can then be used to help examine potential management options as this fishery currently does not have size limits, season closures or other traditional forms of management. We envision this work be useful for the California Department of Fish and Game's Marine Region who are responsible for managing this resource.
The second, major expansion of this work - again lead by our Sea Grant Trainee - has been the classification of red abalone aggregations using both nearest neighbor distances and aggregation size. We have developed indexes of these measures for regions in California with high, medium and low densities of abalone. These measures will allow use to quantify an important aspect of abalone abundance using not just density (numbers per area) but also quantitative measures of aggregation (how far

apart they are). This is particularly critical for free-spawning marine invertebrates such as abalone since they need to be close to conspecifics in order to achieve successful fertilization.

Project modifications
No major project modifications were made however ancillary research topics were developed and completed as described above.

The first major additional research pursued during the course of this project was the development of methods to determine growth transitions for data poor species so that quantitative population models could be constructed to aid in fishery management as well as conservation. The growth data needed to construct growth-transition matrices required for size-structured population dynamics models for some species is lacking using traditional methods. We developed a simple semi-empirical method for converting limited growth data into estimated transition probabilities required as elements in structured matrix models. Rather than approximating transition probabilities by counting actual transition frequencies between sparsely populated size classes, we assumed that a selected function represents the entire data set, We obtain the model parameters by conventional curve fitting, and we construct the matrix model from the assumed model function. To illustrate the method, we use a sparse, scattered sample of growth data from the endangered white abalone. We use the slope and intercept of the von Bertalanffy model function to determine the growth transition matrix elements, where the paucity and or scatter of the data preclude using the traditional counting method. The method we propose can accommodate both linear and non-linear mappings of size into growth rate, as we demonstrate with a Gaussian function, which has been used to model growth of red abalone and red sea urchins. We illustrate how our method can convert confidence intervals from the model function into confidence intervals for the matrix elements. We suggest that this modeling procedure, which is simple to use and is suitable in data poor situations, will be broadly applicable for conservation practitioners in developing quantitative models to evaluate the population viability of declining or endangered species.

The second major addition to the proposed work developed during this project is the work of our Sea Grant Trainee Cynthia Button who is developing two lines of research for her dissertation as an offshoot of this project. The first, we are working to gather vital rate information on wavy turban snails, which are the target of an emerging fishery lacking quantitative population models. We have gleaned from the literature growth rates and

Cynthia is working to develop survival estimates from a tag-recapture study. Furthermore, we are working to quantify female reproductive output from a wide array of female size classes for inclusion in size structured population models. We have completed the fecundity study and a graph outlining our results is included in the trainee report. One can see from the graph that the largest females have the highest reproductive output and that there is no evidence of senescence. This suggests that Marine Protected Areas may be a very useful management tool for this species. The second major line of investigation that we have added to this project is the quantifying aggregations of abalone in the wild. Abalone at the same density may be distributed in very different aggregation patterns (e.g clumped or random). Along with density, the degree of aggregation may have important implications for spawning success as abalone more than 2.5m apart have been shown to have very poor egg-sperm fertilization success. Cynthia and I are working to develop quantitative measures of aggregation, which can then be used in management (e.g. fishing until some minimum aggregation size) or incorporated into population models exploring the impacts of density dependence.

Project outcomes

The two models we have developed during the course of this project, one for the red and one for the white abalone, have been published in the peer-reviewed journal *Ecological Applications*. Descriptions of these models and their development have also been shared in numerous scientific meetings including the Western Society of Naturalists and the International Abalone Symposium. The development of the mortality estimates for red abalone were also featured in the Master's Thesis of Rob Leaf at Moss Landing Marine Lab who is a co-author on the first paper from this work and was involved with this project early on. Rob's work was key in helping to develop mortality estimates for the red abalone matrix. The data sets used for the creation of the models for both red and white abalone are included within this Ecological Applications publication.

The second paper reporting on the results of this project was published in the journal *Ecological Modelling*. This method paper outlines a semi-empirical technique for handling data poor situations. This method may be broadly applicable to species in decline or endangered species, which would benefit from the construction of a quantitative model but for which the data are too sparse to use traditional methods.

