

Integrative approach to quantifying the conservation potential of urchin removal for kelp restoration

Description of the Biological Problem:

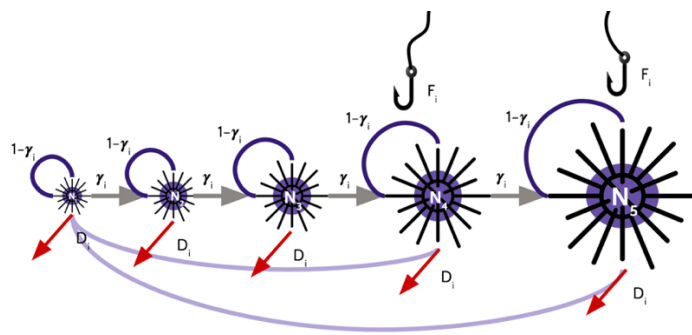
Coastal kelp forests are some of the most biologically abundant, productive, and ecologically important systems in the world (Filbee-Dexter et al. 2014). However, dramatic increases in sea urchin abundance are one of the main drivers of kelp deforestation in temperate mid-latitudinal regions, which can result in ‘urchin barrens’ (Filbee-Dexter et al. 2014). Such barrens not only negatively impact surrounding biodiversity, but also livelihoods, including wild fisheries and recreation. Urchins without their primary food source (kelp) also become barren themselves, where gametogenesis is significantly reduced. In response to global urchin proliferation, many conservation efforts have been deployed to address the negative effects of kelp deforestation, with varying levels of success (Levin et al. 2015).

A new solution proposed to reduce overgrazing of kelp forests (specifically *Macrocystis pyrifera*) is urchin ranching, which involves the manual removal (fishing) of purple urchins (*Strongylocentrotus purpuratus*) from kelp-dependent rocky reef ecosystems, growing out their gonads (ca. 12-15 wks) -- the consumed portion of urchin known as “uni” or roe -- and bringing them to market. Taking into consideration the spatial influence of conservation efforts in places like California, where top-down predator control appears to be weak (Dunn et al. 2019), urchin ranching presents as an affordable and ecologically logistical strategy, however, its efficacy as a conservation approach is currently unquantified and poorly understood (Andrew et al. 2002).

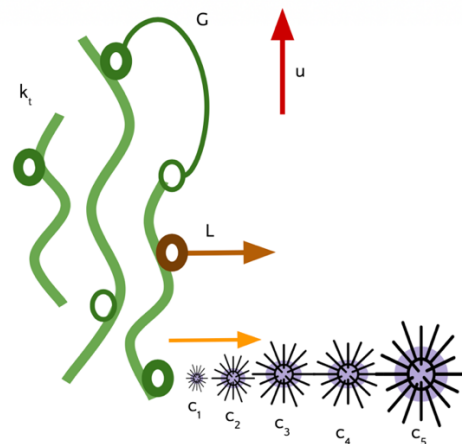
While the scientific community has recently made great strides in understanding the causes and consequences of regime shifts (Scheffer et al. 2003) of coastal kelp forests, it remains highly uncertain if and at what scale urchin removal can increase kelp biomass and restore kelp ecosystems, and whether conservation benefits can be maintained alongside a new seafood production system. Therefore, if the goal of urchin ranching operations is to significantly diminish urchin populations, it is crucial to identify the trade-offs and limitations inherent to this strategy, which requires an investigation into the balance between conservation prospects and market longevity.

Conceptual Diagrams:

Urchin Biomass:



Kelp biomass:



Equations and Parameter Values:

1. Predicted loss due to fishing and natural mortality.

$$Z_i = F_i + D_i$$

2. Size stage-based model to predict urchin population growth. Population growth within each size class is a function of incoming individuals from either recruitment or the previous size class, survivability based on fishing and natural mortality (Z), and then a probability (γ) that over the course of the year urchins will transition into the next size class based on age-specific growth rates and kelp abundance. Here, urchins are broken up into 6 size classes: $N_1=1\text{cm}-1.9\text{cm}$; $N_2=2\text{cm}-2.9\text{cm}$; $N_3=3\text{cm}-3.9\text{cm}$; $N_4=4\text{cm}-4.9\text{cm}$; $N_5=5\text{cm}-5.9\text{cm}$; $N_6=6\text{cm}-6.9\text{cm}$. To estimate Z , we utilized 20 years of observational data on urchin biomass density collected by the Santa Barbara Coastal Long-term Ecological Research program (SBC LTER, *see section "Observational data" for details*) to determine annual urchin loss for each size-group considering growth rate and group transition. We estimated γ by growth metrics previously established for purple urchins established by Kenner 1992 based on the Von Bertalanffy (1957) growth function to determine the probability of surviving urchins in each size class would transition into the next size class over a year.

$$\begin{bmatrix} (1 - \gamma_1)e^{-Z_1} & \gamma_1 e^{-Z_1} & 0 & 0 & 0 & 0 \\ 0 & (1 - \gamma_2)e^{-Z_2} & \gamma_2 e^{-Z_2} & 0 & 0 & 0 \\ 0 & 0 & (1 - \gamma_3)e^{-Z_3} & \gamma_3 e^{-Z_3} & 0 & 0 \\ 0 & 0 & 0 & (1 - \gamma_4)e^{-Z_4} & \gamma_4 e^{-Z_4} & 0 \\ 0 & 0 & 0 & 0 & (1 - \gamma_5)e^{-Z_5} & \gamma_5 e^{-Z_5} \\ 0 & 0 & 0 & 0 & 0 & (1 - \gamma_6)e^{-Z_6} \end{bmatrix}^t \cdot \begin{bmatrix} N_{1,t} \\ N_{2,t} \\ N_{3,t} \\ N_{4,t} \\ N_{5,t} \\ N_{6,t} \end{bmatrix} = \begin{bmatrix} N_{1,t+1} - \text{recruitment} \\ N_{2,t+1} \\ N_{3,t+1} \\ N_{4,t+1} \\ N_{5,t+1} \\ N_{6,t+1} \end{bmatrix}$$

3. Surviving recruits (within a closed system) that will be added to the N_1 size class as a function of the number of reproductive individuals from the N_4 , N_5 and N_6 size classes. Recruitment is represented by a discrete logistic function.

$$\text{recruitment} = Ro \cdot (N_4 + N_5 + N_6) \cdot \left(1 - \frac{N_4 + N_5 + N_6}{K_u}\right)$$

4. Proportion of kelp available to the amount necessary to feed all of the urchins throughout the year (on average an urchin will eat ~450g of kelp per year).

$$M_t = \frac{k_t}{N_t \cdot 450}$$

5. Consumption rates of urchins in each size class (derived from previous research (Rennick et al. in Review)). This equation assumes that the average size of the urchin within each size class is $i + 0.5$ cm.

$$c_{N_i} = ((i + 0.5) \cdot 24 \cdot 365) \cdot 0.009645 + 0.0032674$$

6. Kelp biomass growth over time as the result of a discrete logistic growth function with reductions due to size-specific consumption rates from urchins and harvest.

$$k_{t+1} = \left[1 + (dr_t - dd_t) \left(1 - \frac{k_t}{K} \right) \right] k_t - uk_t - [(N_{1,t}c_1 + N_{2,t}c_2 + N_{3,t}c_3 + N_{4,t}c_4 + N_{5,t}c_5)k_t]$$

7. Harvest as a function of catchability and effort.

$$u_k = q_k \cdot e_k$$

Table of all Parameters and State variables:

type	synta x	units	description
paramete r	t	year	time
paramete r	γ_i	NA	probability surviving population will grow into the next size class based on growth rate
paramete r	F_i	NA	fishing removal probability (Froehlich) (Barnov)
paramete r	D_i	NA	natural mortality probability (Froehlich) (Barnov)
paramete r	M_t	NA	urchin growth probability based on kelp biomass
paramete r	R	$\frac{g}{\text{year}}$	growth rate of kelp
paramete r	a_1	NA	unknown regression parameter
paramete r	a_2	NA	unknown regression parameter
paramete r	b_1	NA	unknown regression parameter

