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Ecuadorian Restrictions for Fisheries: An Agent-Based Model Approach

.

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RESUMEN

Este artículo se centra en el análisis de la pesca en el contexto ecuatoriano utilizando un enfoque basado en modelos de agentes. Ecuador cuenta con una de las áreas marinas protegidas más grandes y alberga una gran cantidad de especies marinas en peligro de extinción debido a sus características particulares que aumentan los nutrientes en la zona. La tasa actual de pesca no es sostenible, por lo tanto, existe espacio para debatir las restricciones actuales a la pesca. Las diferencias entre los pescadores grandes y los pescadores pequeños son clave para comprender un modelo sostenible con viabilidad económica. El resultado del modelo muestra que un incremento en los precios de las licencias no es suficiente para causar cambios en la estructura económica. También demuestra que existe un tradeoff entre las condiciones y el tamaño del Área Marina Protegida con las poblaciones de las diferentes biomasas capturadas. Futura investigación podría centrarse en incorporar las características específicas de Ecuador en modelos más avanzados de pesca, vinculándolos con las particularidades del país en términos de restricciones pesqueras y áreas marinas protegidas.

Palabras clave: Modelos basados en agentes, pesca, restricciones, Ecuador, sistemas de entornos humanos acoplados, NetLogo.

ABSTRACT

This article works on the analysis of fisheries in the Ecuadorian context with an agent-based model approach. Ecuador holds one of the biggest marine protected areas and is home to a great number of endangered marine species for its particularities that increase nutrients in the area. The current fishing rate is not sustainable hence there is space to debate the current fishing restrictions. The differences between big fishers and small fishers are key to understand a sustainable model with economic viability. The result of the model is that an increment in license prices is not enough to cause changes in the economic structure. It also shows that there is a tradeoff between Marine Protected Area conditions and size with populations of the different biomasses fished. Future research could focus on incorporating the specific characteristics of Ecuador in more advanced models of fisheries coupling it with the particularities of the country in terms of fisheries restrictions and marine protected areas.

Key words: Agent-based modeling, fisheries, restrictions, Ecuador, coupled-human environmental systems, NetLogo.

TABLE OF CONTENTS

TABLE INDEX

FIGURE INDEX

INTRODUCTION

Humans have always interacted with themselves and with their environment, these types of system interactions are what are now known as coupled human-environmental systems (CHE). There are multiple human-environment relations that can be modeled this way from agricultural relations to complete cities. However, all the CHE systems share the need to be sustainable and this is currently one of the key challenges for humans (Schlueter et al. 2012). Understanding the dynamics that play on a CHE system and the complexity behind it is what in recent times has inspired new research on this type of system through new approaches and in particular this article.

Fisheries and the systems around them can be represented as a CHE with complex dynamics. Fishers, fish species, ocean and weather changes alongside innovation, tech use, and one of the most important food markets in the world all play a part in the CHE for fisheries. Ocean and fisheries sustainability are key for the future. Aquatic foods are vital for the diet of millions across all continents. However, fishing might not be sustainable in the long run. According to a study by FAO in 2022, the stock that holds Ecuador's shore according to the fishery stock established by FAO is 66,7% unsustainable. This brings the question of how to change this unsustainability based upon the current regulations in Ecuador considering the context of the country.

Ecuador is in a privileged area geographically and is home to the Galapagos Islands and one of the biggest Marine Reserves in the world. However, this sometimes is not enough. According to Galápagos Conservancy, an NGO focused on the Islands conservancy, in 2017 Chinese-flagged vessels were fishing in the Galápagos area, and one was caught with 300 tons of fish that included protected species (Galápagos Conservancy, 2023, para. 8). Big Chinese vessels fishing on the pacific side of America is not uncommon and their wish for fishes that are protected under Ecuadorian law is well known across Ecuadorians. After all the Galapagos Marine Reserve (GMR) is home to the largest global shark biomass (De Leon, et Al. 2016) and China has already depleted local fish stocks and marine living resources from their own nation's water (Alava et al. 2017). Despite this, the problem might not be in the incentive structure for a particular type of fish, but rather in the economic structure that allows fishing on high seas (the practice of catching fish in the open ocean, beyond the exclusive economic zones of individual countries).

Understanding the economics of fisheries is essential to understanding the full complexity of fisheries as a CHE. While the ecological impacts of fishing on high seas have been widely studied, the economic rationale is more difficult to ascertain because of scarce data on the fleets that fish there (Sala et al, 2018). This remark is particularly important since the results of Sala from 2018 show that the current state of fisheries at open sea is enabled by large government subsidies. Hence is probably not sustainable without them There is a big difference between those that are able to fish thousands of kilometers from where their flag waves and those who never leave their meridian. Sustainability should be achieved by everybody but always considering the difference between the magnitude and resources of the economic actors.

There resides the need to check, restrictions upon fisheries and changes in their cost structure. The goal of this article is to evaluate different restrictions under an agent-based model approach with the particularity of a modification in the economic structure of fishers related to subsidies in an approximation of the Ecuadorian context. The hypothesis is that even under the current conditions for marine protected areas (MPAs) the fisheries system is not sustainable considering the differences between small and big fishers with regard to their economic structure in the Ecuadorian context.

Literature review

This model was built with NetLogo 6.3.0. The model is a simplification of a broader work made with the POSEIDON model of ocean fisheries by Bailey et al. in 2017 under the framework of Nicolas Payette a senior Research Associate at Oxford University. The reviewed literature is sustained on a multidisciplinary background that includes biology, economics, fishing, and agent-based simulations. This article aims to expand the previous work made by the POSEIDON research team under a simplification for the Ecuadorian context.

A computational approach to managing coupled human–environmental systems: the POSEIDON model of ocean fisheries, is the article that compiles years of work made on the subject of fisheries as a CHE and agent-based modeling to analyze restrictions from an economic framework that changes. Initially published in 2017 and made by a team of 10 academics this model finds multiple results for a set of different conditions relating to the positioning of fishers, the use of fishing technology, and other parameters. This article offers remarks from broad disciplinary perspectives and implications useful to understand how to design a model that captures the complexity behind fisheries. This article however relates to a broader approximation of any possible fisheries stock and is not contextualized for Ecuador.