Finally, our Sea Grant Trainee for this project Cynthia Button is in the process of finishing her Ph.D. dissertation from the

University of California, San Diego. As mentioned above in the section detailing additional work accomplished (new directions) during this project we expanded the scope of the project to include data needed for a Wavy Turban Snail population model as well as developing aggregation parameters to be incorporated into a density dependent population model for marine invertebrates.

The outcome of the red abalone matrix model has been two fold. First, there is now good quantitative evidence supporting the 178mm size limit for the recreational red abalone fishery in northern California. This size limit protects the size class that has the most impact on population growth. Meanwhile, this result also highlights how bad for the fishery the incidental mortality of sublegal red abalone is. This finding has spurred the development of a abalone fishing brochure designed by Sea Grant staff and paid for jointly with Fish and Game to educate divers on how to fish only legal size abalone rather than first fishing and then measuring the catch and putting back sublegal abalone. This is critical concept as abalone have no blood clotting mechanisms and so if injured during fishing, sublegals will bleed to death even if they are returned immediately. The brochure is now posted on the Fish and Game web page under the Marine Regions abalone section as well as being printed for distribution to the public at popular Sonoma and Mendocino coast abalone fishing sites and elsewhere.
www.dfg.ca.gov/marine/pdfs/abalone_brochure.pdf

Impacts of project

The project has had a number of positive impacts. First, it has functioned to bolster the rationale for the size limits currently used in the recreational red abalone fishery in northern California. Second, it has highlighted the novel result that the mortality of sublegal abalone in the fishery may have more negative impacts than previously recognized. This is because the pre-mature mortality of mid-size females (sublegals) in a long lived species may be felt by the population for many years to come as opposed to the death of large very old female. This new realization has lead to the development of an educational brochure designed for fishers to reduce sublegal mortalities as described in the project outcome section.
As far as the impacts of the white abalone population modeling these results have helped to bolster the recovery plans for the endangered white abalone. The PI on this project Dr. Rogers-Bennett also sits on the white abalone recovery team responsible for drafting the recovery plan for this species. The result that outplanting small adults may likely have a bigger impact on population restoration efforts has helped to focus priorities

for future restoration actions as well as lay out specific future research plans for field work.

Numerous requests have been made for the two published papers resulting from this project and it is hoped that these have contributed to help abalone fisheries and conservation worldwide as well as the conservation of data poor species in general.

Benefits, commercialization and application of project results
The National Marine Fisheries Service's Protected Resources Division has used the results of our project to aid in the drafting of the White Abalone Recovery Plan. The lead on this plan is Dr. Melissa Neuman 562-980-4115 melissa.neuman@noaa.gov

These results were used to identify the size classes and life history parameters of white abalone that would be most beneficial to enhance for restoration. Our model results suggested that by increasing the survival of small adults this would have the greatest benefits for increasing population growth rate and population recovery.

The California Department of Fish and Game's Marine Region has used the results of our project to aid in the management of the red abalone resource in northern California. This resource is managed using a combination of methods including 7-inch size limits. Our modeling work provides a theoretical basis for this size limits and suggests that the limit is appropriate and does not require changing. Mr. Tom Barnes CDFG, tom.barnes@noaa.gov 858-546-7167

The results of this work suggest that the current 7-inch size limit being used to manage the red abalone fishery in northern California is set appropriately and that there is no support from a quantitative fishery modeling perspective to increase or decrease the existing size limit. In this case, the socioeconomics benefit from maintaining the current regulations, which our results suggest are appropriate for sustaining this valuable recreational fishery.

Economic benefits generated by discovery, exploration and development of new, sustainable coastal, ocean and aquatic resources (i.e., aquaculture, marine natural products, foods, pharmaceuticals).

The red abalone resource is roughly multimillion dollar per year industry bringing 38,000 recreational fishers and their friends and families to the local coastal communities of northern California. Sustainable management of this valuable resource is critical to the continued flow of resources into northern California's coastal economies in counties such as Sonoma and Mendocino in the heart of the red abalone fishery. The work from this proposal will aid in the careful management of this species supporting sustainability of the resource. Red abalone is the largest abalone in the world and is a very popular target fishery for locals as well as those that travel long distances to even remote locations along the coast for fishing opportunities.

