The Economics of Fisheries Management
Course Notes

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[1]This set of notes is intended as a guideline for the main concepts covered in class, but is by no means a replacement for in-class discussion. Please feel free to contact me with any comments or suggestions reading this document.

[2]I would like to thank D. Jacy Brunkow and Adar Thau for their comments and help formatting and editing these notes.

Contents

The objective of this course is to develop a practical understanding of the main concepts of resource economics, their applications to fisheries, and their implementation in real life settings of fisheries management. The course is structured in way so theoretical concepts covered in the classroom will be applied in the context of real-life management challenges. At the end of the course, students should have a clear understanding of (i) the linkages between fisheries biology and the economic incentives from a user's perspective, (ii) the sources of conflict and inefficiency, and (iii) the methodologies to overcome management challenges.

1 The Static Model for Fisheries

In this module we will cover the main concepts used in fisheries management, also known as reference points. We will work through their derivation, intuition and applicability in the real world. But before we move into the fisheries model, we need to familiarize ourselves with a few preliminary concepts.

1.1 Preliminaries to fisheries economics

1.1.1 Supply and demand

We often refer to supply and demand as the two forces that determine the outcome of a market for a given good or service. Nevertheless, it will become evident that, in economics, definitions matter a lot. First, we need to clarify what we mean by a property right:

Definition 1.1. The economic property right an individual has over a commodity (or an asset) is the individual's ability, in expected terms, to consume the good (or service of the asset) directly or indirectly through exchange [1].

Though seemingly straightforward, we will see later on that property rights can be a tricky subject for fisheries. Please note that this definition is about economic property rights, and not the legal definition of a property right that is provided and enforced by a given society or government [1]. With these notions in mind, it is only natural to introduce the concept of transaction costs:

Definition 1.2. Transaction costs are the costs associated with the transfer, capture, and protection of property rights [1].

If we follow these two definitions, the concept of a market should be self-evident:

Definition 1.3. The market is the instance where the transaction of property rights takes place [2].

As the definition includes the word transaction, there must by at least two parties involved. One party willing to trade a certain good (or service), and another looking to acquire that good (or service). These two parties provide what is known as supply and demand in a market setting.

These definitions are general enough to describe every interaction between individuals in a market. But we can make this argument more concrete by specifically talking about producers and consumers. More specifically, producers supply goods (or services), and consumers buy them [3]. The way in which these two types of individuals engage in a market is known as the market price:

Definition 1.4. The market price of given good (or service) is the quantity, in monetary units, at which the producer and consumer will participate in a market transaction.

Generally speaking, we say that as the market price goes up (down), producers will increase (decrease) the quantity of the good, or service, they provide, while consumer will decrease (increase) the quantity of the good they demand. Figure 1 represents this relationship with the classic supply and demand graph.

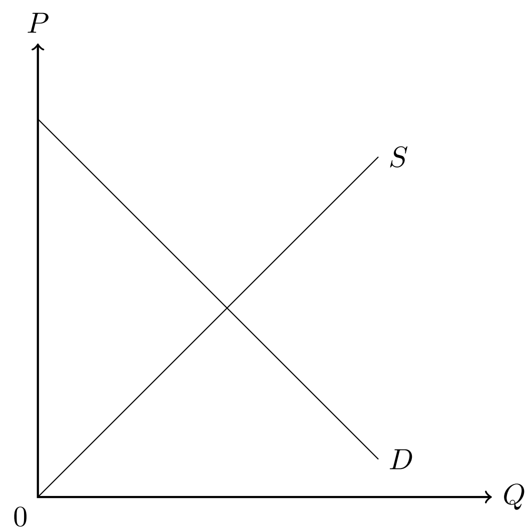

Figure 1: Graphical representation of a market. Q is the quantity of the good (or service), P is its market price, and the curves S and D represent market supply and demand, respectively.

Despite its fairly simple composition, this graph provides an incredible amount of insight for economists. We are able to establish market dynamics, equilibrium points, and efficiency measures that inform policy making. We will tackle these concepts in the next section.

1.1.2 Market equilibrium

To analyze the properties of a market allocation, we require an appropriate concept for equilibrium. Formally:

Definition 1.5. A market equilibrium is the state of the world in which the actions of both producers and consumers are consistent with each other.

In other words, a market equilibrium is the point at which supply equals demand. Going back to our simple market representation, we can find the market equilibrium by identifying the point of intersection between the supply and demand curves. Figure 2 tells us that the equilibrium for this market will be characterized by the pair (Q^*, P^*). In other words, if these producers and consumers were to interact in a market setting, *in the absence of transaction costs*, the total quantity Q^* would be transacted at price P^*.

If we want to remain rigorous in our argument, note that we have worked with the underlying assumption that both producers and consumers are price takers. This assumption means that no individual is able to alter demand or supply in such a way that affects the outcome of the market. This idea is usually referred to as a *competitive* equilibrium. From now on, when we talk about market equilibrium we will be referring to the competitive equilibrium, unless specified otherwise.

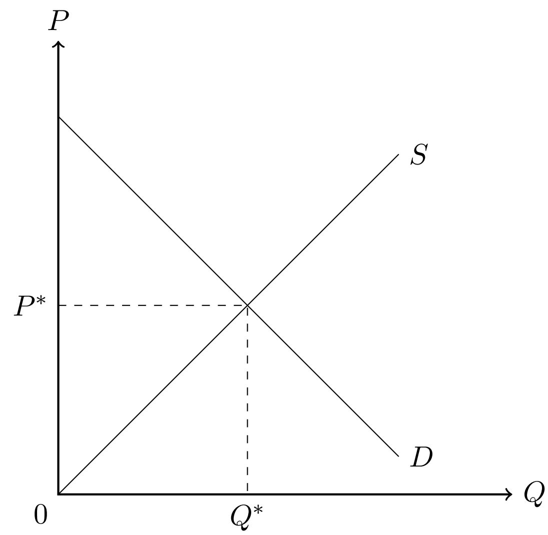

Figure 2: Graphical representation of the market equilibrium. Q^* and P^* represent the equilibrium quantity and price, respectively.

First coined by Adam Smith as the invisible hand [4], market equilibrium is one of the most powerful concepts of economics. If this outcome is the natural result of individuals interacting in a given market, we can derive some properties from this state. First, however, we need a few more definitions. Let's start with surplus:

Definition 1.6. Producer (consumer) surplus is the difference between the amount at which they are willing to sell (buy) a given good (or service) and the amount they actually sell (buy) [**manki2014principles**].

Note that to define surplus we used the word "willingness." Remember that our graphical representation of the market works like any graph, so we can interpret the y-axis as the marginal willingness to sell and pay, given a certain quantity on the x-axis. That is, the supply curve is the marginal willingness to sell of the producers, and the demand curve is the marginal willingness to pay of the consumers. For instance, P^* is the price consumers are willing to pay for an additional unit of the good (or service), given that Q^* is being supplied in the market. Also, when discussing producers, marginal willingness to sell is often interchanged with marginal cost of production.

