Social-ecological models with social hierarchy and space applied to small scale fisheries

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1 ABSTRACT

Socio-ecological models combine models of ecological systems with human social dynamics in order to better understand human interaction with the environment. One such model of human behavior is replicator dynamics. Replicator dynamics are derived from evolutionary game theory and model how societal influence can change opinions about resource extraction. Previous research on replicator dynamics have shown how evolving opinions on conservation can change how humans interact with their environment and therefore change population dynamics of the harvested species. However, these models have all assumed that human societies are homogenous with no social structure. In this study, we develop a two-patch socio-ecological model with social hierarchy in order to study the effect that social inequity has on decision making. We also analyzed the spatial components of this two-patch model and observed the effect of fish movement on decision making and fish population dynamics. We found that, contrary to our hypothesis, social influences became less significant in our two patch model. Instead, we found that fish movement across patches was a major driver of changes to population dynamics. This indicates the importance of including spatial components to socio-ecological models. Further, this study highlights the importance of understanding species movements when making conservation decisions.

2 INTRODUCTION

The study of social ecological models is a growing field in ecology as they treat human behavior1 as a variable as opposed to a set parameter. This allows for the study of how human decision making can change in response to environmental factors and in turn, change how humans interact with resources and profits (Chris T. Bauch 2005; Innes, Anand, and Bauch 2013; Oraby, Thampi, and Bauch 2014; Chris T. Bauch et al. 2016; Sigdel, Anand, and Bauch 2017; Thampi, Anand, and Bauch 2018). As human societies grow increasingly intricate and interconnected, these models can help us to analyze how our social structures can influence the environment around us (Liu et al. 2007). These models provide important insight not only into how human decision making can influence the ecological processes but it can also show hidden processes, reveal regime shifts that would otherwise be hidden, and identify vulnerabilities of systems that don't exist within the purely social or ecological models (Liu et al. 2007; Young et al. 2007; Lade et al. 2013). Socio ecological models have even showed different dynamics at different scales and different amounts of human connectivity (Cumming, Morrison, and Hughes 2017). They can also be utilized in systems where data is difficult to collect, as parameters can be changed in order to analyze different hypothetical scenarios. Socio-ecological models can also inform effective policy decisions. Conservation plans often do not reach their conservation goals, and these setbacks are often attributed to a lack of stakeholder participation. This can be due to an emergence of conflict for stakeholders, where the conservation plan in place directly hinders their practices, therefore deterring them from participating in the restorative efforts. Socio-ecological models can identify where these areas of potential conflict can arise, compromises that can be made in the system, and alternative conservation practices that encourages participation from all stakeholder groups (Ban et al. 2013). Further, as these models are simulations of human and environmental interactions, they allow flexibility in that they can be adapted to fit the specific system of study and improve place-based management practices (Young et al. 2007; Liu et al. 2007; Felipe-Lucia et al. 2022)

Due to their adaptability, socio-ecological models can use a wide range of strategies to represent human decision making. One such method is replicator dynamics, which model human decision making where an individual makes conservation decisions based on weighing the perceived benefits of conservation with the costs as well as the social pressure to conform to the group stance on conservation. Individuals will therefore "replicate" the behavior of their peers by changing their harvest practices based on the opinion of the majority (Chris T. Bauch and Bhattacharyya 2012). They have been used to show how social learning is a key component to vaccination uptake public health, and preexisting social norma can actually suppress vaccine uptake despite frequent disease outbreaks (Chris T. Bauch and Bhattacharyya 2012; Oraby, Thampi, and Bauch 2014). They can also have conservation application as well as their application to pest invasion models have shown ways to simultaneously mitigate pest outbreaks and the cost to address them in the timber industry (Barlow et al. 2014). Further, land use changes have been modeled to have completely different dynamics when human decision making was added to these models (Innes, Anand, and Bauch 2013). However, all previous models of human behavior have assumed that human societies are homogenous, and all people are subject to the same social influence and dynamics. No replicator-dynamics model has incorporated social inequality or hierarchy, despite the fact the most human societies have varying levels of social influence within them.

Contrary to this assumption made by previous models that human groups are homogenous, the vast majority of real-world societies exhibit some form of hierarchy or inequality. Societies with different social subgroups can often exhibit an "us vs. them" mentality and compete for resources (Borgatti 2003). Social status can greatly alter peoples' interaction with the environment. Competition over resources has been shown to be exacerbated by social hierarchies and 'top-down' regulation whereas when social connectivity is considered in management plans, this has been shown to not only improve management outcomes, but reduce costs as well (Krackhardt and Stern 1988; Grafton 2005; Bodin and Crona 2009). Further, members of social networks have been shown to have varying levels of connectivity with others based on attributes such as ethnicity, and this can in turn alter an individual's relationship with the environment and their views on conservation (Barnes-Mauthe 2013). Barnes-Mauthe (2013) also showed that fishing communities can exhibit homophily, which is the tendency for people to obtain information and opinions from those who are similar to themselves before seeking views from those who are perceived as different. Therefore, people in different social groups may be receiving different information and opinions about conservation and acting accordingly (McPherson, Smith-Lovin, and Cook 2001). For example in Kenya, communication among fishers has been shown to be among fishers using the same gear type which has inhibited successful regulation of the whole fishery (Crona and Bodin 2006). Further, in the Southwest Madagascar octopus fishery, fishing method and location typically falls along gendered lines. When fishing restrictions were imposed on tidal flats, this affected fishing access for women while maintaining this livelihood for male fishers (Baker-Médard 2017). In Thailand, ethnicity has been shown to be a source of fishing conflict which has exacerbated resource depletion (Pomeroy et al. 2007). The existence of social structures is extremely prevalent in human societies and this has been shown to alter how people interact with the environment. However, there has been no previous replicator dynamics study that considers how social hierarchies alters harvest practices.