To understand the needs and particularities of the Ecuadorian context and fisheries there is a different set of articles and references used. The work of Guarderas in 2019 sets the reasons on why there so much marine biomass in the Galapagos and near Ecuador in general. To determine the particularities of the fisheries and regulations in Ecuador and other countries, the Food and Agriculture Organization presents multiple country profiles through the years in the *Fishery and Aquaculture Country Profile*. This contains data on the legal structure for fisheries operations alongside data on fisheries operations per country.

METHODS

This agent-based model simulates the interactions between two types of fishers (big and small) and two types of biomasses (biomass and endangered biomass). The model is set in a marine environment and each step represents a day. The fishers are autonomous agents that make decisions based on their individual goals and the current state of the environment. Big fishers are comparatively slower and more efficient at catching fish, but they also impact the environment more based on their world and bank balance parameters. The small fishers although, fasters are less efficient at catching fish, therefore, having a smaller impact on the environment. The biomass is also made up of autonomous patches that follow a given growth rate per type of biomass. The biomass can be just biomass or endangered biomass. The biomass agents reproduce more quickly and diffuse more based on the biomass parameters. Table 1 shows all the parameters modifiable by an experiment alongside a short description of each one.

Table 1: existing parameters

Category	Parameter name	Range	Units	Description
World Parameters	number-of-small-fishers	theoretically unlimited	Boats	Initial number of small fishers for the model
World Parameters	number-of-big-fishers	theoretically unlimited	Boats	Initial number of big fishers for the model
World Parameters	small-carrying-capacity	Between 1 and 10000	Tons	Carrying capacity of a small fisher
World Parameters	big-carrying-capacity	Between 1 and 10000	Tons	Carrying capacity of a big fisher
World Parameters	small-exploration-radius	Between 0 and world-width	-	Exploration ratio of a small fishers
World Parameters	big-exploration-radius	Between 0 and world-width	-	Exploration ratio of a big fisher
World Parameters	small-exploration-probability	Between 0 and 1	-	Probability for small fisher to explore
World Parameters	big-exploration-probability	Between 0 and 1	-	Probability for big fisher to explore. Portmanteau for tech use (fishing techniques, sonar tech, etc.)
World Parameters	small-catchability	Between 0 and 1	-	Catchability for a small fisher. Portmanteau for tech use (fishing techniques, sonar tech, etc.)
World Parameters	big-catchability	Between 0 and 1	-	Catchability for a big fisher
World Parameters	small-speed	Between 0 and 1	Patch per day	Moving speed for a small fisher
World Parameters	big-speed	Between 0 and 1	Patch per day	Moving speed for a big fisher
World Parameters	mpa	Between 0 and 10,5	-	MPA Size
Biomass Parameters	endangered-growth-rate	Between 0 and 1	-	Growth rate for the endangered biomass
Biomass Parameters	growth-rate	Between 0 and 1	-	Growth rate for the biomass
Biomass Parameters	endangered-diffusion-rate	Between 0 and 1	-	Diffusion rate for the endangered biomass

Biomass Parameters	diffusion-rate	Between 0 and 1	-	Diffusion rate for the biomass
Bank Balance Parameters	price-of-fish-endagered	Between 0 and 1000	Dollars per tonn	Price per ton for the fish
Bank Balance Parameters	price-of-fish	Between 0 and 1000	Dollars per tonn	Price per ton for the endangered fish
Bank Balance Parameters	small-daily-costs	Between 1 and 1000	Dollars per day	Daily costs a small fisher uses per day
Bank Balance Parameters	big-daily-costs	Between 1 and 1000	Dollars per day	Daily costs a big fisher uses per day
Bank Balance Parameters	license-price-small	Between 0 and 1000	Dollars per day	License price for a small fisher
Bank Balance Parameters	license-price-big	Between 0 and 1000	Dollars per day	License price for a big fisher
Bank Balance Parameters	subsidies-small	Between 0 and 1000	Dollars per day	Subsidies given daily to a small fisher
Bank Balance Parameters	subsidies-big	Between 0 and 1000	Dollars per day	Subsidies given daily to a big fisher

The ABM is designed to study the interactions between the fishers and the biomass and to explore how these interactions can lead to changes in the population of each type of agent and patch. This is achieved with the changes in the variables for the bank balance variables, the destination variables, and the biomass variables that happen at each step and the interaction with the parameters defined in the setup. Each step represents a day, and the model only runs for a maximum of 3650 steps for computational purposes (hence each model is set to run a maximum of 10 years). A complete list of the variables that interact in the model with their category alongside a short description can be found in Table 2. Every time a step passes a flow repeats each step changing the state for all the agents and patches under the defined parameters in the setup. Figure 1 shows this flow in a simplified version. The model can be used to simulate various scenarios, such as changes in fishing regulations (through changes in the bank balance parameters) or the environment (through changes in the world and biomass parameters). There are however four fundamental functions that happen at each step a simplified version of these is shown in Table 3.

Table 2: existing variables

Category	Variable	Description
Biomass variables	favourite-destination	Current favorite destination of a type of fisher
Biomass variables	profits-at-favourite-destination	Last calculated profits at favorite destination of a type of fisher
Biomass variables	biomass	Current existing biomass at given a patch
Biomass variables	endangerd-biomass	Current existing endangered biomass at given a patch
Destinantion variables	current-destination	Current favorite destination of a type of fisher at a given step
Destinantion variables	trip-destination	Destination that gets updated based upon exploration, exploitation, or imitation of a type of fisher
Bank balance variables	trip-costs	Costs incurred per type of fisher since the dock
Bank balance variables	bank-balance	Current bank balance per type of fisher at a given step
Bank balance variables	biomass-in-hold	Current biomass in hold per type of fisher at a given step
Bank balance variables	endangered-biomass-in-hold	Current endangered biomass in hold per type of fisher at a given step
Bank balance variables	profits	Profits (or loss) acquired at dock per type of fisher for the biomass
Bank balance variables	endangered-profits	Profits (or loss) acquired at dock per type of fisher for the endangered biomass