To quantify the amount of surplus in this economy, we compare the equilibrium outcome for both supply and demand. Let's start with consumer surplus. According to our definition, we have to subtract the total amount of willingness to pay from the price they are actually paying. Since the demand curve is the marginal willingness to pay of consumers, the total willingness to pay will be the area under the demand curve from the origin up to Q^*. The total amount consumers pay, however, will be the area below the projection from P^* to the intersection between supply and demand. Figure 3 denotes consumer surplus as CS, which would be the triangle formed by $|P^*E\bar{P}|$. In the case of producer surplus, this analysis is reversed. That is, the total cost of producing up to Q^* minus the total amount that consumers pay up to the same point. Figure 3 shows how producer surplus, PS, can be calculated for our example, which is given by the triangle formed by $|P^*E0|$. The total surplus in this market would be the sum of consumer and producer surplus.

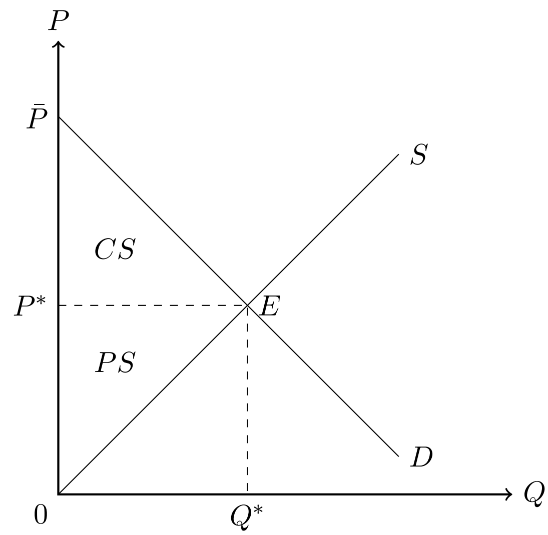

Figure 3: Graphical representation of surplus in this market. CS and PS represent the consumer and producer surplus, respectively.

Now we can start discussing the implications of the market equilibrium in terms of policy. First, let's introduce one more definition:

Definition 1.7. A market equilibrium is *Pareto Optimal* if there is no other way to rearrange production so that someone is made better off without making someone else worse off [5].

The market equilibrium, under several assumptions, is the most desirable state of the world because it maximizes the total surplus (sum of producer and consumer surplus) [6], and there is no better way we could allocate improve the market allocation. Formally, this is known as the First Theorem of Welfare Economics:

Theorem 1.1. *In the absence of transaction costs, a market equilibrium is Pareto Optimal [5].*

In other words, if we could tweak this market in whatever way we wanted, there is no other allocation that could make consumers or producers better off without making the other worse off.

So far, we have covered the basic concepts behind market equilibrium and the properties that arise from the interaction between producers and consumers. Obviously, we have barely scratched the surface of this fascinating topic, but we have enough to start thinking about how these concepts could translate to fisheries. Before we do that, however, we have to cover the notions behind population dynamics.

1.1.3 Population dynamics

The biological dynamics of a fish population can be fairly complicated, in fact, its study is an entire discipline of science by itself. A manager, however, is not required to have deep knowledge of those relationships, but must understand the overall dynamics and patterns of exploitation [7]. For our purpose, we will focus on the aggregate measure of population dynamics and its role for fisheries. The first concept we are going to review in this section is the idea of growth:

Definition 1.8. The net natural growth of the fish stock is the net increase in the biomass of the fish population between two points in time [7].

Net natural growth, growth from here onwards, is equal to the new, young fish entering the stock plus the individual growth of fish already in the stock minus the natural mortality within the stock. Though there are many models that aim to describe the growth of the stock, we will use the Gordon-Schaefer model [8], which proposes that the growth depends on the size of the stock, a growth rate, and a theoretical carrying capacity of the environment. At small stock sizes, growth is small but it increases as the stock grows until it reaches a maximum. Growth declines with further increases in stock size due to limits placed by its environment. Figure 4 shows these dynamics graphically by plotting the relationship between growth and the size of the stock.

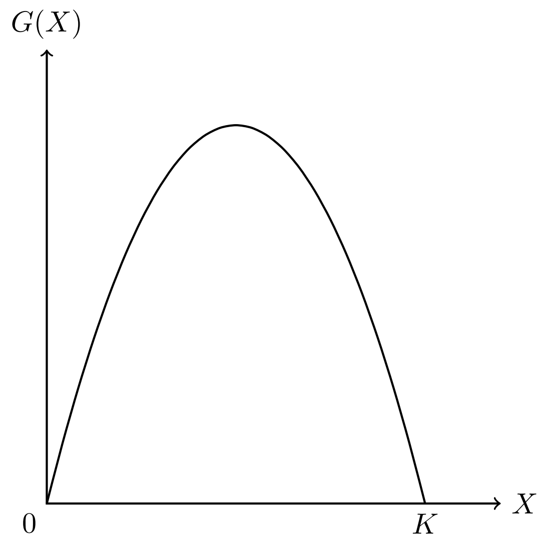

Figure 4: Growth as a function of stock size. X is the stock size, $G(X)$ is the growth of the stock as a function of X, and K is the environmental carrying capacity.

Over time, as the population reaches its carrying capacity, K, or the maximum population size its environment is able to support, growth is zero. Notice that growth is also zero when the population is zero. These two points mean that if all the factors that affect growth remain constant, the population is stable at both extinction and carrying capacity . The concept of equilibrium for a fish population is then given by:

Definition 1.9. A fish population is in equilibrium if the growth of the population is zero.

This model, although simple, has been the cornerstone behind management for most fisheries across the world. There are obvious disadvantages to using this approach, but there are many benefits of having such a simple but elegant model to describe population dynamics.[1].

Now that we have a model for how fish populations transition over time, we can start thinking about the human component. Usually, we think of fishing as an extra source of mortality, which we call *fishing mortality.* Fishing mortality is the result of humans applying fishing effort, and it describes how effective humans are catching fish. In equilibrium, with a constant amount of fishing effort, it is only expected that the stock level will decrease. In other words, as the amount of fishing effort increases, the stock in equilibrium decreases. Figure 5 shows how this relationship may look for a given fish stock.