Small scale fisheries are a particularly relevant system to apply replicator dynamics as fishing practices and policies are often made by communal decision makers. Research on small-scale fisheries is a growing and essential field as they are drastically understudied yet affect many people around the globe. Worldwide, about 32 million fishers make their livelihood in small-scale fisheries, a subsector in which 90 to 95% of fish is distributed for local consumption. These marine products are a vital source of nutrition for these communities ("HIDDEN HARVEST-The Global Contribution of Capture Fisheries" 2012). Due to tight social structures, community decision making, and strong reliance on the environment, small scale fisheries are systems that are well represented by socio ecological models and replicator dynamics (Thampi, Anand, and Bauch 2018). Conservation efforts in small scale fisheries have often been unsuccessful, especially when the social and economic components of the industry have been ignored (Salas, Barragán-Paladines, and

Chuenpagdee 2019; Prince et al. 2021). However, even when human interactions and decision making have been considered, socio-ecological models have often treated individuals in human societies homogeneous. As human societies are often complex and hierarchical, this simplifying assumption that everyone interacts with the environment and within their community equally can lead to lack of participation in conservation by some groups within a community (Barnes-Mauthe 2013; Cumming, Morrison, and Hughes 2017). Mismanagement of fisheries have even been shown to exacerbate these inequalities (Cinner et al. 2012; Baker-Médard 2017). Further, the specific dynamics of the fishery in question have been shown to be an important component to models, as models with multiple patches can actually mitigate overfishing if there is a high migratory ability of the harvested species (Cressman, Křivan, and Garay 2004).

Instituting effective conservation strategies can be especially difficult if the organism being protected has a migratory pattern that crosses over multiple management jurisdictions such as country borders (Ogburn et al. 2017; Garrone-Neto et al. 2018; Ramírez-Valdez et al. 2021). Borders can also create challenges when gathering population data that requires extensive fieldwork Hebblewhite and Whittington (2020). The fragmentation of management can also result in a mismatch of conservation strategies that become ineffective when these management bodies do not coordinate efforts (Siddons, Pegg, and Klein 2017). Research on the importance of coordinated research efforts has been conducted on many species of terrestrial animals with large migratory ranges and have consistently shown that cooperation among government bodies is essential to protecting population health of highly migratory species or species whose native ranges expand across multiple countries (Plumptre et al. 2007; Gervasi et al. 2015; Meisingset et al. 2018). Because fish are generally highly migratory, this issue is especially relevant in international waters or waters where different government bodies share jurisdiction (Mchich, Auger, and Raïssi 2000). For this reason, research on two patch fishing models is a commonly used method as different management strategies can be modeled in each patch. Previous research on two-patch fishing models has shown that movement rates between patches can effect population stability when there is different fishing pressures in each patch (Mchich, Auger, and Raïssi 2000; Cai, Li, and Song 2008). Economic output can also be maximized in multi-patch fishing models as high dispersal can result in a higher overall yield of the system than the yield of each patch combined (Auger, Kooi, and Moussaoui 2022). High dispersal across patches is commonly found to be an essential component to maximizing population health and economic gain from fishing (Freedman and Waltman 1977; Moeller and Neubert 2015; Auger, Kooi, and Moussaoui 2022). Two patch models help us to understand better the population dynamics of fish species who face different pressures in each patch and have even resolved conflicts between fishing groups (Mchich, Auger, and Raïssi 2000). However, no previous research has combined two patch fishing models with a hierarchical human decision making model in order to study how space and social dynamics affect fishery dynamics.

In this study, we couple a human-decision replicator dynamics model with social hierarchies with a two-patch fishing model in order to understand how decision making. The objectives of this study are: 1) to compare the output of this model with that of previous replicator dynamics studies without spatial or social hierarchical components, 2) Find the effects of social hierarchies in decision making and how that effects fishing dynamics 3) determine the significance of fish dispersal in our two patch model.

3 METHODS

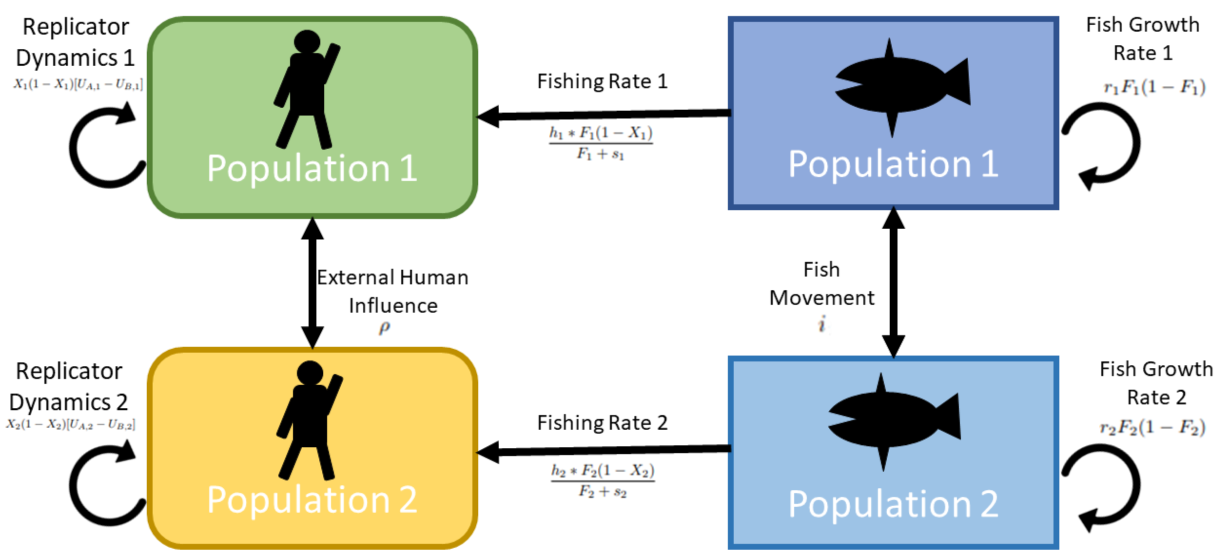

Figure 1: A conceptual representation of our model as a two-patch extension of Chris T. Bauch et al. (2016). Here, fish populations (F_1 and F_2) in each patch increase through natural growth and movement of fish into the patch. Fish populations are decreased through emigration out of the patch and human fishing activity. The number of fishers (X_1 and X_2) change in response to fish population levels, the cost of stopping fishing activity, and the opinions of those in the patch and those in the other.