parameter	b_2	NA	unknown regression parameter
parameter	R_0	$\frac{1}{\text{year}}$	reproduction number for urchin recruitment
parameter	K_u	urchins	carrying capacity of urchins
parameter	K	g	carrying capacity of kelp
parameter	u	g	harvest
parameter	q	$\frac{\text{g}}{\text{boat}}$	catchability
parameter	e	boat	fishing effort
parameter	c_i	$\frac{\text{g}}{\text{year}}$	consumption rate of urchins of size class i
parameter	u	g	harvest
parameter	t	year	time
state	k_t	g	kelp biomass at time t
state	$N_{i,t}$	# of urchins	number of urchins in size class i at time t

Many assumptions were made in the development of this model. This model does not consider external recruitment, emigration, migration or metapopulation dynamics which might influence the stability of urchin populations within each size class. Additionally, urchin population growth, survivability, and reproduction are not currently dependent on kelp. Therefore, at high urchin abundances, kelp biomass will become negative. Because urchin populations can continue growing and surviving without the presence of kelp, we could not assume that urchins would decline in the absence of kelp. Therefore, in the coding of this model, an additional function was added to ensure that kelp biomass was never below 0 (see code). Urchin growth, consumption rates, transition probabilities and death rates remain constant through time. This model assumes that only urchins in the 4, 5 and 6. Size class can reproduce and will be susceptible to fishing. Urchins in this model do not get bigger than 6.9cm. For kelp, we assume that it follows a logistic growth pattern and that the only metric preventing kelp from reaching carrying capacity is size-specific purple urchin consumption.

Methods:

Following the development of this model, I aimed to determine equilibrium conditions for giant kelp (*Macrocystis pyrifera*) and purple urchins (*Strongylocentrotus purpuratus*) through time without fishing and then evaluate how incorporating fishing dynamics changes equilibrium values for urchins and kelp through time.

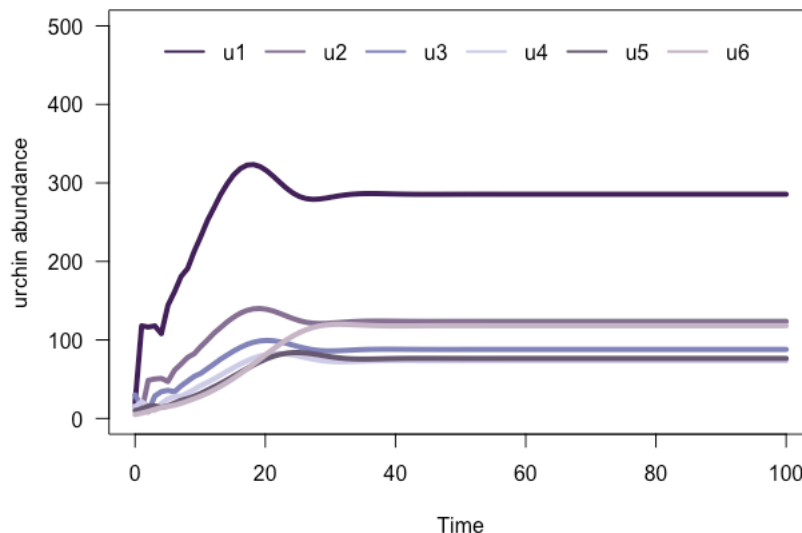
For this model: $K=400\text{kg}$ of kelp; $u=0$; $a_1=1.25$, $a_2=0.05$, $b_1=0.15$ and $b_2=0.05$; $R_0=4.5$; $K_u=400$ urchins; and for each timestep, N_i will be a different value until equilibrium is met.

I began by running this simulation through R (version 4.1.0) (see attached code). For the initial values for purple urchins $N_1=20$ urchins; $N_2=15$ urchins; $N_3=30$ urchins; $N_4=15$ urchins; $N_5=10$ urchins; and $N_6=5$. These initial values were based off of size distribution and frequency measurements from the Santa Barbara LTER. For the initial value of kelp $k=500\text{kg}$. Changes in purple urchin abundance and giant kelp biomass was projected in a conceptualized 100m^2 temperate kelp forest for 50 years to determine the relationship between urchin population size and kelp biomass. The model simulation was then run at three different levels of fishing pressure: 1) No fishing 2) mild fishing 3) heavy fishing to determine if urchin ranching may be contributing to kelp forest regeneration.