[1] If you would like to learn more about ways on how to model fish populations, I would recommend the book called

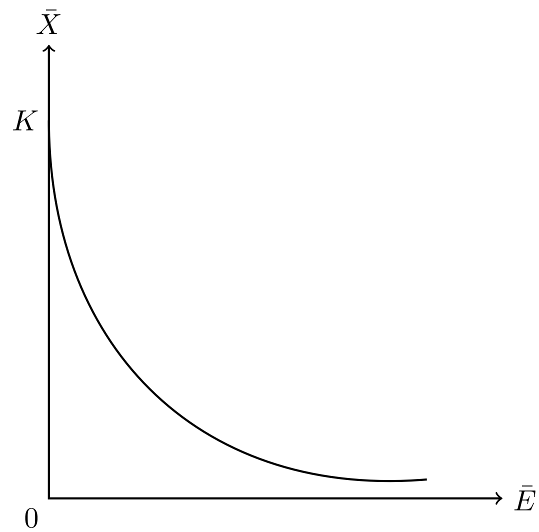

Figure 5: Equilibrium stock level as a function of fishing effort. X is the stock size while E is fishing effort. The bar denotes that we are referring to the equilibrium levels.

We can now combine the dynamics of growth and fishing effort. First, minimal amounts of effort will lead to a relatively high level of equilibrium stock (figure 5), which in turn also means very little growth (figure 4). More effort, on the other hand, will push the equilibrium stock down, increasing growth accordingly. Too much effort, however, will push the stock down beyond the peak of the inverted parabola along, thus causing a decrease in growth as well. In equilibrium then, since the size of the stock does not change over time, the catch should be equal to the growth of the stock:

Definition 1.10. The sustainable level of catch equals the growth of the stock in equilibrium.

Therefore, the sustainable level of catch must follow the same inverted U-shape of the growth relationship, but with respect to the effort level in equilibrium. Figure 6 shows a graphical representation of this relationship.

1.2 Fish and fisheries in the market paradigm

Now we have all we need to start thinking about fisheries from an economic perspective. This section will explore the ideas behind these dynamics in a market context, and how policy making can be tailored to tackle management objectives.

1.2.1 Production in a fishery context

When we talked about a regular market, we emphasized the fact that market allocations maximize the total surplus of both producers and consumers. In the case of a fishery, however, this relationship is not as straight forward. First, nature produces fish in a way that is dependent of fishers' actions. Second, extracting fish from the ocean is not free. The best way to think about the problem is to assume that the fishery is analogous to a firm: the fishery produces a good, in this case fish, which it sells in the market at a given price, but there is an associated production

"Quantitative Fisheries Stock Assessment" by R. Hillborn (1992) [9]

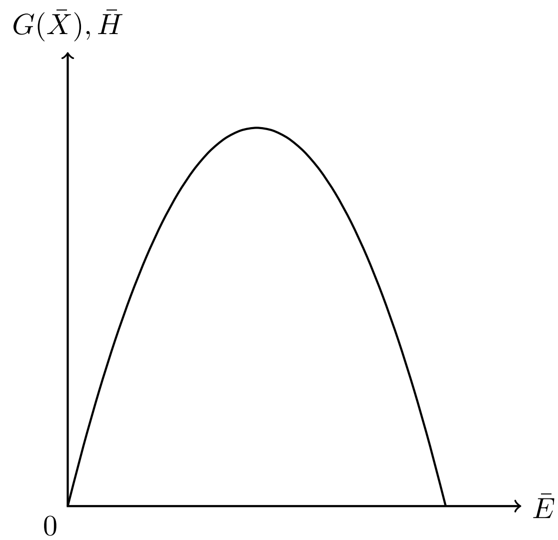

Figure 6: Equilibrium growth/catch as a function of fishing effort. H stands for harvest or catch.

cost with any unit sold.

From the previous section, we know how that when graphed, the sustainable catch looks for any given level of effort looks like an inverted parabola. If the catch of this species takes place in a competitive market, where prices are taken as given, then the total source of revenue would be a one-to-one map with harvest. Figure 7 shows how the equilibrium revenue varies with the amount of effort. Again, this figure is just a direct transition of the sustainable catch that we derived earlier.

To interpret the cost of production, we must consider fishing effort. That is, we assume that fishing activities are costly, and that cost depends on how much effort is exerted in equilibrium. The total cost of effort must be increasing in effort. For simplicity, in our analysis we assume that the total cost of fishing has a linear relationship with the amount of fishing effort. Figure 7 shows how the concept of total revenue and total cost relate to each other based on the level of fishing effort in equilibrium.

Now we have all the elements to derive a measure of efficiency for this industry. We only need one more indicator, which is known as utility or rents. Utility measures the profitability of any given activity at a certain point in time, and it is calculated as the difference between total revenue and total cost. If such a difference happens to be positive, then the fishery generates rents. If the difference is equal to zero, then there are no rents in the fishery. If the difference is negative, the fishery is at a net loss.

1.2.2 Open access

We will start with the most primitive source of equilibrium, open access. Consider the case when a fishery has never been exploited in the past. If only one person was to fish the stock, the equilibrium will occur when fishing effort is very low, and according to our notions, with small, but positive rents being generated. Unless that fisher is able to exclude others from entering, other fishers will notice this source of rents and will enter the fishery as well. As long as there are positive rents to be

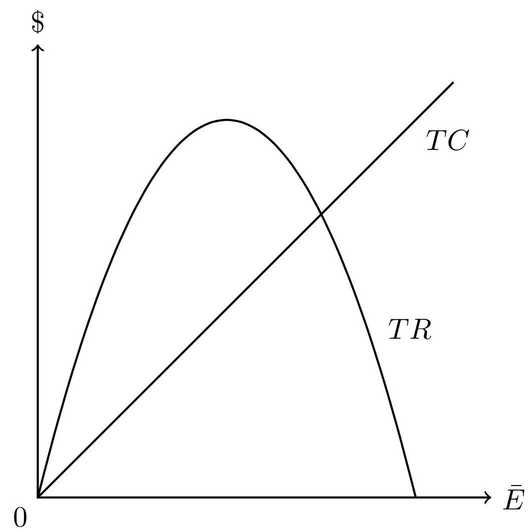

Figure 7: Total cost and revenue in equilibrium. The y-axis represents monetary units, while TR is total revenue and TC is total cost as a function of fishing effort.

captured, fishers will keep entering, increasing the level of effort until all the rents are dissipated. If effort increases so much that no one is capturing any rents, but rather starting to lose money, fishers will abandon the activity and the system will converge to the point of equilibrium where zero rents are generated. Formally, this type of equilibrium is known as open access and can be defined as:

Definition 1.11. Open access is the equilibrium point, in terms of effort, where all the rents in the fishery are fully dissipated.

Note that we made the term explicit to our notion of effort. The source of inefficiency in this case has to do with the fact that costs increase with the level of effort, but revenue is concave in effort. If fishing effort was measured in terms of fishing licenses or operating boats, that would mean there are too many of them in the fishery.

1.2.3 Maximum sustainable yield

Suppose that instead of leaving the fishery unattended, the corresponding authority decides to implement some sort of management control. The first point to use as a reference is clearly where the sustainable catch is maximized, the peak of the inverted parabola. According to our simple economic model, the level of effort that generates the maximum amount of sustainable catch generates rents. Under these assumption, and unlike open access, rents are no longer dissipated as a result of reducing effort. This is the most widely used form of management, and it can be defined as:

Definition 1.12. Maximum sustainable yield is the point, in terms of effort, where the equilibrium harvest of the fishery is maximized.