3.1 Model Construction

We build on the work of Chris T. Bauch et al. (2016) by extending their approach to a two-patch model (Figure **??**). The fish population models are as follows:

$$\frac{dF_1}{dt} = r_1 F_1(1 - F_1) - \frac{h_1 * F_1}{F_1 + s_1} - i_2 F_1 + i_1 F_2 \tag{1}$$

$$\frac{dF_2}{dt} = r_2 F_2(1 - F_2) - \frac{h_2 * F_2}{F_2 + s_2} - i_1 F_2 + i_2 F_1 \tag{2}$$

Where the change in fish populations is dependent on r, the net population growth of each patch, and both populations follow logistic growth. The second term: $\frac{h*F}{F+s}$, denotes fish lost to human activity. h is the harvesting efficiency of the respective human population and s controls the supply and demand of the fishery. Because we are now working with a two-patch model, the i parameter denotes the immigration out of each patch and into the other. In this study, we are assuming a closed population between the two patches. Therefore, fish move directly from patch to patch and do not disperse elsewhere.

For the model of human activity and opinion, we used replicator dynamics from evolutionary game theory to simulate societal influence on an individual's opinion. Social dynamics are represented by the proportion of conservationists in a population (X) and the proportion of harvesters $(1 - X)$. These two groups interact with one another using the term $(X)(1 - X)$ which simulates individuals "sampling" other individuals in the population. If one opinion dominates in the population (i.e. $X >> (1 - X)$ or $(1 - X) >> X$), the rate of changing opinions will be slow as the power of societal pressure makes it challenging for the other opinion to gain traction. However, if X and $(1 - X)$ are close, the rate of change in opinion will be high as society has a split opinion on conservation versus harvest. In this model, each person holds an opinion (conservation or harvest) by weighing the benefits of conservation (U_A) against the benefits of harvest (U_B). This gives the replicator equation:

$$X(1 - X)[U_A - U_B] \tag{3}$$

$$X(1 - X)[\Delta U] \tag{4}$$

As individuals "sample" the opinions of others in their group, they can switch from A to B if $U_B > U_A$ and vice versa. In our model, we adapt U_A from Bauch 2016 with the added influence of the other population's opinion. U_A is therefore given by:

$$U_{A,1} = \frac{1}{(F_1 + c_1)} + d_1 X_1 + \rho_1 X_2 \tag{5}$$

$$U_{A,2} = \frac{1}{(F_2 + c_2)} + d_2 X_2 + \rho_2 X_1 \tag{6}$$

Where $\frac{1}{(F+c)}$ represents the perceived rarity of fish populations within a patch. As F and c (the rarity valuation parameter) decrease, this term will increase, therefore adding to the perceived benefit of protecting fish populations. d refers to the social influence that each population has on itself, and as an individual encounters a conservationist (X), the social benefit of also being a conservationist is shown in d. ρ has this similar effect, but denotes the social effect on the opposite population on decision making. Individuals in each population are receiving information about the conservation practices of the other, and the influence that this has on each population is encapsulated by ρ.

U_B (the perceived benefits of harvest) is:

$$U_{B,1} = \omega_1 + d_1(1 - X_1) + \rho_1(1 - X_2) \tag{7}$$

$$U_{B,2} = \omega_2 + d_2(1 - X_2) + \rho_2(1 - X_1) \tag{8}$$

Where ω is the cost of conservation (i.e. revenue lost by not fishing) where now, d is the social benefit of switching to harvesting $(1-X)$ and ρ_1 is the other population's ability to change the opinion of an individual to be a harvester.

Plugging equations (5), (6) and (7), (8) into equation (3) gives:

$$\frac{dX_1}{dt} = k_1 X_1(1 - X_1)[\frac{1}{F_1 + c_1} - \omega_1 + d_1(2X_1 - 1) + \rho_1(2X_2 - 1)] \tag{9}$$

$$\frac{dX_2}{dt} = k_2 X_2(1 - X_2)[\frac{1}{F_2 + c_2} - \omega_2 + d_2(2X_2 - 1) + \rho_2(2X_1 - 1)] \tag{10}$$

Where specifics of the derivation are outlined in the appendix. Coupling the fish population and human opinion models gives:

$$\frac{dF_1}{dt} = r_1 F_1(1 - F_1) - \frac{h_1 * F_1(1 - X_1)}{F_1 + s_1} - i_2 F_1 + i_1 F_2 \tag{11}$$

$$\frac{dF_2}{dt} = r_2F_2(1-F_2) - \frac{h_2 * F_2(1-X_2)}{F_2+s_2} - i_1F_2 + i_2F_1 \tag{12}$$

$$\frac{dX_1}{dt} = k_1X_1(1-X_1)[\frac{1}{F_1+c_1} - \omega_1 + d_1(2X_1-1) + \rho_1(2X_2-1)] \tag{13}$$

$$\frac{dX_2}{dt} = k_2X_2(1-X_2)[\frac{1}{F_2+c_2} - \omega_2 + d_2(2X_2-1) + \rho_2(2X_1-1)] \tag{14}$$

Where the fishing pressure is now a function of the number of harvesters in a population ($\frac{hF(1-X)}{F+s}$). Further, the opinion of each population will shift based on the perceived fish stock health of their respective patch weighed against the costs and benefits of conservation. As fish stocks decrease, individuals will sway more toward conservation, thereby relieving this fishing pressure. However, we now have an external influence in this model: the opinions of people in the other population. The strength of this external influence is ρ, and in this study, we plan to simulate inequalities in human societies with this parameter.

3.2 Fish Parameters

For our basic analysis, we chose to model a two-patch fishery where the harvested fish species has a mid-range growth rate and regularly diffuses across the two patches, such as the parrotfish modeled in Thampi, Anand, and Bauch (2018). From the human side, the two groups of fishers have the same social influence on one another, representing a non-hierarchical social structure. The default fish growth rate of both patches is 0.35 fish per year. For the harvesting efficiency, we chose a maximal fishing rate of 0.5. These numbers were adapted from a coral reef fishing model Thampi, Anand, and Bauch (2018) where r = 0.35 and h = 0.5 are the mid-level growth rate and max fishing rates analyzed by this paper. For the emigration and immigration parameters, we chose 0.2 for each as these are the values used in the two-patch fishing model described in Cai, Li, and Song (2008). We used the s parameter described in the Chris T. Bauch et al. (2016) model of s = 0.8.