For this model in an unfished context: $\gamma_1 = 0.99$; $\gamma_2 = 0.9$; $\gamma_3 = 0.7$; $\gamma_4 = 0.5$; $\gamma_5 = 0.3$; $\gamma_6 = 0.1$ and $Z_1=0.9$; $Z_2=0.5$; $Z_3=0.3$; $Z_4=0.3$; $Z_5=0.1$; $Z_6=0.1$. For each timestep, N_i will be a different value until equilibrium is met. To represent 'mild fishing pressure' the Z term for urchins in the N_4 N_5 and N_6 size classes were increased by 40% to represent the harvest of 40% of urchins annually from the three largest size classes. To represent 'heavy fishing' the Z term for urchins in the N_4 N_5 and N_6 size classes were all raised to 90% to represent a 90% removal rate of urchins in the three largest size classes by either fishing or mortality.

Results:

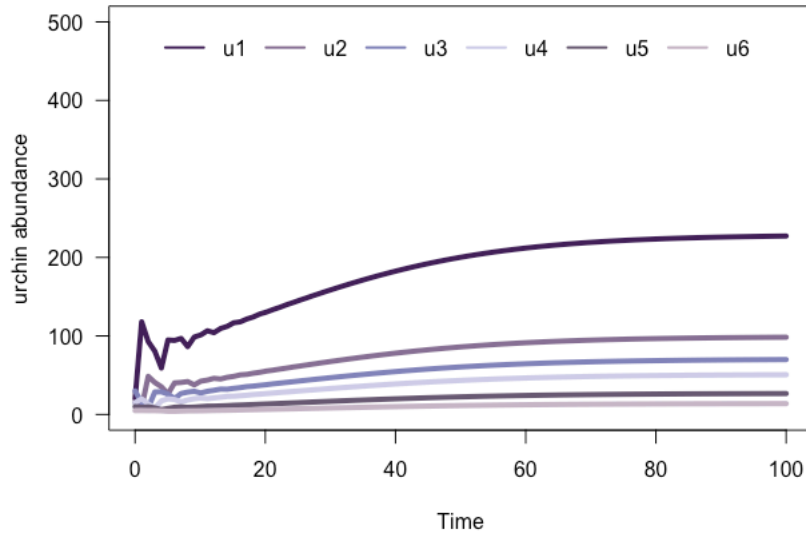
Figure 1: Modeling Size-Structured Urchin Populations Through Time: Without Fishing



Without fishing pressure ($Z_1=0.9$; $Z_2=0.5$; $Z_3=0.3$; $Z_4=0.3$; $Z_5=0.1$; $Z_6=0.1$), each size class of urchins will rise to an individualized carrying capacity over time. Each individual equilibrium value for the size classes is dependent on the carrying capacity of the recruit stage (N_1), the transition probability for each size class (γ_i) and the predicted loss (Z) of the previous size class. The rate in which it reaches equilibrium is dependent upon R_0 (the reproduction value) and the initial value of individuals in the N_4 N_5 and N_6 size classes. In this case, urchins cannot skip size classes and therefore the annual repopulation of each size class is determined by the previous