Figure 1: simplified flow

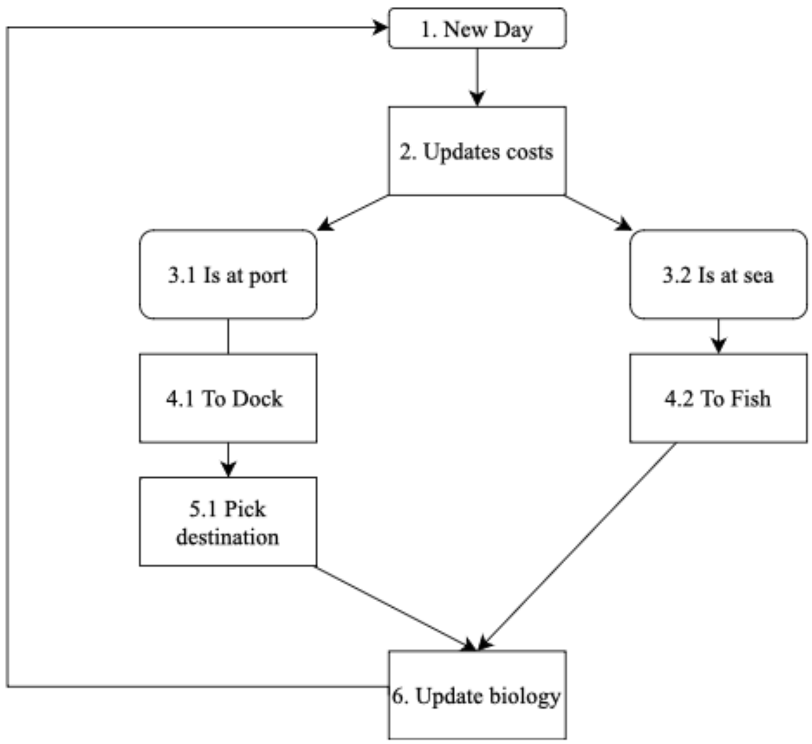

Table 3: fundamental functions

Function	**Description**
To dock	Fisher function varies from type of fisher and allows the fisher to sell, evaluate their bank balance and prick a new favorite location
To fish	Fish function varies from type of fisher and updates bank balance variables per agent and world variables for biomass
To update-biomass	Patch function that updates the biological state variables
To pick-destination	Function that modifies the destination of a type of fisher through exploration, exploitation or imitation Is embedded on the dock function

To dock

This function is only usable when Fisher is located at the port. This function allows a given fisher agent to sell all the biomass they have on hold, evaluate their total bank balance, and pick a new favorite destination (embedded with the favorite destination function). There are two parts for each time is called. Firstly, the fisher sells all their hold for the price of the specific biomass, calculates profits under their cost structure (trip costs, subsidies, licenses), and sets their costs on zero since the fisher is not fishing at the dock and evaluates and updates their bank balance. After this, the fisher updates the favorite destination with the evaluation of the type of profit. What happens is an analysis of whether profits from endangered biomass are greater or equal to profits from biomass. This is accomplished with the help of a local variable named local-profits that is set to be equal to the greater profit. If local-profits are greater than profits-at-favorite-destination, favorite destination gets updated and profits-at-favorite-destination gets set to local-profits. To finish a new destination is chosen based upon the pick-destination function.

To fish

This function allows a given fisher agent to catch biomass under the parameters defined in the setup but also updates the biomass for both types based on the caught biomass by the fisher. Once the fisher caught all the biomass possible under its parameters sets the current-destination to port and heads there.

To pick-destinantion

This function is the one that works for the exploration, exploitation, and imitation the fishers can do. First checks if a local variable that is set to be a random float between 0 and 1 is less than the exploration-probability parameter defined for the type of fish if not, the fisher explores. To explore first is defined a random radius r that is a local variable defined between 0 and the exploration radius of the type of fish that is calling the function. That local variable changes from the type of fish. For both types of fishers, it follows a random Poisson distribution with a mean equal to the exploration-radius parameter of the type of fish. If somehow the random float between 0 and 1 is greater than the exploration-probability of that type of fish, then the fisher checks for the favorite location of an equal type of fisher and evaluates their profits-at-favourite-location against their own. If the profits of the fisher are greater than the profits of its pair, then the fisher just decides to go to its last favorite location, if not imitates the location of the selected pair.

To update-biology

This function changes the state of each type of biomass in a patch for the following step. This is done by first diffusing the biomass following the established parameter for diffusion per type and the growth rate. Every 365 steps, biomass grows by a factor defined by the following function:

$$biomass_{s,b} = biomass_{s-365} * growthRate_b + (biomass_{s-365} * \partial)$$

$$\partial = \ (1 - (\frac{biomassbiomass_{s-365}}{\frac{(carryingCapacity_B + carryingCapacity_b)}{2}}$$

$$Where:$$

$$biomass_{s,b}: is\ the\ new\ value\ of\ the\ biomass\ type\ b\ on\ the\ step\ s$$

$$growthRate_b: is\ the\ growth\ rate\ for\ biomass\ type\ b$$

$$carryingCapacity_B: is\ the\ carrying\ capacity\ of\ big\ fihsers$$

$$carryingCapacity_b: is\ the\ carrying\ capacity\ of\ small\ fishers$$

Experiments

This section describes the experiments realized with the model. For each experiment, 50 models were run. The way to characterize the sustainability of the runs is the differences in the number of fishers and biomass. This is an analysis of the evolution of the difference between the number of fishers and the biomass of the biomass. There is also a level of analysis on the difference of bank balances for big and small fishers and the evolution of the biomass between experiments. All the parameters used across the experimentations can be found in Annex C.

Experiment 1.

In this experiment, the goal is to search for the evolution of the model following real-world approximation of parameters. There are two different types of biomasses (an endangered and a non-endangered), each one with different rates for diffusion and growth. There is also an approximation of the differences in financial structure between big and small fishers. For this experiment, there are no policy-focused implementations since is just a representation of the current state of fisheries in Ecuador with a limited number of fishers to test for stabilization.

Experiment 1: results.

Results for the first experiment show a sustainable evolution of both biomasses. There is however an interesting phenomenon, a drop of 91% for small fishers and 51% for big fishers. Is important to notice the initial number of fishers for both types is low thus there is no chronic depredation. When it comes to the results related to the bank balances this experiment shows the best outcomes for fishers on the monetary dimension. These results are visible in figure 2 and table 4.