The white abalone fishery has been closed for more than a decade in California. Recovery of the species is that goal of restoration actions. The work developed in this proposal will aid in decisions regarding which restoration actions are needed most. In the future, after abalone populations are restored recreational divers might once again be able to see white abalone populations in the wild bringing in tourism dollars to California. White abalone populations were once found on deep reefs that support endangered purple corals and elk kelps. With healthy recovered abalone populations and conservative management, California's abalone resources might once again be in a position to support fisheries generating more economic benefits.

Issue-based forecast capabilities to predict the impacts of a single ecosystem stressor, developed and used for management (i.e., climate change, extreme natural events, pollution, invasive species, and land resource use).

The creation of these size-based abalone models can be used to help predict the impacts of ecosystem stressors such as climate change. Once experimental evidence shows for example that one life history trait of a particular size class is impacted by a stressor that new variable can be incorporated into the model and the changes this brings can be compared with the "base" model that does not include the impacted variables. If there are very few differences between the impacted version of the model and the "base" version then the prediction would be that the stressor could have negligible impacts, however if there are large differences and these are negative this could be used to make predictions about the impacts of potential stressors. In our paper, see citation below, we examine the potential impacts of extreme natural events such as El Niños and recruitment booms. The model could also be used to help make predictions about climate change.

Tools, technologies and information services developed

Tools developed during this Sea Grant project include two size-structured abalone matrices; one for use with red abalone for evaluating management strategies in California and the second for white abalone to examine potential options for conservation efforts in California. These models can also be adapted for use with other marine invertebrates for which size specific vital rate information exists (e.g. growth, fecundity and survival). This may be particularly useful for novel invertebrate fisheries in need of evaluating potential management strategies such as Wavy Turban Snails.

Publications

Peer-reviewed journal articles or book chapters

Title: Elasticity analyses of size-based red and white abalone matrix models: Management and conservation.
Authors: Rogers-Bennett, L. and R.T. Leaf.
Date: 2006
Journal Name: Ecological Applications
Issue/Page Numbers: 16:213-224

Title: Estimating growth transitions for stage-based matrix models of endangered species with limited data.
Authors: Rogers-Bennett, L. and D.W. Rogers
Date: 2006
Journal Name: Ecological Modelling
Issue/Page Numbers:195:237-246

Brochures, fact sheets

Title: You Hold The Future In Your Hands
Authors: Sea Grant and CDFG
www.dfg.ca.gov/marine/pdfs/abalone_brochure.pdf

Workshops/presentations

Western Society of Naturalists - Monterey, CA. Nov. 2005 - Presented the results of our matrix modeling work with abalone

Western Society of Naturalists - Ventura, CA. Nov. 2007 Cynthia Button Presented a talk on the results of our work quantifying red abalone aggregations.

National Shellfish Association - Monterey, CA. March 2006 - Presented a talk on the results of our work to develop parameters for the matrix models and then the creation and elasticity analysis of the models.

International Abalone Symposium - Puerto Varas, Chile Feb 2006 - Presented the results of our abalone matrix modeling results.

Dissemination of results

Two papers in peer reviewed science journals.
Four talks presented at US and International conferences.
One Master's thesis and one Ph.D. thesis.
One abalone brochure posted on the web on the Fish and Game web page.

Cooperating organizations

Federal

NOAA Fisheries, Protected Resources Division

Local and state

California Department of Fish and Game, Marine Region
University of California, San Diego

Nongovernmental

International Abalone Society

Academic

Bodega Marine Laboratory, University of California, Davis
University of California, San Diego

International implications

Marine invertebrates including abalone are being fished heavily worldwide. Abalone are now in decline in many parts of the world including Canada, Mexico, Australia, and South Africa. The work we have done completing this Sea Grant project has implications for the wise management of abalone resources worldwide. We have demonstrated how to model the species of interest using a size based matrix model and how this can be used to test the elasticities of each element to determine which have the most influence on population growth. These are the vital rates and size classes that will then need to be conserved to protect the resource and ensure sustainability.

Keywords

Abalone, Fishery Management, Quantitative Modeling, Endangered Species, Elasticity Analysis, Sustainability