1.2.4 Maximum economic yield

Finally, suppose that the fishery is managed as a firm with the objective to maximize rents. If all that matters for society is the value that is derived strictly from harvesting the stock, then the maximum economic yield is analogous to a manager maximizing the value that society receives from the fishery. Given our assumptions for the shape of the curves for total revenue and cost, the amount of effort that maximizes the value of the fishery is even less than the level of effort that renders the maximum sustainable yield. Formally, we can define this new equilibrium point as:

Definition 1.13. Maximum economic yield is the equilibrium point, in terms of effort, where the rents of the fishing activity are maximized.

1.2.5 Reference points for management

Each of the three different equilibrium points is known as a "reference point" in fisheries jargon. This connotation comes from the fact that, usually, management of a given fishery strives to achieve one of the three. Obviously, there are advantages and disadvantages to each, but maximum sustainable yield is by far the most popular of the three [10].

Figure 8 shows a graphical representation of each reference point in our model, reporting both the associated levels of effort and the utilities each equilibrium level achieves. In general and starting from E_{OA}, where utility is zero and effort is maximized, decreases in effort lead to increases in the rents of the fishery up to E_{MEY}, where utility is maximized at U_{MEY}. Any further reduction of effort beyond that point will lead to a reduction in rents generated by the fishery. If the goal of a manager is to maximize the amount of effort in equilibrium, the fishery should be left alone without any control in open access. If the goal of the manager is to produce as much as possible, he/she should follow take the necessary actions to direct the fishery towards the point of maximum sustainable yield. Finally, if the manager seeks to maximize the extractive value of the fishery to society, he/she should take the actions to direct the fishery towards the point of maximum economic yield.

1.2.6 The social cost of fisheries

In our previous analysis, we made the assumption that the costs associated with fishing effort completely capture all the relevant cost that society incurs when exploiting a fishery (i.e., capital investment, permits, fuel expenses and wages). This assumption will not be true, however, when fishing wages do not reflect the real opportunity cost of labor. This is the case when there are high levels of unemployment and fishing is the main source of income. When fishers face those circumstances, their opportunity cost falls to levels close to zero, as they have no other opportunities available in terms of labor occupation.

Under such conditions, our static model can be used by removing wages or opportunity cost of fishing from the cost per unit of effort. Figure 9 shows how the reference points will vary compared to the previous case. We can see that maximum social benefits, MSU, will require higher levels of fishing effort than the point of maximum economic yield, MEY. Moreover, if the fishery were run based on these adjusted costs, the open access equilibrium level of effort, SOA, will be greater than the one achieved at the point of zero profits, OA. In addition, note how increases in effort reduce the profits from MEY to MSU, and are completely dissipated at OA. Total wages, on the other hand, are not dissipated until reaching the extreme point of SOA, where the fishery is so impoverished that the activity can only cover the operational costs. Finally, it is important to keep in mind that even when net benefit of society is being maximized, effort levels are higher than MEY, although still lower than MSU.

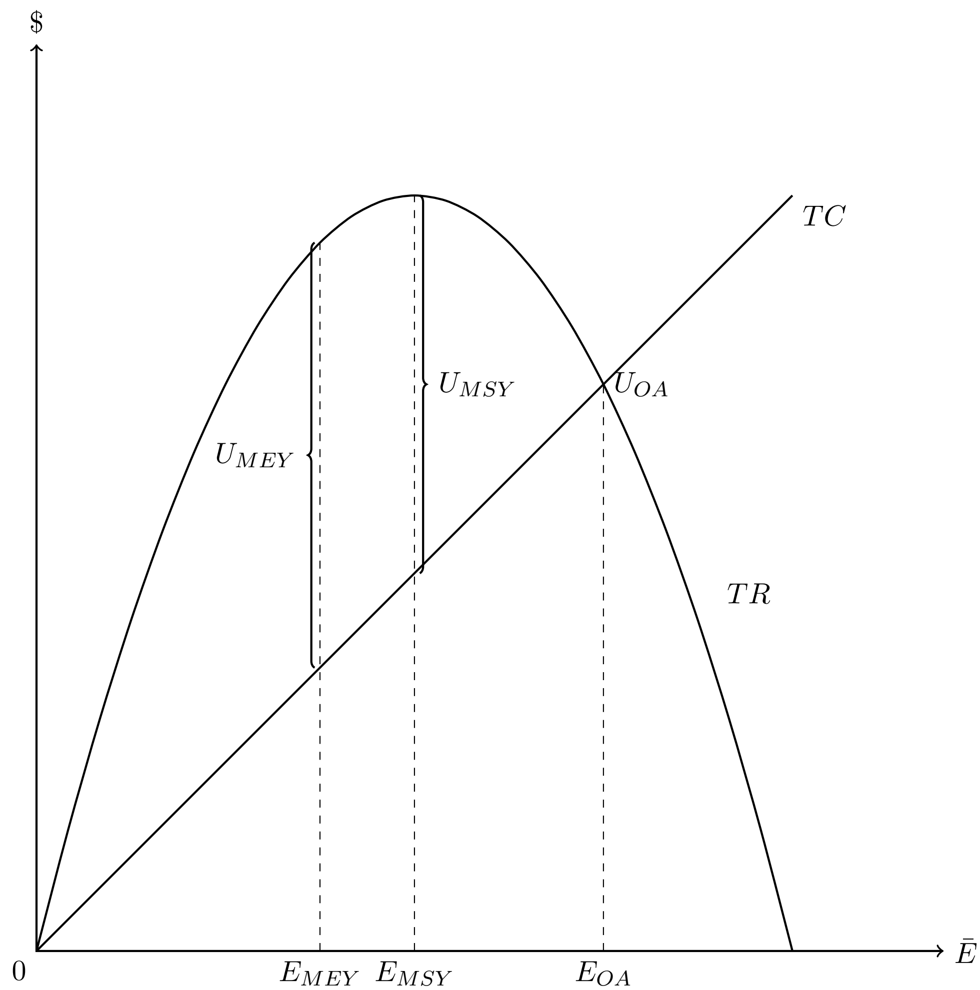

Figure 8: Reference points of the static model for fisheries. OA, MSY and MEY stand for open access, maximum sustainable yield and maximum economic yield, respectively. The associated levels of effort and utility for each reference points are denoted with the letters E and U, respectively.

Now that we have covered the main concepts behind the static analysis we will start thinking about time dynamics. I encourage you reflect on the implications of the static model for fishers. By now, you should be comfortable answering the following questions:

- What are the key differences between OA, MSY and MEY?
- What are the expected effects of a subsidy on gas?
- If you were to decide on a management scheme, which one would you choose?
- Can you come up with any strategies to compensate for a reduction in effort?
- If you were to impose a tax, how would you go about it? Can you graph its effects?