3.3 Human Parameters

The rate at which humans interact with one another is described by the parameter k. In our default model, we used k = 1.014 as adapted from the Thampi, Anand, and Bauch (2018) default model. We used the default rarity valuation parameter c from Thampi, Anand, and Bauch (2018) where c = 1.68. The cost of conservation default parameter is $\omega = 0.35$ from Chris T. Bauch et al. (2016). Further, as our default model will have no human social hierarchy, we d = $\rho = 0.5$ for our social learning rate as adapted from Chris T. Bauch et al. (2016) which models social decision making regarding deforestation.

3.4 Analyses

Write this once you know

4 RESULTS

First, we compared the dynamics of the uncoupled fish model with that of the socio-ecological model by holding the $(1 - X)$ variable to a constant. We found that fish populations remained stable as long as the proportion of the populations remained 50% or lower (figure 2a). This shows that given our default parameters, only half of individuals from each patch can fish at one time. However, if the distribution of fishers between patches was uneven, with one patch being fished sustainably and the other experiencing overfishing, both patches were able to recuperate stable population dynamics as the immigration parameter allowed for the overfished patch to benefit from fish coming from the other patch (figure 2b). Figure **??** shows our coupled socio-ecological model where replicator dynamics influence how many individuals are fishing. Here, the human population maintains fishing levels over 50% for each patch, thereby overfishing both patches.

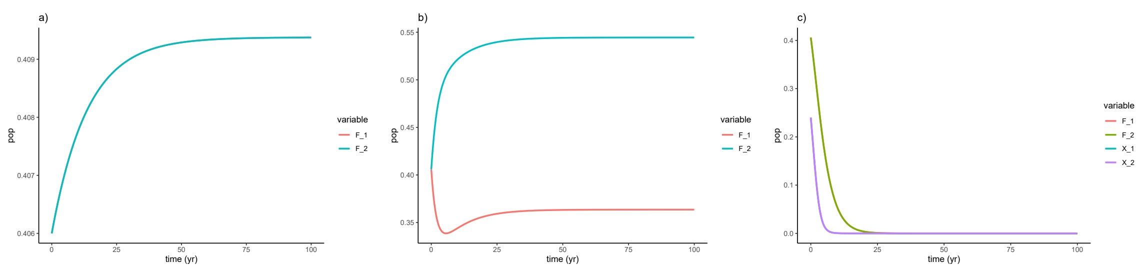

Figure 2: Fish model uncoupled from social dynamics

Next, we altered the parameters to reflect sustainable fishing practices as shown in table 1 in order to create a healthy system (Figure 3). Next, we simulated scenarios where one patch's practices were so unsustainable that both patches began to move toward stock collapse (Figure 4). This is different than the uncoupled model, where unsustainable practices could be mitigated by immigration from the other patch of fish stock. Instead, because of the parameters used in this analysis, humans keep fishing despite lower yields due to their

Table 1: Parameters used to model a sustainable fishery

Parameter	Population_1	Population_2	Def
r	0.4	0.4	Fish net growth
s	0.8	0.8	Supply and demand
h	0.25	0.25	Harvesting efficiency
k	1.014	1.014	Social learning rate
ω	0.2	0.2	Conservation cost
c	1.5	1.5	Rarity valuation
d	0.5	0.5	Social norm strength (within pop)
i	0.2	0.2	Fish immigration (from patch)
ρ	0.5	0.5	Social norm strength (opposite pop)

influence over one another. Therefore, in order to improve fishing conditions for both patches, we explored how changing human parameters can influence the dynamics of the whole system. We found, for example, that decreasing the rarity valuation parameter from 1.5 to 0.25 is sufficient to prevent population collapse (Figure 5). GET BAUCH MODEL 11 TO RUN AND THEN PUT THESE PARAMS THOUGH TO SEE WHICH ARE INFLUENCING

(ref:ss_unsustainable) One group unsustainable practices scenario. Shows that one groups bad fishing can tank whole system MAYBE PUT IN WHICH PARAMS CHANGED

(ref:ss_revive) changing the rarity valuation parameters can recover the system WRITE WHAT IT IS

Next, we tested our hypotheses that social hierarchy can change the system's dynamics by running several scenarios and comparing the effect that changes in ρ can have on the model. We found, contrary to our predictions, that social hierarchy tended to not have significant overall influences on the model. Table **??** shows the parameters used in this analysis. We found that due to a decrease in ρ_1, fishers in patch 1 exhibited more conservation practices for a longer amount of time (Figure 6) yet still eventually overfished their patch. This is consistent with many other scenarios we ran, and shows that differences in ρ_1 vs ρ_2 has a lower influence on this model than other parameters. Further, as none of the scenarios we ran showed oscillations in the proportion of conservationists in each patch, this shows that the non-linear dynamics of the system become less significant as multiple patches to the model.

Table 2: Default parameter values used in this analysis

Parameter	Population_1	Population_2	Def
r	0.35	0.35	Fish net growth
s	0.8	0.8	Supply and demand

Parameter	Population_1	Population_2	Def
h	0.5	0.25	Harvesting efficiency
k	0.17	1.014	Social learning rate
ω	0.35	0.35	Conservation cost
c	1.5	1.5	Rarity valuation
d	0.5	0.5	Social norm strength (within pop)
i	0.1	0.4	Fish immigration (from patch)
ρ	0.5	0.5	Social norm strength (opposite pop)

After finding that social influence is a less substantial parameter in this model, we tested how significant fish dispersion was in the system. We found that it has a huge overall effect on the system's dynamics. Here, we modeled sustainable fishing in patch 1 and unsustainable fishing in patch 2 (Table **??**) with no dispersion (Figure 7) and very little dispersion (Figure 8). We found that even small amounts of dispersion are enough to recuperate crashed fish stocks in patch 2. On the other hand, no changes to d or rho could have the same effect. This shows that our immigration parameters have a significantly stronger influence than any social dynamics DOULBE CHECKGOING OUT 200 YEARS