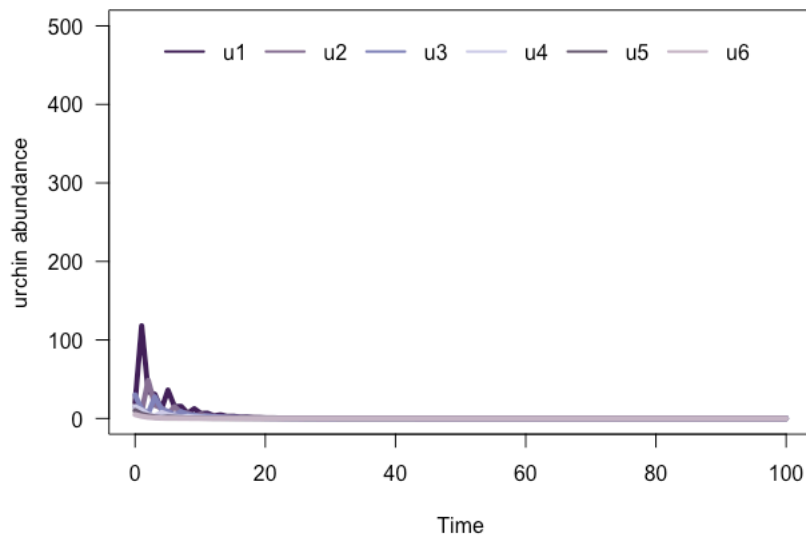
size class. Given the chosen parameter values, the equilibrium values for each size class are: $N_1=285$ urchins; $N_2=123$ urchins; $N_3=88$ urchins; $N_4=74$ urchins; $N_5=76$ urchins; $N_6=118$ urchins.

Figure 2: Modeling Size-Structured Urchin Populations Through Time: With Mild Fishing



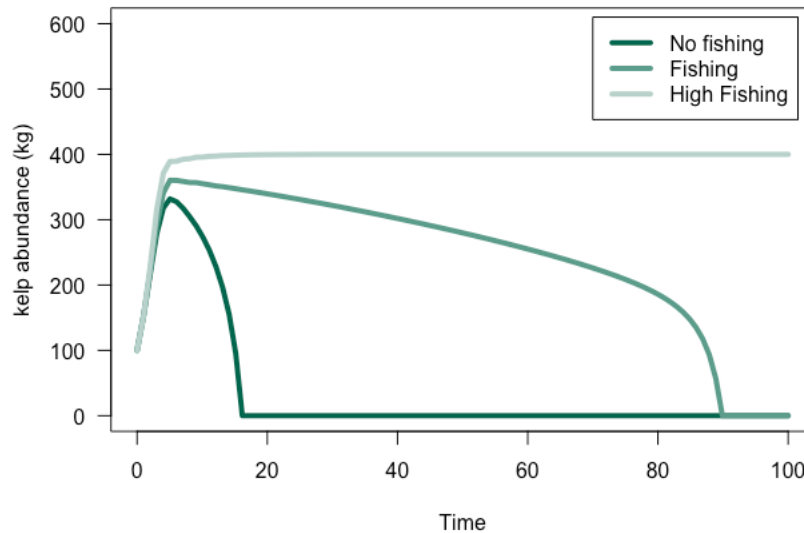
With mild fishing pressure ($Z_1=0.9$; $Z_2=0.5$; $Z_3=0.3$; $Z_4=0.7$; $Z_5=0.5$; $Z_6=0.5$), each size class of urchins will still rise to an individualized carrying capacity over time. Given the chosen parameter values, the equilibrium values for each size class are: $N_1=227$ urchins; $N_2=98$ urchins; $N_3=70$ urchins; $N_4=51$ urchins; $N_5=27$ urchins; $N_6=14$ urchins.

Figure 3: Modeling Size-Structured Urchin Populations Through Time: With Heavy Fishing



With heavy fishing pressure ($Z_1=0.9$; $Z_2=0.5$; $Z_3=0.3$; $Z_4=0.9$; $Z_5=0.9$; $Z_6=0.9$), each size class of urchins will still rise to an individualized carrying capacity over time. Given the chosen parameter values, the equilibrium values for each size class are: $N_1=3$ urchins; $N_2=2$ urchins; $N_3=1$ urchin; $N_4=6$ urchins; $N_5=2$ urchins; $N_6=5$ urchins.

Figure 4: Modeling Kelp Biomass Through Time at Varying Levels of Urchin Fishing



Kelp biomass (kg) through time under varying conditions of purple urchin fishing pressure. Without fishing, kelp biomass is projected to crash. Under mild and heavy fishing conditions, kelp is able to persist. Given the chosen parameter values, the equilibrium values for each size class are: $k_{\text{no fishing}}=0$ kg; $k_{\text{mild fishing}}=0$ kg; $k_{\text{heavy fishing}}=400$ kg.