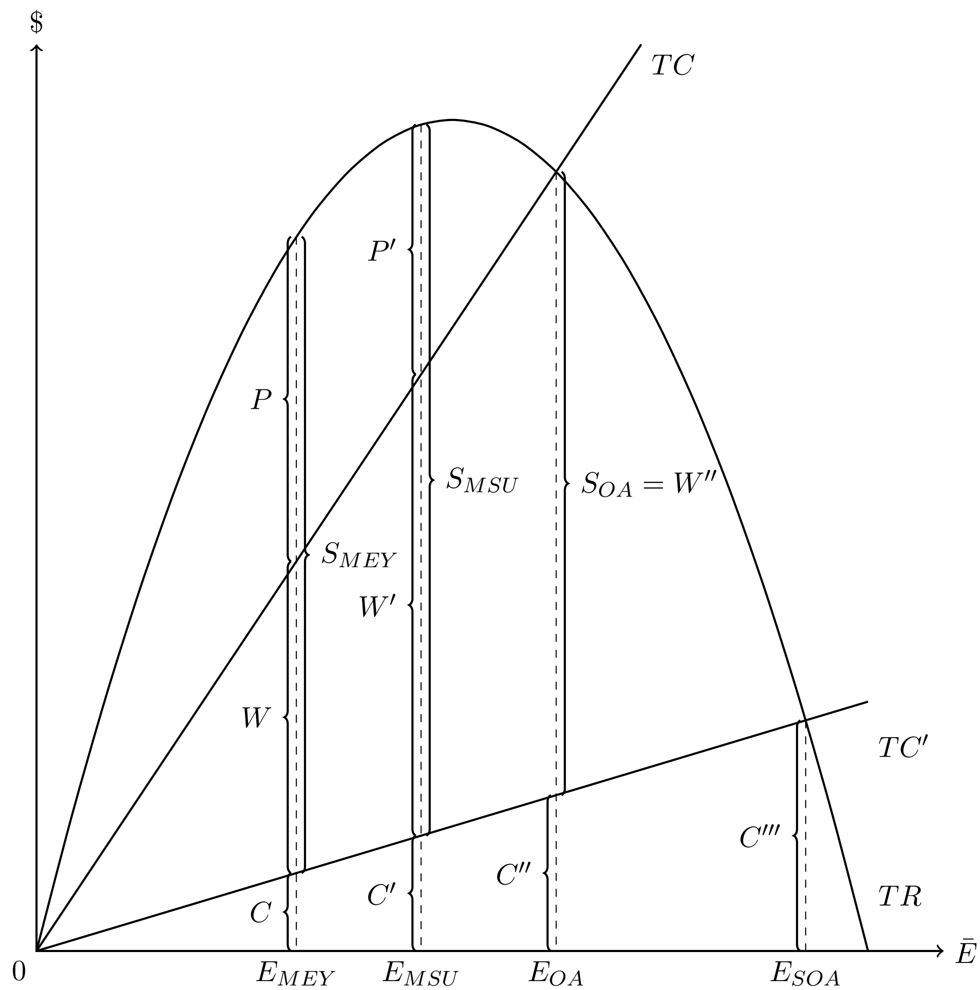

Figure 9: Social benefits with respect to the reference points in the static model for fisheries. SOA, and MSU stand for social open access and maximum sustainable utility, respectively. TC' refers to the cost curve when wages are not considered. S stands for the social benefits perceived at each reference point. P, W, and C refer to profits, wages and non-wage costs at different levels of effort, respectively.

2 The Dynamic Model for Fisheries

In the previous section we went over the canonical example of a single fishery that was exploited by a somewhat uniform set of agents that we called society. Despite its broad use in worldwide fisheries, the static model has several limitations. In this module, we will tackle two of those limitations: i) multiple users, and ii) time dynamics. These extensions will start imposing significant constraints on our analysis, but they should be always considered in any management scenario. We will discuss how to think about these issues, and how they might be relevant for fisheries management.

2.1 Strategic interactions between users

The first modification we will introduce to our fisheries model, is the concept of strategic interaction. Humans (*Homo sapiens sapiens*) have one characteristic that separates them from all other animal species in this planet: symbolic thought [11]. Among other things, the capacity to have symbolic thought means that we can solve problems without necessarily having to interact with the real world. In other words, imagination. Because we are able to imagine things, we can project the implications of our actions. If we have an expectation about how our actions and the world around us will affect us, that means that we can also project the consequences of others' actions as well. As this process is repeated over time, we update our projections creating a feedback loop that informs every posterior decision with our previous experiences. The process of decision making, while taking into consideration one's, as well as others' actions and consequences, is what we will refer to as *strategic behavior*.[2]

To start thinking about strategic interaction, we will make use of a sub-discipline known as *game theory*. Game theory is the study of strategic interactions between individuals, and how the incentives that each of them faces conditions cooperation and competition among them. One particular and useful setting for strategic interactions is known as the *prisoner's dilemma*.

2.1.1 Prisoner's dilemma

Originally developed in 1950 by Merrill Flood and Melvin Dresher [14], the prisoner's dilemma is the tale of two bandits that get caught and questioned at the police station. Though the police have enough evidence to convict them for a minor charge, they are suspicions that the bandits were involved in a bank robbery. The police proceed to question each of them separately, and offer each immunity if they give away their partner. If neither confesses, both will serve time for the minor charge. If only one confesses, he will walk free while the other serves a long sentence. If both confess, both will serve an intermediate sentence [6].

At first, this setting may seem trivial, but this simple game has many applications for the analysis of strategic behavior. Because this is a course about fisheries, we can frame a fisheries problem using the same structure as the original prisoner's dilemma. Consider a newly discovered fishery shared by two countries, country A and country B. Both countries have to decide between regulating or not the access to the fishery. If both countries regulate, the fishery will be healthy and will generate an intermediate level of social benefit for both. If no country regulates, the fishery will be under social open access with zero social benefit for both. Finally, if only one country regulates while the other doesn't, the one that regulates bears administrative costs while the other free rides from partial regulation in the fishery; this outcome actually favors the free rider by providing positive benefits by avoiding management costs.

The most practical way to think about this problem is to use a game in its normal form. To save you the mathematical intricacies of this definition, think of a normal form game as a set of payments for each player that take into account all of their possible actions as well as all the other actions available for all the players in the game.[3] In our example, we have two players and two possible actions for each. Therefore, we need four different payments for each player. Usually, economists represent these type of problems using a matrix diagram, where the actions of players are structured in rows and columns. The outcome of the game is specified by the combinations of rows (actions of the row player) and columns (actions of the column player) that are possible for a

[2] If you would like to learn more about how some people have thought (very hard) about these ideas, I encourage you to examine "The Critique of Pure Reason" by Kant (1781) and "Being and Time" by Heidegger (1927) [12, 13].