Table 3: Default parameter values used in this analysis

Parameter	Population_1	Population_2	Def
r	0.4	0.35	Fish net growth
s	0.8	0.8	Supply and demand
h	0.25	0.5	Harvesting efficiency
k	1.014	1.014	Social learning rate
ω	0.2	0.35	Conservation cost
c	1.5	1.5	Rarity valuation
d	0.5	0.5	Social norm strength (within pop)
i	0	0	Fish immigration (from patch)
ρ	0.5	0.5	Social norm strength (opposite pop)

(ref:dispersionscenario_Slow) Slow dispersion where $i = 0.1$. Unsustainable practices in one patch. Note: no adjustment to rho or d could fix fishing scenario

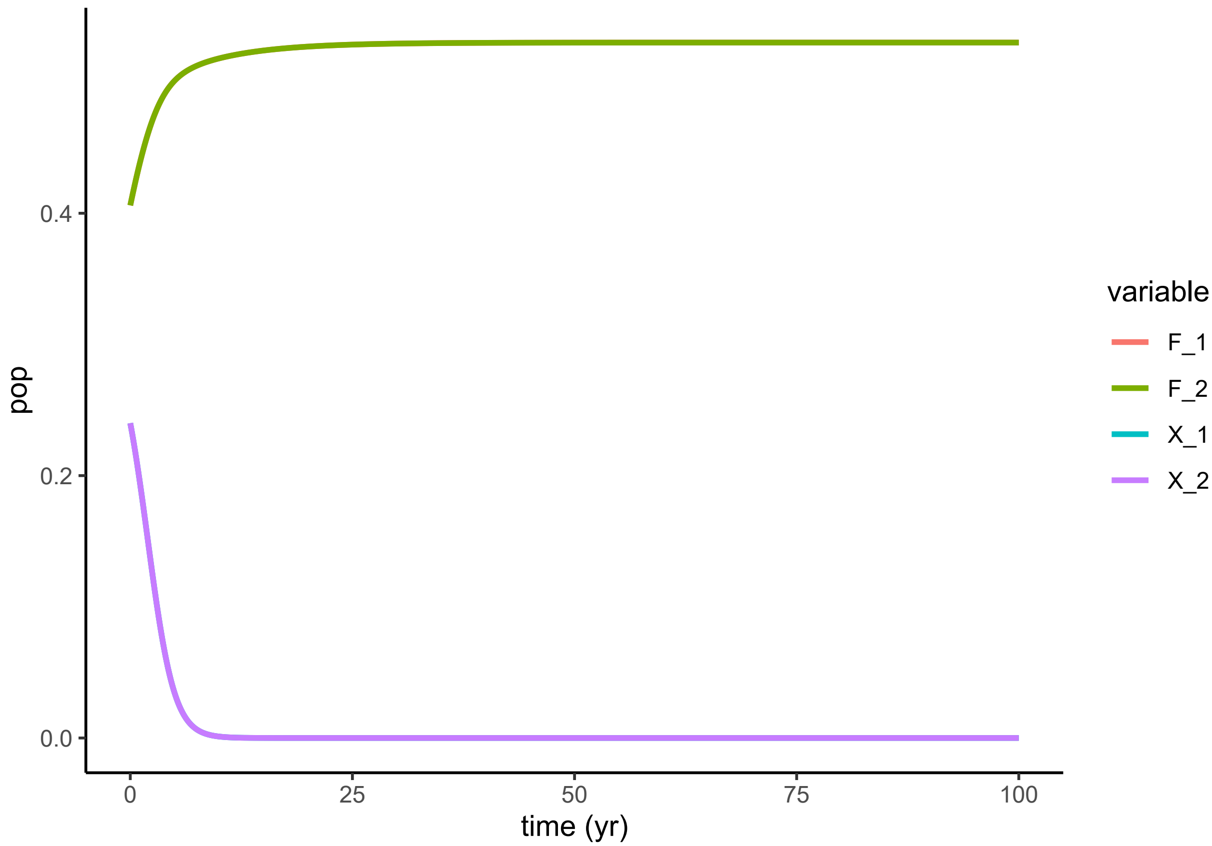

Figure 3: Changing fish growth, conservation cost, and harvesting efficiency for sustainable practices