Figure 2: evolution of biomasses from experiment 1

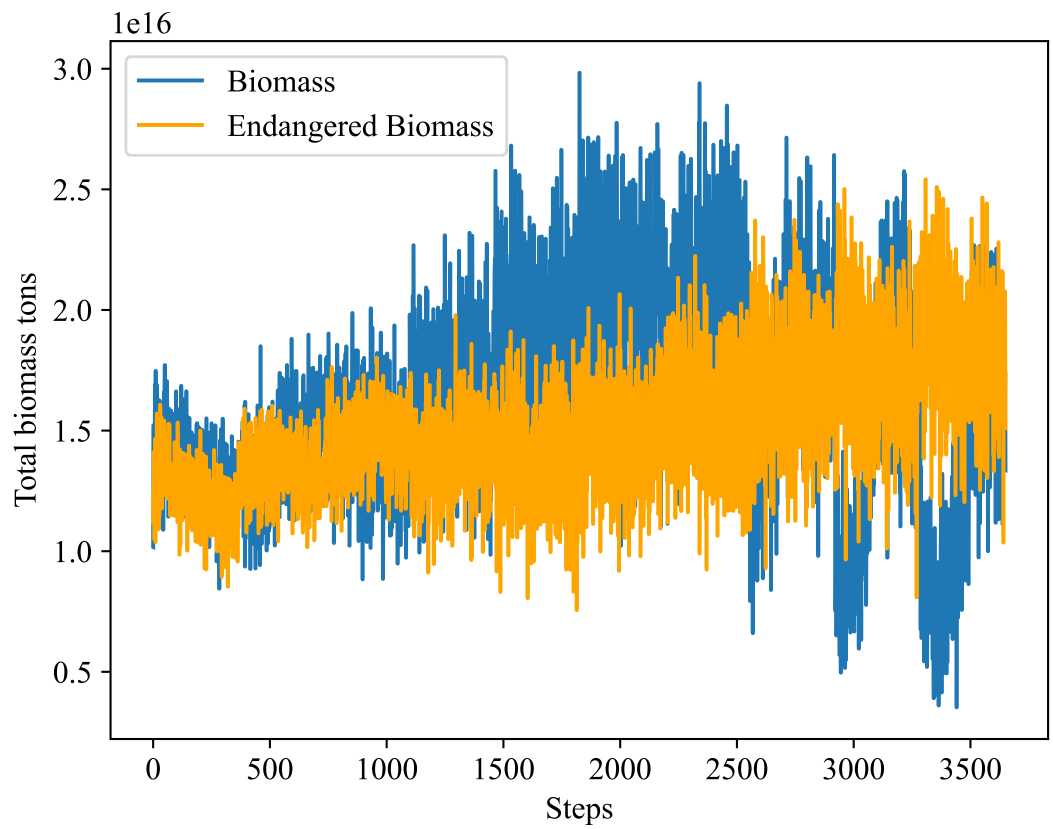

Table 4: differences in steps from experiment 1

	Step 0	Step 3650	Absultute difference	Relative Difference
Average of small fishers	12	1	-11	-91%
Average of big fishers	120	59	-61	-51%
Average of endangered biomass (tons)	1E+16	2E+16	4E+15	35%
Average of biomass (tons)	1E+16	1E+16	3E+15	32%
Average bank balance of big fishers ($)	1E-06	7E+22	7E+22	n/a
Average bank balance of small fishers ($)	0E+00	3E+23	3E+23	n/a

Experiment 2: first policy modifications.

This experiment is the first approach to modify the parameters to establish a sustainable ecosystem for both the biomass and the fishers. The only parameters modified from experiment 1 are the license prices which are incremented for the big fishers and reduced for the small fishers. MPA size does not change, and small fishers are still able to fish in the protected area.

Experiment 2: results

The results for experiment 2 are like those of experiment 1 but there is an increment of 2E+17 tons of endangered biomass and 3E+17 tons of biomass. Both these increments are over 4000% from experiment 1, showing that license implementation in the model relates to the amount of total biomass in the world. These results are visible in figure 3, table 5 and table 8.

Figure 3: evolution of biomasses from experiment 2

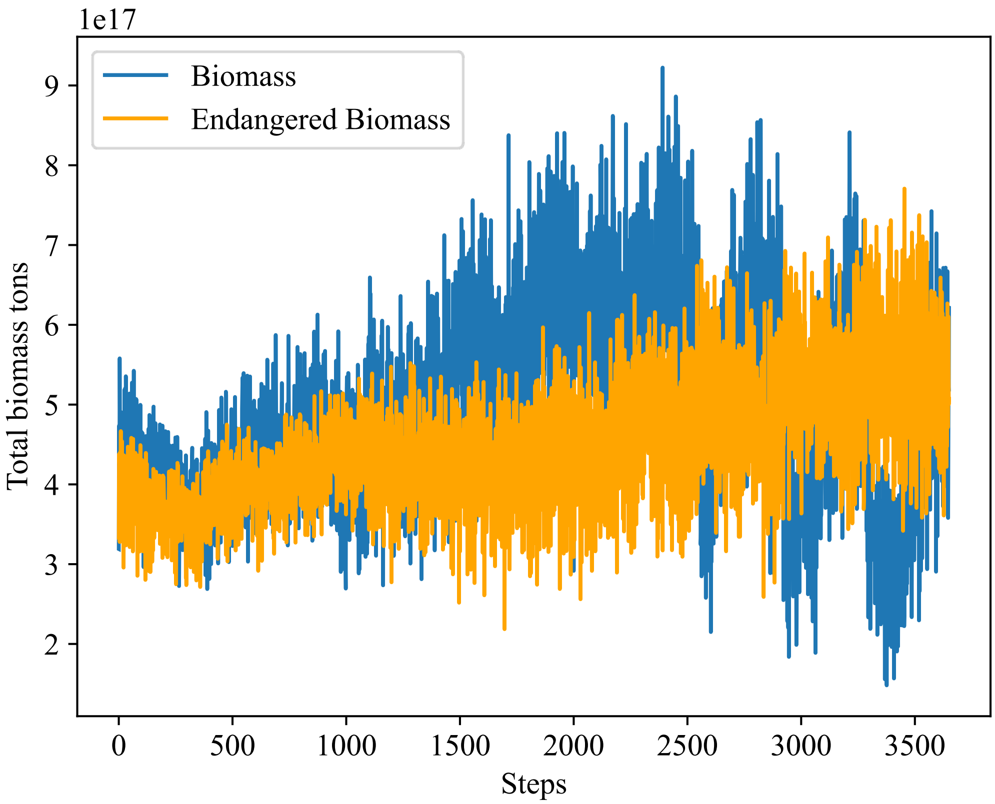

Table 5: difference in steps from experiment 2

	Step 0	**Step 3650**	**Absultute difference**	**Relative Difference**
Average of small fishers	12	1	-11	-90%
Average of big fishers	120	59	-61	-51%
Average of endangered biomass (tons)	3E+17	5E+17	2E+17	54%
Average of biomass (tons)	3E+17	6E+17	3E+17	96%
Average bank balance of big fishers ($)	0E+00	3E+24	3E+24	n/a
Average bank balance of small fishers ($)	0E+00	2E+25	2E+25	n/a

Experiment 3: hybrid policies implementations.