[3] If you would like a more rigorous treatment of the mathematics behind game theory, Osborne and Rubinstein (1994) offer a comprehensive and technical review of the main ideas of the discipline in their book: "A course in game theory" [15].

given game.

For our fishery example, Figure 10 uses a payment matrix to represent the game in its normal form. Every combination of rows and columns stands for a different course of action in each country, to regulate (R) and not to regulate (NR). The outcome of each combination is shown as the respective pair of payments in the box. For instance, if country A chooses to regulate (R) and country B chooses to regulates as well (R), country A and country B both will perceive benefits of 2. If country A chooses R, while country B chooses NR, country A perceives -1 and country B perceives 3. The same logic applies for every possible combination of actions.

		Country B	
		R	NR
Country A	R	(2,2)	(-1,3)
	NR	(3,-1)	(0,0)

Figure 10: The game of the new transboundary fishery. Country A is the row player, while country B is the column player. R and NR actions stand for regulate and not to regulate, respectively. All payments are given by the combination of rows and columns.

Now we have everything we need to analyze strategic behavior for our newly discovered fishery. First, let's focus on country A. Suppose that country B will always chose R. Because the payment from NR is greater than the payment from R ($3 > 2$), country A will choose NR. If country B were to always choose NR instead, the best course of action for country A is to choose NR as well ($0 > -1$). It seems that country A will always choose NR in this case, which brings us back to what was missing from this module, definitions:

Definition 2.1. A strategy is a complete contingent plan, or decision rule, that specifies how the player will act in every possible distinguishable circumstance in which she might be called upon to move [16].

In our fishery game, regardless of the actions taken by country B, country A will always be better off by choosing NR. Therefore, the strategy that country A would follow is to always play NR. Which brings us to our next definition:

Definition 2.2. A given strategy is (strictly) dominant if it (uniquely) maximizes the player's payoff for any strategy that her rivals might play.

2.1.2 Nash equilibrium

In this game there were only two choices available for each country. Given the symmetry of the game, both countries' dominant strategy is to play NR. If you recall our previous definition of an equilibrium, there is no way any of the countries will play a different strategy. In fact this is a famous property of strategic interactions:

Definition 2.3. A Nash equilibrium is the outcome in which each player is playing his best strategy in response to the best strategy of the other players.

Nash equilibrium is one of the biggest contributions to the economic discipline [17], and it shows how powerful self-interest can be. For instance, if country A and country B comprised the entire population of earth, analogous to the idea of total surplus, the overall benefit of the world would be the sum of the benefits in both countries. The option that maximizes the total benefit is for both countries to choose R. Nevertheless, because they make their decisions independently, the Nash equilibrium in this game suggests that none of them chooses to regulate at all.

This type of problem arises all the time in fisheries (e.g., international treaties), but they are also true for any type of interaction in which the actions of one individual will affect another's and vice-versa. Many types of negotiation and extraction policies are strategic in nature, and the use of game theory for analysis can be a huge advantage when it comes to policy design. In the next section we will learn a little bit more about about how time plays a role in fisheries management, and how to use a game theoretical framework for its analysis.

2.2 Resource dynamics over time

If you recall our discussion about population dynamics, when we defined population growth, we emphasized that growth occurs over time. Our static model for fisheries looks at the equilibrium points where the system has stabilized, without paying much attention to the path for such equilibrium. The rest of this module is devoted to examining the question of how time dynamics affect fisheries management. We will start by incorporating time into our decisions.

2.2.1 Time preferences

From an economic perspective, the effect of time can be thought as a diluting effect. For instance, suppose that you won a contest that gives you the opportunity to choose the prize. You can request \$100 immediately, or \$110 next year. After checking with your bank, the 4 percent interest will give you only \$104 after a year, so it seems like the best idea would be to get the \$110 next year. Nevertheless, you go ahead and cash-out the \$100 right away. If the value of money was to remain unchanged over time, then it will make no sense to get the payment now. The problem, however, is that there is an opportunity cost associated with money, you could be doing something else with \$100 now, making the year-long wait not worth the extra \$10.

In general, individuals (and society) prefer payments now, when compared to receiving the same amount at some point in the future. Moreover, the farther away that future payment is, the less they will value the same payment, compared with its equivalent value in the present. The rate at which those future payments will lose value as they move further down the road is known as the discount factor:[4]

Definition 2.4. The discount factor is the effective rate at which the value of payments decrease over time.

Time preferences allow us to project the consequences of our decisions into the future, so we can compare and rank them according to our preferences. The way we usually make these comparisons is by using what is known as the net present value:

[4] You might have heard a similar argument using the discount rate. The discount rate, is in fact a component of the discount factor, although they work in different directions. For instance, if you were to be indifferent between \$100 now and \$104 next year, that means that you as an individual, discount the value of every dollar in the future at 4 percent for every time period that passes. This is analogous to saying that your discount factor is $\sim$.96, or that every time period into the future a dollar loses $\sim$4 percent of its value.

Definition 2.5. Net present value is the sum of all relevant net payments, weighted by the discount factor throughout time.

Note that this definition specifies that the discount factor is applied throughout time. In our example, we only have two time periods, now and next year. If we include another time period, a second year into the future, we also need to discount it appropriately. For simplicity assume that there are three years in your horizon, now, year one and year two. You will receive three payments of \$100 distanced by a year, and starting now. Suppose further that your discount factor is 0.96. The value of \$100 now is \$100. The value of \$100 next year, as we saw earlier, would be \$96. If we are consistent with our logic so far, the value for the second year has to be less than \$96. Imagine that you are able to fast forward from now to year one. At that point in time, the value of \$100 in year two would be \$96. Going back in time to the present then, the value of \$96 next year would be the discount factor times the discounted payment, or $92 = 0.96 \times 96 = 0.96^2 \times 100$. The net present value of those payments, will be the sum of each discounted payment: $NPV = 1 \times 100 + 0.96 \times 100 + 0.96^2 \times 100 = 288.16$. Extending the discounting effect further into the future follows the same logic, the discount factor is exponentiated by the number of periods into the future when the payment is received.