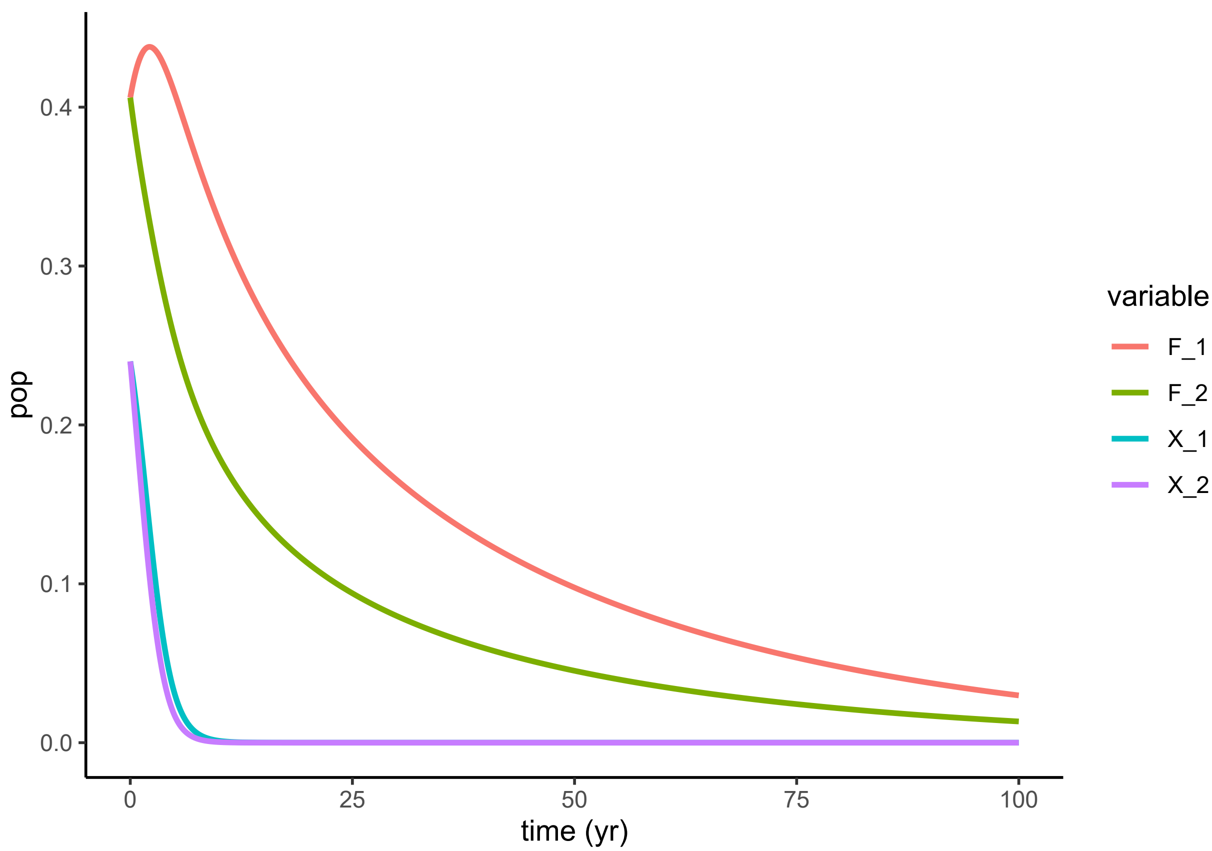

Figure 4: (#fig:SocialScenario_Unsustainable)(ref:ss_unsustainable)

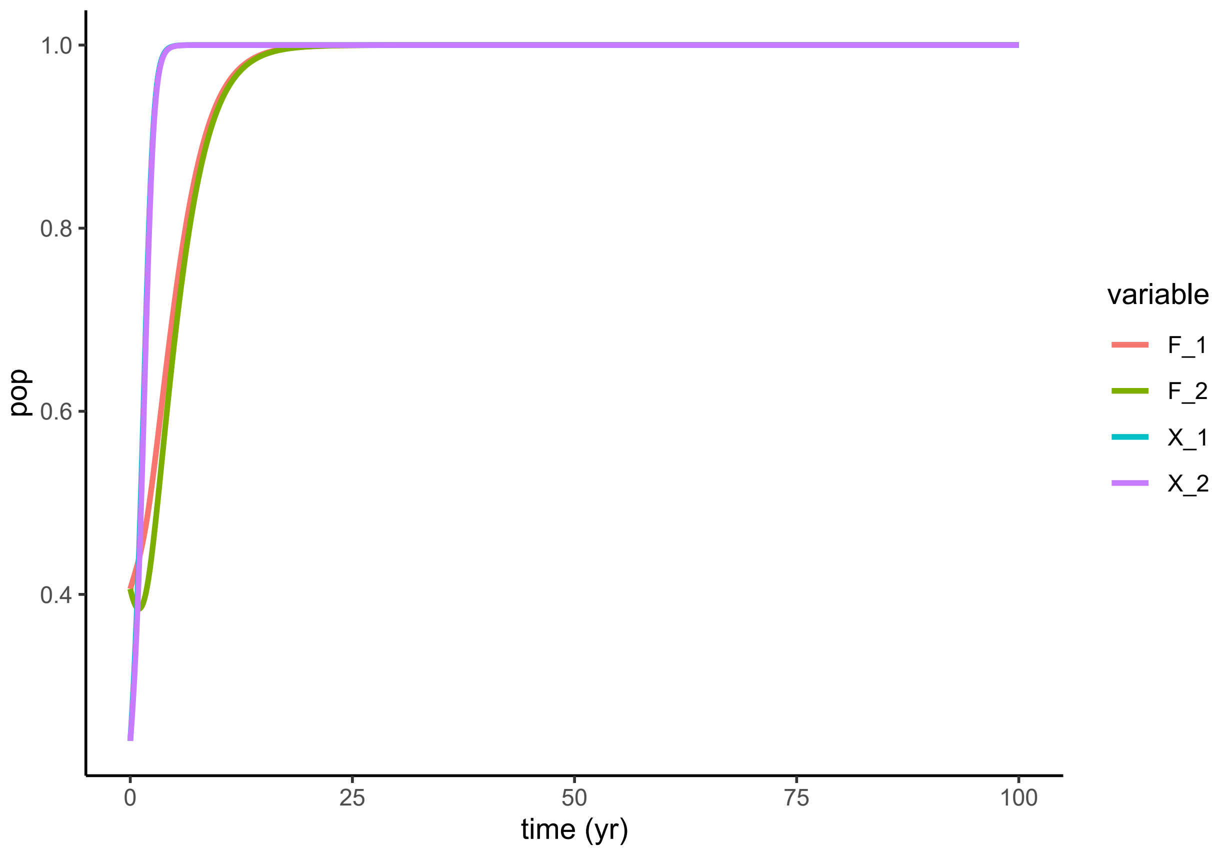

Figure 5: (#fig:SocialScenario_Revive)(ref:ss_revive)