Analysis, Discussion and Next Steps:

Our society is witness to the degradation of vital ecosystems and natural processes around the world. While it is important to act quickly to preserve and protect our environment, we still need to test whether well-intended initiatives do have conservation outcomes and, more importantly, do not cause other environmental problems. Through my research of California urchin-kelp interactions and dynamics (Rennick et al. in review), it has become clear that there has yet to be a thorough investigation of urchin population dynamics contribution to kelp deforestation and the destruction of temperate kelp forests globally. Yet, the political and economic framework for managing and developing these conservation initiatives trudges forward, while we have yet to determine if the systems we have in place work - and if so, to what extent. This investigation into the success of a new conservation initiative at the fishing, aquaculture and conservation nexus not only helps inform such actions in California happening now, but can help guide other regions around the globe considering such integrated approaches. The purpose of designing this model was to produce a standardized framework for quantitatively evaluating conservation efforts of urchin removal for kelp restoration, and help test the viability of urchin ranching supply and demand on the West Coast of the United States. Particularly, regions of California have been designated by executive order as an Aquaculture Opportunity

Area, which makes our understanding of how seafood production systems are developed and can exist sustainably, even more crucial.

As anticipated, the model determines that less urchins generally corresponds to higher kelp biomass, so at levels of mild to heavy fishing, urchin populations were reduced and kelp biomass remained high. However, despite the fact that under mild fishing conditions, the system will equilibrate with the greatest number of urchins, kelp biomass was able to persist through time. Most likely, kelp is still able to persist despite high urchin abundances in the smaller size classes because they do not eat as much as the larger urchins (Rennick et al. in review). Therefore, we interpret that kelp biomass appears to be most dependent on the abundances of urchins from the bigger size classes. As fishing effort in this model targets urchins from the largest size classes, urchin fishing was a successful mediation strategy to maintain kelp biomass given the assumptions made in this model. Therefore, if the fishery has potential to be successful should it be able to gain traction in the marketplace.

While operating models do not provide precise estimates in a data limited environment -- which is the case here -- they allow testing of a system without disturbing the “true” environment. In fact, operating models are a core feature of fishery assessments (e.g., Management Strategy Evaluation) (Holland et al. 2010). Using the model, I was able to test under what circumstances, including harvest control type (open- vs quota fishery) and level of urchin ranching (e.g. frequency and total landings), could potentially increase kelp biomass. Though successful in maintaining kelp biomass under the modeled conditions when fishing was added into the system, one major limitation that could arise is access to sufficient levels of feed for the ranched urchin. Urchins can be fed kelp, other seaweeds, or artificial ingredients during the grow out phase (Onomu et al. 2020). Assuming kelp is the ideal feed (Senaratna et al. 2005), it is unclear if the quotas for wild kelp allocated along the coast are enough to meet the demand, especially if demand for purple urchin grows. The model has yet to include annual feed requirements to compare to wild (CA) sources relative to the scale of production over time which will be the next step in assessing whether purple urchin fishing is recovering more kelp than it is requiring for input.

While the work produced in this paper is a promising first step in producing a standardized framework for quantitatively evaluating conservation efforts of urchin removal for kelp restoration, and help test the viability of urchin ranching supply and demand on the West Coast of the US, there is more analysis needed to strengthen these results. Moving forward, I intend to create a function in which fishing pressure changes as time moves on to mimic market growth, which I will model after both market projections and the past development of the similar red urchin fishery. In doing so, I would additionally would like to figure out the amount of kelp necessary to support both in situ populations and farmed urchins which are held and grown for 12-15 weeks and compare that to the amount of kelp recovery (if any) predicted to occur on reefs. I would like to alter initial conditions to see if the trajectory of kelp recovery changes under varying initial conditions of both urchins and kelp, and to perform more robust sensitivity analyses on the parameters in this model to better understand the mathematical drivers in this model. I would like to include kelp availability in the urchin growth function based on Ebert 1968 estimates to more accurately reflect the population interactions between kelp and urchins. Lastly, I want to include metapopulation analysis to see how recruitment from external environments may alter this model, and include a function for steepness in the recruitment function.

Citations:

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