The relevance of time preferences to fisheries becomes obvious as we acknowledge that the stock grows over time, and that users (or society) value payments differently across time as well. Suppose that we are facing the end of times, but we still have some time to harvest a fishery. If the profit that society perceives from this fishery is just given by the catch level, then it would be optimal to harvest the entire stock because next period the universe will not exist anymore. If we go back one more period, we have two choices: high or low levels of harvest. If we choose high levels of harvest, the stock will be low next period and the harvest before the end of times will be low as well. If we have low levels of harvest now, the stock will recover before the end of times, providing high levels of harvest. That being said, all that matters is our decision of how much harvest we choose today. We can represent this problem using a simple schematic, also known as a game in its *extensive form*, where high and low levels of harvest are represented by the letters H and L:

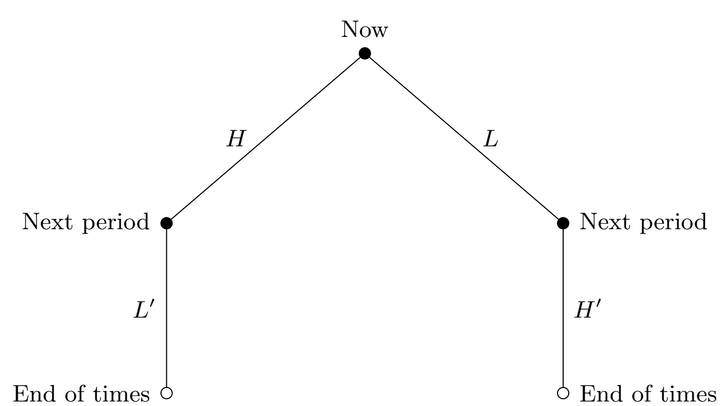

Figure 11: Two period fishery problem. H and L stand for high and low levels of harvest now, while H' and L' stand for high and low levels of harvest next period, respectively. From top to bottom, every node denotes a moment in time.

As we mentioned earlier, to compare different decisions across time, we have to bring all future payments to present value. In the schematic representation in figure 11, the peak of the structure is the moment at which we will be making the decision, therefore there are two possible paths. If we choose a high level of harvest we will harvest H now and L' in the future. If we choose low harvest now we would get L now and H' in the future. Suppose that our discount factor is given by the letter β. The net present value of choosing high levels of harvest now is: $NPV_H = H + \beta L'$, while the net present value of choosing low levels of harvest now is: $NPV_L = L + \beta H'$. If we ask the question, when would we choose high levels of harvest now? We can follow the logic below:

$$\begin{aligned}
& NPV_H > NPV_L && \text{(When its NPV is greater than the alternative)} \\
\iff & H + \beta L' > L + \beta H' && \text{(Or the sum of its discounted payments)} \\
\iff & \frac{H - L}{H' - L'} > \beta && \text{(Solving for } \beta\text{)}
\end{aligned}$$

The final inequality tells us that high levels of harvest now would be preferred whenever the ratio of the harvest differences (left hand side) is greater than the discount factor (right hand side). For instance, imagine that high and low levels of harvests remain the same across the two periods, which makes the left hand side of the equation equal to one. Since the value of the discount factor penalizes future payments, it will never have a value above one, thus high levels of harvest will be the preferred option. Leaving everything constant, if the differential in the current period grows (high levels of harvest exceeds by far low levels of harvest now), the quantity on the left hand side of the inequality will be above one, making high levels of harvest now the preferred course of action. If, on the other hand, the differential in the next period increases (high levels of harvest exceeds by far low levels of harvest in the next period), the quantity on the left hand side may decrease enough to be less than the discount factor, making the low levels of harvest option preferable to its alternative. Notice that the more we penalize the future (lower discount factor), the bigger the differential required in the next period to motivate alternative levels of harvest.

Time preferences matter a lot. Even for our two period fishery problem, time preferences are a key determinant for which options are optimal. That is not to say that the growth of the stock doesn't matter; the harvest differentials in the future are indeed a function of how much fish is left in the water to reproduce and harvested next period, which in turn, is a direct function of the stock's reproductive capabilities. Now, if you recall our discussion about population dynamics, stock growth was an inverted parabola with respect to the stock level; that is, growth is highest when the stock is at half of it's carrying capacity. This makes the problem a little bit more complicated because we have to think about every single possibility of growth. To save you the trouble of figuring out the details, I replicated the two period fishery, but with a continuous growth function. Therefore, rather than choosing high or low harvest, you would pick the exact amount of harvest in the current period to maximize the net present value of the fishery.[5]

Figure 12 shows the optimal harvest for the two-period fishery as a function of the discount rate and the net growth rate of the stock. First, note that as the net growth rate increases (g_1 towards g_4), the optimal amount of harvest in the current period decreases. Similarly, as the potential yield in the future increases, harvest decreases accordingly as it is optimal to use the curvature of the growth function to get a greater payment in the future. Also, notice how increases in the discount factor (less penalty for payments in the future) also decrease the optimal amount of harvest. As the future becomes more and more valuable, it is optimal to leave more fish in the water so the yield next period increases.

[5] This is a two-period / one user version of the model proposed by Levhari and Mirman (1980) [18].

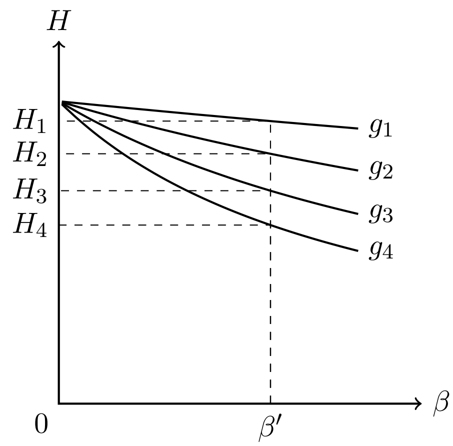

Figure 12: Two-period fishery with continuous harvest decision. The plot shows optimal harvest decisions in the first period, H, as a function of the discount factor, β, and different net growth rates, g. Net growth rates are numbered in increasing order with g_1 being the lowest and g_4 being the highest.

These results, even from a simple model, help us see the role of both growth and time preferences when it comes to deciding how much to extract from a fish stock. Real-life examples will go beyond two periods, so we can use both analytical and numerical methods to study optimal extraction for the given stock. For economists, whenever we are concerned with a given optimal extraction prescription, we often look for is what is known as a policy function, which we will cover next.

2.2.2 Policy function

In our two-period fishery problem, we discussed how our harvest decision will vary as function of our time preferences and the characteristics of the stock. There is one more factor that we have not talked about yet: the size of the stock. In other words, the problem of deciding how much to harvest in the first period, given our time preferences, the rate of growth of the stock, and the stock level that we observe before making our decision.

Because our harvest problem revolves around the state of the world that we are able to observe, or the stock in the water in the first period, we denote the stock as a *state variable* [19]. In this problem, we are able to control the amount of harvest in the first period, thus the harvest is referred to as the *control variable* [19]. The net present value of our decision is what we would like to maximize, which we can refer to as our *value function* linking our decision with its consequences over time [19]. The notion of time preferences and the reproductive potential of the stock are the parameters of the problem. The strategy that maximizes the value function for any state of the world is known as the policy function:

Definition 2.6. A policy function is the control variable prescription for any possible value of the state variable, such that the value function is maximized.