This is the first trial to establish hybrid policies. This experiment differs from Experiment 2 on the code level that establishes the MPA forbidding small fishers from fishing in the MPA, the MPA size, and the subsidies established for big and small fishers.

Experiment 3: results.

The results for experiment 3 differ from the previous two experiments. When a comparison is made between experiment 3 and experiment 1, there is an evolution in favor of the amount of total biomass, however, in the comparison between experiment 3 and experiment 2, experiment 2 shows poorer results for biomass conservancy. This implies that reducing the MPA size even when the small fishers become unable to fish in the area and subsidies go to zero is not enough. The bank balance for small fishers and big fishers is reduced by 97% and 98% respectively. These results are visible in figure 4, table 6, and table 8.

Figure 4: evolution of biomasses from experiment 3

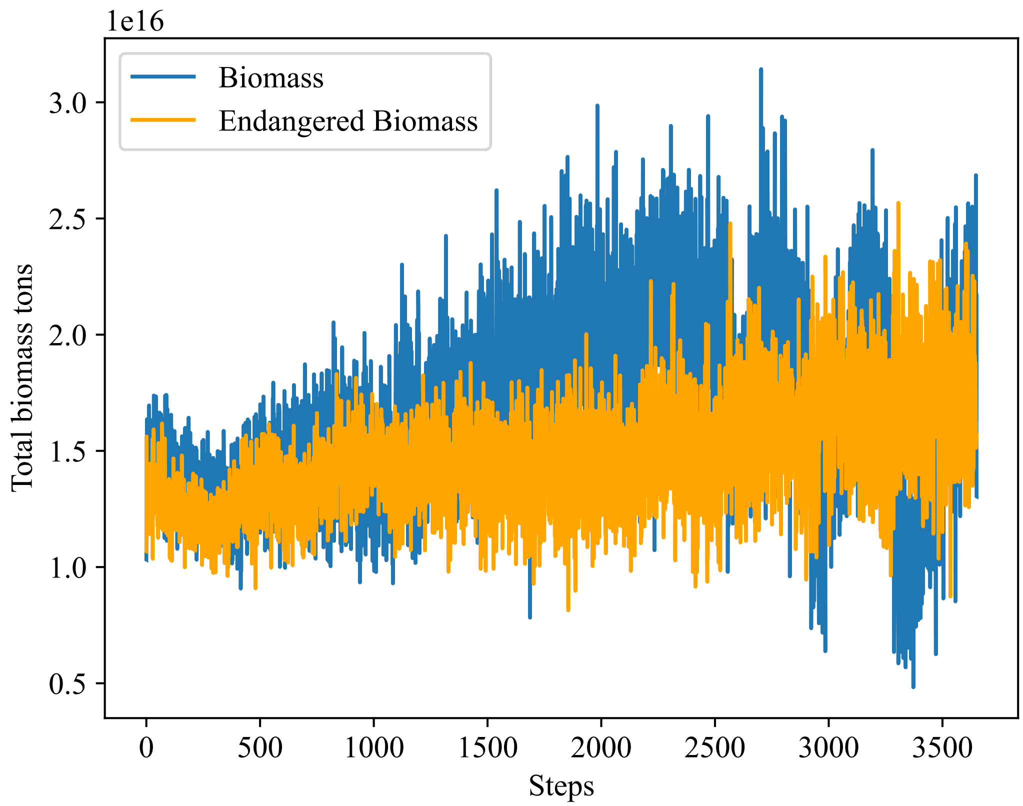

Table 6: differences in steps from experiment 3

	Step 0	Step 3650	Absultute difference	Relative Difference
Average of small fishers	12	1	-11	-88%
Average of big fishers	120	59	-61	-51%
Average of endangered biomass (tons)	1E+16	2E+16	5E+15	48%
Average of biomass (tons)	1E+16	1E+16	3E+15	26%
Average bank balance of big fishers ($)	0E+00	7E+22	7E+22	n/a
Average bank balance of small fishers ($)	0E+00	7E+23	7E+23	n/a

Experiment 4: advanced hybrid policies implementations.

This experiment differs from experiment 3 on the amount of big and small fishers that are initially created and the size of the MPA that grows 3 units. The goal is to test a better world approximation considering the number of real fishers that can operate in each area.

Experiment 4: results.

This experiment shows encouraging results for endangered ocean conservancy. The conditions used generate an increment of 8E+15 tons from experiment 3 and an increment of 1E+16 from the first experiment when it comes to endangered biomass but also a decline of 172% in the non-endangered biomass from experiment 3. Is important to remark that the number of small fishers is 600x superior to those of previous experiments, but these results point in the direction that there is a tradeoff between increasing MPA zones that are not allowed for any type of fisher and the amount of non-endangered biomass that is caught.

Is curious to see the evolution of the average amount of biomass that exists after the 2000 step where for the characteristics of the MPA zone, one stays relatively constant (non-endangered biomass) but the other one increases significantly probably because the endangered species begin a cycle of growth not sustainable because they are not being caught at significant rates. The results of bank balances are the worst of all experiments. These results are visible in figure 5, table 7, and table 8.