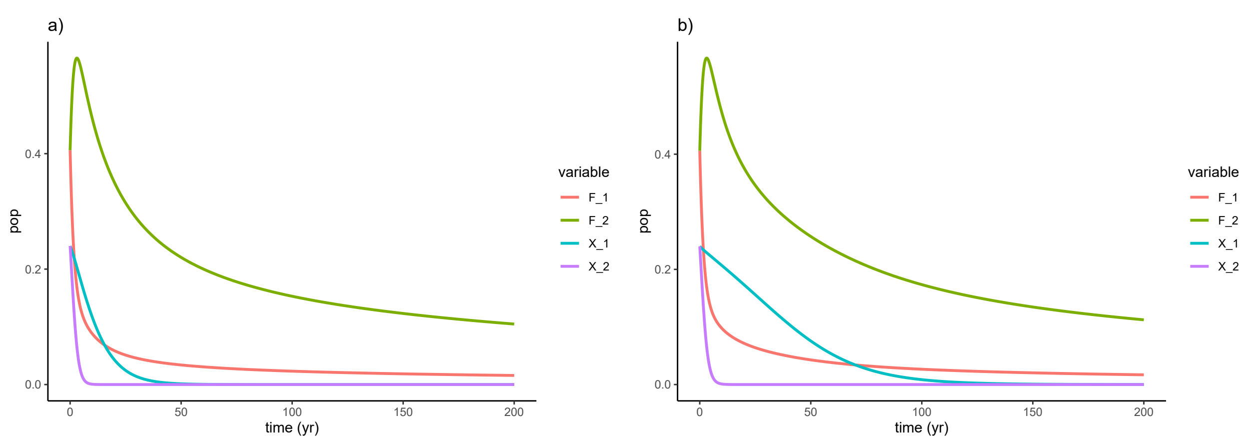

Figure 6: blah

(#fig:HierScenario,)