Figure 5: evolution of biomasses from experiment 4

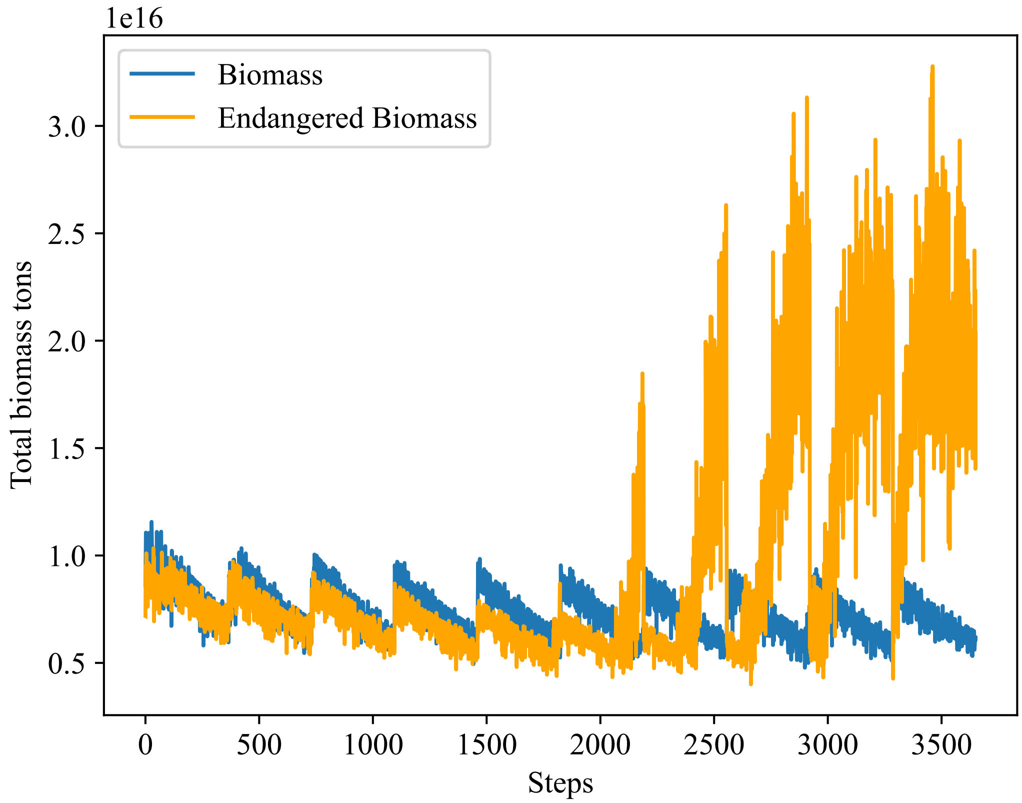

Table 7: differences in steps from experiment 4

	Step 0	Step 3650	Absultute difference	Relative Difference
Average of small fishers	1200	112	-1088	-91%
Average of big fishers	120	32	-88	-73%
Average of endangered biomass (tons)	7E+15	2E+16	1E+16	187%
Average of biomass (tons)	9E+15	6E+15	-2E+15	-27%
Average bank balance of big fishers ($)	0E+00	1E+16	1E+16	n/a
Average bank balance of small fishers ($)	0E+00	1E+23	1E+23	n/a

Table 8: differences between experiments

	Experiment 1	**Experiment 2**	**Experiment 3**	**Experiment 4**
Final endangered biomass (tons)	4E+15	2E+17	5E+15	1E+16
Change from last experiment endangered biomass (tons)	-	2E+17	-2E+17	8E+15
Change from experiment 1 - endangered	0%	4422%	30%	238%
Final biomass (tons)	3E+15	3E+17	3E+15	-2E+15
Change from last experiment biomass (tons)	-	3E+17	-3E+17	-5E+15
Change from experiment 1 - biomass	0%	9467%	-15%	-172%

CONCLUSIONS

As stated by Bailey et al. in 2018 there is a need for new approaches to generate policies in the domain of coupled human complex systems. In the Ecuadorian fisheries case, these are particularly important for the biological conditions that make Ecuador so special around fisheries. There are several findings based on the experiments made and their particularities, besides the obvious ones such as that when the number of fishers increments the pressure on the fish population increments, there are two key findings that sustain the initial hypothesis. An increment in license prices is not enough to cause changes in the economic structure that causes unsustainability since subsidies still play a bigger part. There is a tradeoff between MPA conditions and size with populations of the different biomasses. These findings suggest that there is a need for a new approach on the restrictions on fisheries in general, one that considers the subsidy level based on the particularities of the fishers and what type of biomass they are catching.

Of course, this new approach is extremely difficult to take into the debate since fisheries are a coupled-human environmental system not only for the relation between environment and humans but the relation between humans and humans. The differences in impact on the sustainability varies from size of the fisher and the size of the fisher (and the economic structure behind them) varies from flag to flag. The debate then perhaps should be on new institutions to regulate the impact of fishers based on how far from home they are fishing and how much of that fishing rate makes economic sense simply because of subsidies given to them. After all fisheries are a global issue and international cooperation is fundamental for sustainable management.

To finish there is also lots of room for future work on the particularities of fisheries in the Ecuadorian case based on the agent-based modeling approach. Potential modifications to this model should include a reproduction dimension of the fishers to be able to see different results on the evolution of the number of fishers based on the economic incentives around them. Also, a disintegration of the catchability probability into different parameters so that it stops being a portmanteau parameter hence allowing for a more detailed analysis of the impact of tech use in the results for the type of fishers and the evolution of biomass with restrictions on tech. These modifications could be done on the POSEIDON model of fisheries coupling it with the Ecuadorian particularities on dealing with fisheries and marine protected areas.