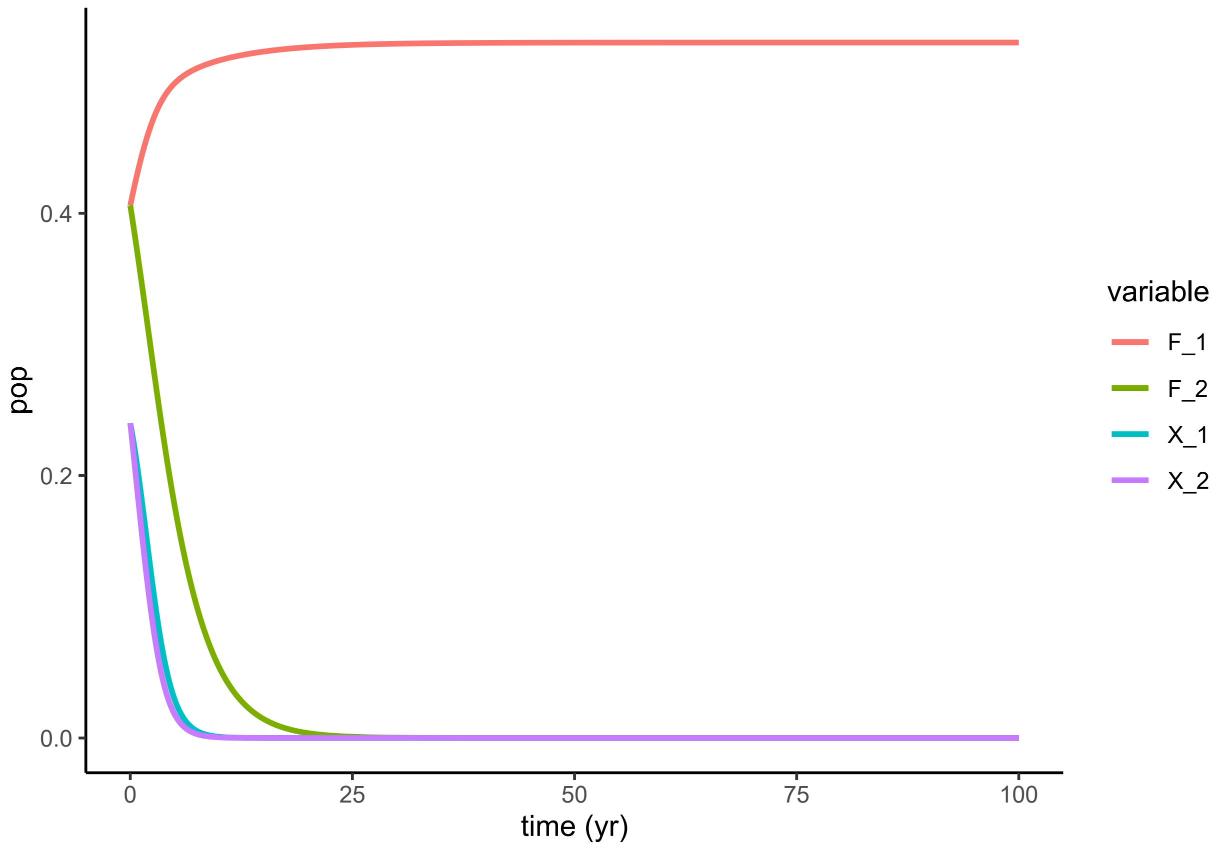

Figure 7: no dispersion. Unsustainable practices in one patch

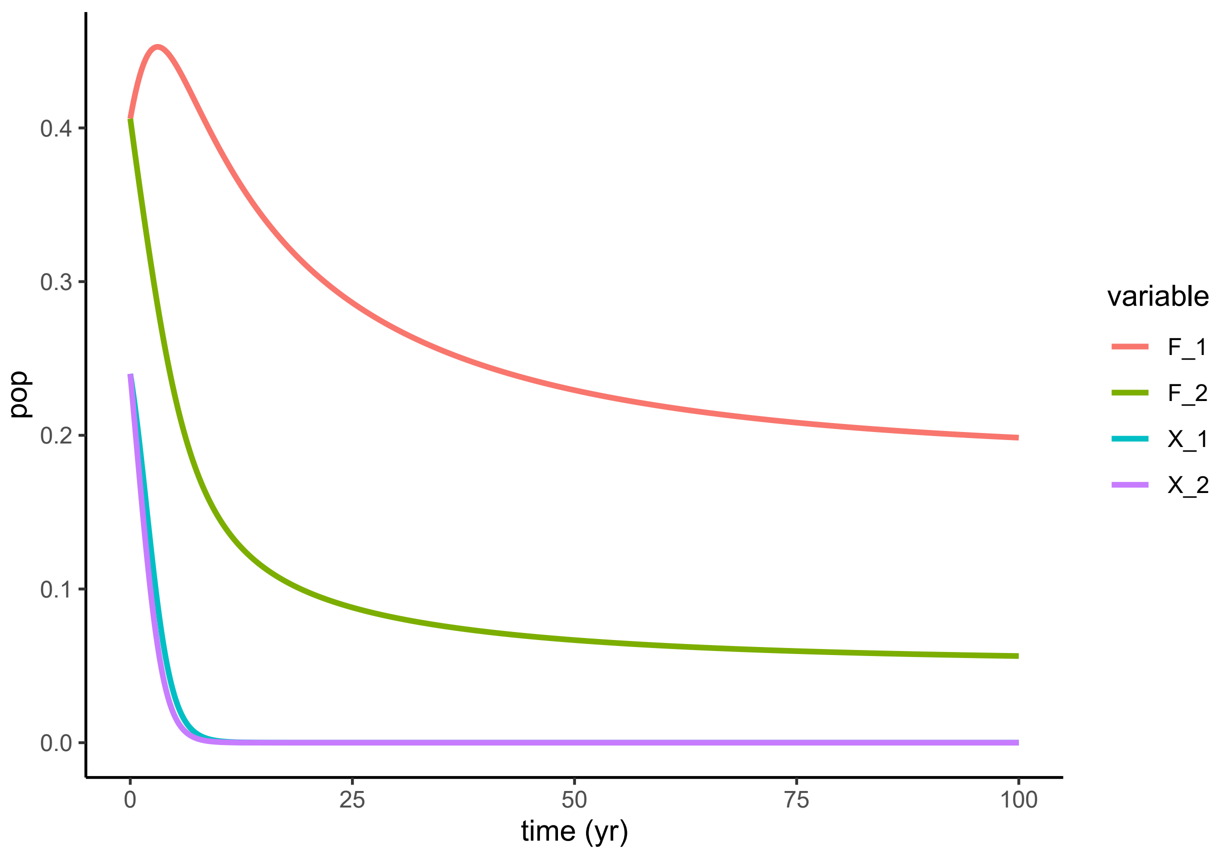

Figure 8: (#fig:DispersionScenario_Slow)(ref:dispersionscenario_Slow)

In order to test how the rho parameter influences the model, we ran a series of parameter planes with each variable paired with changes in rho. We found that at no point, did rho have an effect on the sustainability of the fish population (Fig whatevs). This shows that the outside social influence in our model actually has little effect on fishing practices. ALSO D

INSERT PROP PARAM PLANE (lol when it starts working again) HERE TO SHOW NOT USEFUL

Ok so it's graphs like this that are super confusing. Why does patch 1 have 100% conservationists but 100%fish and vice versa?? In this graph rho = 0 so there should not be any outside influence.

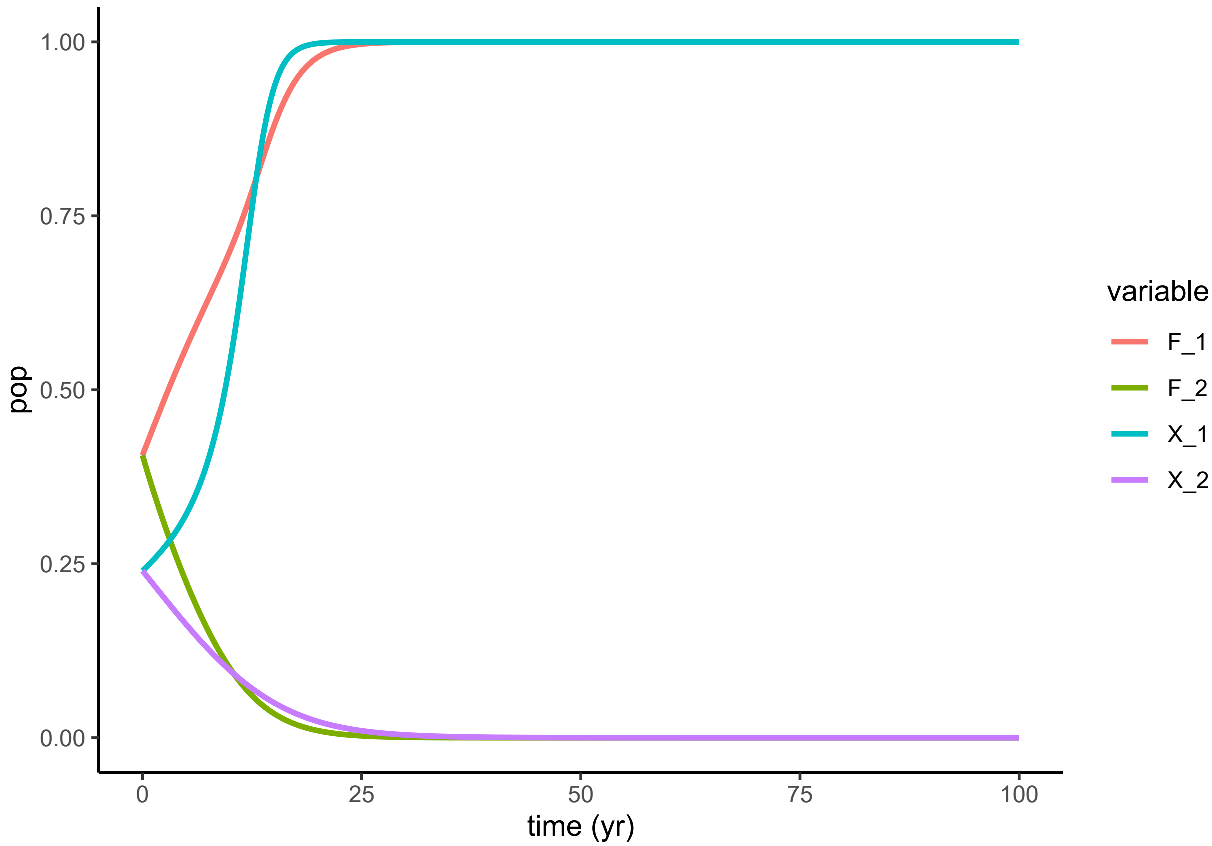

Figure 9: (#fig:dispersionscenario_norho)No social dynamics. Taking away rho doesn't really improve dynamics, but instead allows pop1 to take advantage of their sustainable fishing

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