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ANNEX A: COMPLETE NETLOGO CODE

```
;; Marcelo Avendaño


;; create fishable patches
globals [
  fishable-patches
]
;; breed for mpa
breed [ xs x ]
;; breed for port
breed [ ports port ]
;; breed for small-fishers
breed [ small-fishers small-fisher ]
;; breed for big-fishers
breed [ big-fishers big-fisher ]
;; there is two types of biomass
patches-own [ biomass endangered-biomass]

;; arguments for small-fishers
small-fishers-own [
  favourite-destination-small
  profits-at-favourite-destination-small
  current-destination-small
  trip-destination-small
  trip-costs-small
  bank-balance-small
  biomass-in-hold-small
  endangered-biomass-in-hold-small
  profits-small
  endangered-profits-small
]

;; arguments for big-fishers
big-fishers-own [
  favourite-destination-big
  profits-at-favourite-destination-big
  current-destination-big
  trip-destination-big
  trip-costs-big
  bank-balance-big
  biomass-in-hold-big
  endangered-biomass-in-hold-big
```

```
 profits-big
 endangered-profits-big
]


;; setup function
to setup
 clear-all

;; create a port
 create-ports 1 [
  set xcor max-pxcor
  set color lime
  set shape "square"
 ]

;; set initial biomass
 let biomass-to-be 0
 set biomass-to-be big-carrying-capacity + small-carrying-capacity
 ask patches [ set biomass biomass-to-be * random-float 1 ]

;; set initial endangered-biomass
 let endangered-biomass-to-be 0
 set endangered-biomass-to-be big-carrying-capacity + small-carrying-capacity
 ask patches [ set endangered-biomass endangered-biomass-to-be * random-float 1 ]

;; call mpa area
 setup-mpa
 recolor-patches

;; create small-fishers
 create-small-fishers number-of-small-fishers [
  set color yellow
  move-to one-of ports
  set favourite-destination-small patch-here
  pick-destination-small
 ]
;; create big-fishers
  create-big-fishers number-of-big-fishers [
  set color red
  move-to one-of ports
  set favourite-destination-big patch-here
  pick-destination-big
 ]
```

```
  reset-ticks
end

;; create a marine protected area (mpa)
to setup-mpa
  set-default-shape xs "x"
  let mpa patches with [ abs pxcor < mpa-border and abs pycor < mpa-border ]
  ask mpa [ sprout-xs 1 [ set color cyan ] ]
  set fishable-patches patches with [ not member? self mpa ]
end



to go

  if ticks >= 3650 [
    stop
  ]

  ;; small-fishers activities
  ask small-fishers [
    set trip-costs-small trip-costs-small + small-daily-costs
    ifelse patch-here = current-destination-small [
      ifelse any? ports-here [ dock-small ] [ fish-small ]
    ] [
      face current-destination-small
      forward small-speed
    ]
  ]

  ;; big-fishers activities
  ask big-fishers [
    set trip-costs-big trip-costs-big +  big-daily-costs
    ifelse patch-here = current-destination-big [
      ifelse any? ports-here [ dock-big ] [ fish-big ]
    ] [
      face current-destination-big
      forward big-speed
    ]
  ]

  ;; update biomass
  update-biology
```

```
  tick
end



to pick-destination-small ; small-fisher procedure
  ifelse random-float 1 < small-exploration-probability [
    ; explore:
    let r random-poisson small-exploration-radius
    ;; small can explore outside of the mpa

    ;; the following line is modified to change if the fisher can fish in the mpa or not

    ;; uncomment next line to allow small fishers to go the mpa
    ;;set trip-destination-small [ one-of patches in-radius r ] of favourite-destination-small

    ;; if the mpa changes, comment the next line
    set trip-destination-small [ one-of fishable-patches in-radius r ] of favourite-destination-
small
  ]
  [
    let other-small-fisher one-of other small-fishers
    ifelse profits-at-favourite-destination-small >= [ profits-at-favourite-destination-small ] of
other-small-fisher [
      ; exploit:
      set trip-destination-small favourite-destination-small
    ] [
      ; imitate
      set trip-destination-small [ favourite-destination-small ] of other-small-fisher
    ]
  ]
  set current-destination-small trip-destination-small
end

to pick-destination-big ; big-fisher procedure
  ifelse random-float 1 < big-exploration-probability [
    ; explore:
    let r random-poisson big-exploration-radius
    set trip-destination-big [ one-of fishable-patches in-radius r ] of favourite-destination-big
  ] [
    let other-big-fisher one-of other big-fishers
```

```
  ifelse profits-at-favourite-destination-big >= [ profits-at-favourite-destination-big ] of
other-big-fisher [
    ; exploit:
    set trip-destination-big favourite-destination-big
  ] [
    ; imitate
    set trip-destination-big [ favourite-destination-big ] of other-big-fisher
  ]
 ]
 set current-destination-big trip-destination-big
end


to dock-small ; small-fisher procedure
 let revenues biomass-in-hold-small * price-of-fish
 set biomass-in-hold-small 0
 set profits-small revenues - trip-costs-small + subsidies-small - license-price-small
 set trip-costs-small 0
 set bank-balance-small bank-balance-small + profits-small


 let endangered-revenues endangered-biomass-in-hold-small * price-of-fish-endangered
 set endangered-biomass-in-hold-small 0
 set endangered-profits-small endangered-revenues - trip-costs-small + subsidies-small -
license-price-small
 set trip-costs-small 0
 set bank-balance-small bank-balance-small + endangered-profits-small


;; small-fish die if bank-balance is negative or zero
 if bank-balance-small <= 0 [
   die
 ]


;; small-fishers choose favourite destination

 ;; small fishers check if profits from endangered-biomass > biomass
 let local-profits 0

 if endangered-profits-small > profits-small [
   set local-profits endangered-profits-small
 ]
```

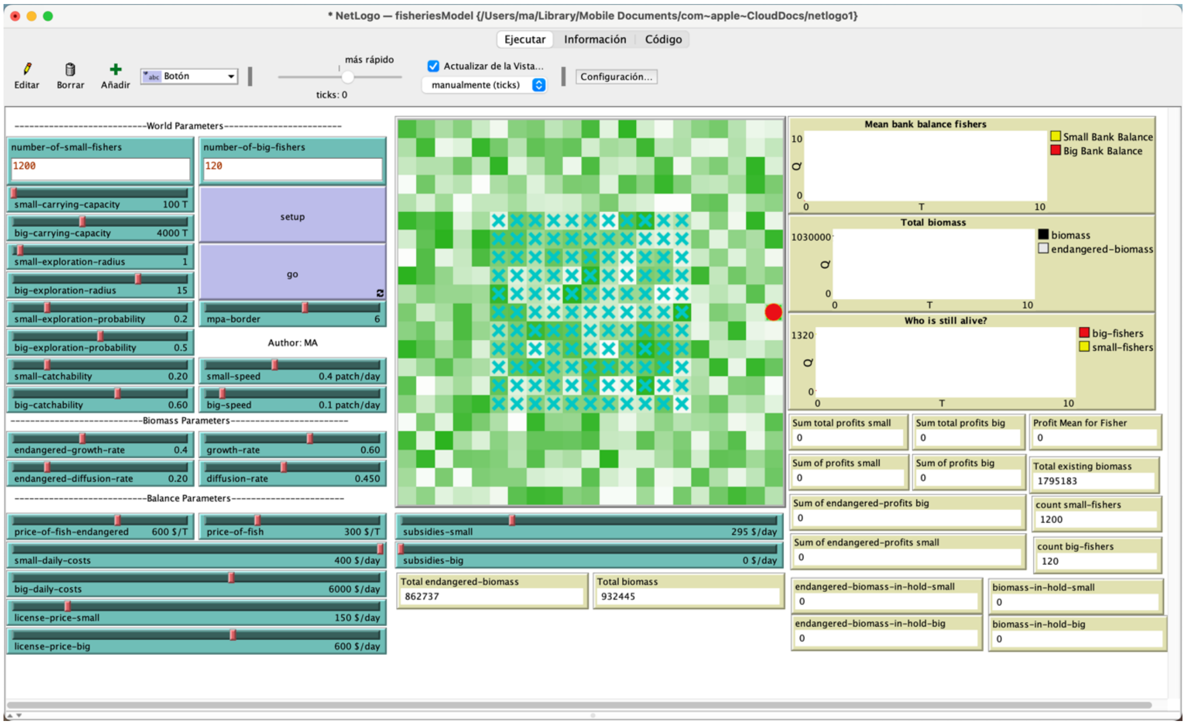
```
  if endangered-profits-small < profits-small [
    set local-profits profits-small
  ]

  ifelse trip-destination-small = favourite-destination-small [
    set profits-at-favourite-destination-small local-profits
  ] [
    if local-profits > profits-at-favourite-destination-small [
      set favourite-destination-small trip-destination-small
      set profits-at-favourite-destination-small local-profits
    ]
  ]
  pick-destination-small
end

to dock-big ; big-fisher procedure
  let revenues biomass-in-hold-big * price-of-fish
  set biomass-in-hold-big 0
  set profits-big revenues - trip-costs-big + subsidies-big - license-price-big
  set trip-costs-big 0
  set bank-balance-big bank-balance-big + profits-big


  let endangered-revenues endangered-biomass-in-hold-big * price-of-fish-endangered
  set endangered-biomass-in-hold-big 0
  set endangered-profits-big endangered-revenues - trip-costs-big + subsidies-big - license-
price-big
  set trip-costs-big 0
  set bank-balance-big bank-balance-big + endangered-profits-big


;; big-fish die if bank-balance is negative or zero
  if bank-balance-big <= 0 [
    die
  ]


;; big-fishers choose favourite destination

  ;; big fishers check if profits from endangered-biomass > biomass
  let local-profits 0

  if endangered-profits-big > profits-big [
    set local-profits endangered-profits-big
```

```
  ]

  if endangered-profits-big < profits-big [
    set local-profits profits-big
  ]

  ifelse trip-destination-big = favourite-destination-big [
    set profits-at-favourite-destination-big local-profits
  ] [
    if local-profits > profits-at-favourite-destination-big [
      set favourite-destination-big trip-destination-big
      set profits-at-favourite-destination-big local-profits
    ]
  ]
  pick-destination-big
end


;; small fishing method
to fish-small ; small-fisher procedure
  let biomass-caught biomass * small-catchability
  set biomass biomass - biomass-caught
  set biomass-in-hold-small biomass-in-hold-small + biomass-caught
  set current-destination-small [ patch-here ] of one-of ports
  set pcolor red

  let endangered-biomass-caught endangered-biomass * small-catchability
  set endangered-biomass endangered-biomass - endangered-biomass-caught
  set endangered-biomass-in-hold-small endangered-biomass-in-hold-small + endangered-
biomass-caught
  set current-destination-small [ patch-here ] of one-of ports
  set pcolor red
end


;; big fishing method
to fish-big ; big-fisher procedure
  let biomass-caught biomass * big-catchability
  set biomass biomass - biomass-caught
  set biomass-in-hold-big biomass-in-hold-big + biomass-caught
  set current-destination-big [ patch-here ] of one-of ports
  set pcolor red

  let endangered-biomass-caught endangered-biomass * big-catchability
```

```
  set endangered-biomass endangered-biomass - endangered-biomass-caught
  set endangered-biomass-in-hold-big biomass-in-hold-big + endangered-biomass-caught
  set current-destination-big [ patch-here ] of one-of ports
  set pcolor red
end



;; function to update biomass and endangered-biomass

to update-biology
  diffuse biomass diffusion-rate
  recolor-patches
  if ticks mod 365 = 0 [
    ask patches [
      set biomass biomass + (
        biomass * growth-rate *
        (1 - (biomass / (big-carrying-capacity + small-carrying-capacity) / 2))
      )
    ]
  ]

  diffuse endangered-biomass endangered-diffusion-rate
  recolor-patches
  if ticks mod 365 = 0 [
    ask patches [
      set endangered-biomass endangered-biomass + (
        endangered-biomass * endangered-growth-rate *
        (1 - (endangered-biomass / (big-carrying-capacity + small-carrying-capacity) / 2))
      )
    ]
  ]

end



;; recolor patched based on the changes in biomass
to recolor-patches
  let bound 0
  set bound small-carrying-capacity + big-carrying-capacity
  ask patches [
    set pcolor scale-color blue (biomass / 2) bound 0
  ]
```

```
  let endangered-bound 0
  set endangered-bound small-carrying-capacity + big-carrying-capacity
  ask patches [
    set pcolor scale-color green (endangered-biomass / 2) endangered-bound 0
  ]
end
```

ANNEX B: NETLOGO GUI



ANNEX C: USED PARAMETERS IN EXPERIMENTS

Category	Parameter name	Experiment 1	Experiment 2	Experiment 3	Experiment 4
World Parameters	number-of-small-fishers	12	12	12	1200
World Parameters	number-of-big-fishers	120	120	120	120
World Parameters	small-carrying-capacity	600	600	600	100
World Parameters	big-carrying-capacity	5500	5500	5500	4000
World Parameters	small-exploration-radius	1	1	1	1
World Parameters	big-exploration-radius	15	15	15	15
World Parameters	small-exploration-probability	0,2	0,2	0,2	0,2
World Parameters	big-exploration-probability	0,5	0,5	0,5	0,5
World Parameters	small-catchability	0,2	0,2	0,2	0,2
World Parameters	big-catchability	0,6	0,6	0,6	0,6
World Parameters	small-speed	0,4	0,4	0,4	0,4
World Parameters	big-speed	0,1	0,1	0,1	0,1
World Parameters	mpa	6	6	3 (code modification)	6 (code modification)
Biomass Parameters	endangered-growth-rate	0,5	0,5	0,5	0,4
Biomass Parameters	growth-rate	0,75	0,75	0,75	0,6
Biomass Parameters	endangered-diffusion-rate	0,2	0,2	0,2	0,2
Biomass Parameters	diffusion-rate	0,45	0,45	0,45	0,45
Bank Balance Parameters	price-of-fish-endagered	600	600	600	600
Bank Balance Parameters	price-of-fish	300	300	300	300

Bank Balance Parameters	small-daily-costs	185	185	185	400
Bank Balance Parameters	big-daily-costs	2040	2040	2040	6000
Bank Balance Parameters	license-price-small	60	10	10	150
Bank Balance Parameters	license-price-big	0	300	300	600
Bank Balance Parameters	subsidies-small	20	20	0	0
Bank Balance Parameters	subsidies-big	420	420	0	0