Leaving aside the formal terminology, the best way to think of the concept of a policy function is a recipe. Suppose that you are interested in baking a pie for some guests. Despite the happiness they will feel after eating the pie, ingredients are not free, so you would like maximize your guests' happiness without wasting ingredients. Because most people have some sort of intake capacity, there will likely be a point where they won't be any more happy if they eat an additional piece of pie, so you would like to avoid wasting pie too. If the baking process is completely standard, given the number of guests, you are looking to have a master recipe that allows you to achieve maximum guest satisfaction at a minimum cost. The state variable in this problem is the number of guests, the control variables are the amount of ingredients you need to purchase, and the value function is the overall satisfaction of being a good guest minus the cost of baking the pie. The policy function would be the recipe, in which you consider the number of guests to figure out the amount of ingredients you must purchase.

For our fishery problem, the policy function (commonly known as the *control rule* in fisheries jargon) will be a comprehensive plan of harvest for any possible level of stock that will always maximize the net present value of the fishery. In other words, you tell the policy function how much stock there is in the water, and it will tell you the quantity that you need to harvest for any possible state of the world. Building in our previous example for the two-period fishery with continuous harvest decisions, the policy function would be to harvest a constant fraction of the stock. That fraction would be a function of the parameters of the model, time preferences and the net growth rate of the stock. Figure 13 shows this relationship with respect to different growth rates and a given observed level of stock. As the net growth rate of the stock increases, transitioning from g_1 toward g_4, the optimal prescription is to harvest less aggressively because the recovery of the stock becomes more and more valuable. Moreover, for each type of stock, it is optimal to harvest more as the observed stock level increases.

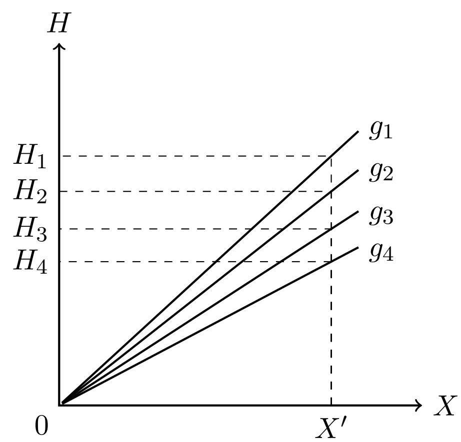

Figure 13: Two-period fishery with continuous harvest decision. The plot shows optimal harvest decisions, H, in the first period as a function of the available stock, X, and different net growth rates, g. Net growth rates are numbered in increasing order with g_1 being the lowest and g_4 being the highest.

The concept of the policy function is a powerful one. Reminiscent of one of the ideas covered in the section on strategic interactions, the policy function is the ultimate strategy. It gives the contingent response to any potential state of the world, such that the maximum value of the fishery is always achieved. Moreover, the policy function can be extended to fishery problems that go beyond two periods, have other users involved, and, as our next section will cover, problems that deal with uncertainty regarding the future.

2.2.3 Uncertainty

In our two-period fishery problem, we knew how much the stock would grow after we extract a given amount of harvest. But more often than not, there are several limitations to forecasting natural processes, and especially when it comes to fisheries [20]. Economists deal with this problem by using what is known as *expectations*:

Definition 2.7. An expectation is a forecast made by the decision maker regarding the state of the world in the future.

In our fishery model, we associated the state of the world with the state variable, the stock level. Therefore, the decision maker has an expectation of how the stock may grow in the future as a result of the harvest in the current period. To operationalize this notion, we will make use of the expected value:

Definition 2.8. The expected value for the state of the world is the weighted sum of the value for all possible states of the world and their respective probability of occurrence.

This definition suggests that we can still make decisions about an uncertain future if we know two things: the possible states of the world and how likely they are. For instance, consider the simplified version of our two period game with some uncertainty. Suppose there is some probability, p, that our previous prediction was right. That is, if we have a high level of harvest in the current period, the harvest next period will be low. It follows that the probability of being wrong is then given $(1-p)$, which means that there is some probability of our forecast being wrong, and having a high level harvest today actually results in high levels of harvest in the next period too. For simplicity, suppose that the opposite is also true. Figure 14 illustrates this problem graphically.

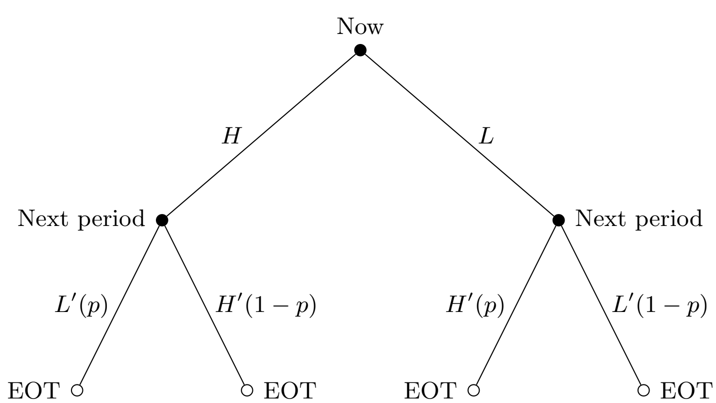

Figure 14: Two period fishery problem with uncertainty. H and L stand for high and low levels of harvest now, while H' and L' stand for high and low levels of harvest next period, respectively. The probability of having a good (bad) forecast is p $(1-p)$. From top to bottom, every node denotes a moment in time.

Recall from our previous solution that our decision of having high or low levels of harvest was a function of the ratio of the differences between harvest levels. We can do the same here, but we account for uncertainty by using the expected value of the state of the world. For example, if we choose to have a high level of harvest, the expected value of our decision in the future will be the probability of having a low level of harvest times the value of that low level of harvest, plus the probability of having high levels of harvest times the value of that high level of harvest, $p \times L' + (1-p) \times H'$. The expected value of choosing a low level of harvest in the future follows a similar approach. Suppose again that our discount factor is given by the letter β. The net present value of choosing high levels of harvest now is: $NPV_H = H + \beta(p \times L' + (1-p) \times H')$, the net present value of choosing low levels of harvest now is: $NPV_L = L + \beta(p \times H' + (1-p)L')$. Now we can ask the question, when would we choose high levels of harvest now? We can follow the same logical process as we did earlier:

$$
\begin{aligned}
& NPV_H > NPV_L && \text{(Difference in NPV)} \\
\iff & H + \beta(p \times L' + (1-p) \times H') > L + \beta(p \times H' + (1-p) \times L') && \text{(Substituting)} \\
\iff & \frac{H - L}{H' - L'} > \beta(2p - 1) && \text{(Solving for } \beta \text{ and } p\text{)}
\end{aligned}
$$

Including uncertainty in the problem requires at least one additional parameter, in this case p, which is showing up on the right hand side of our equation. To understand this result, remember our previous discussion on the role of the discount factor. You can think of the quantity in parenthesis as another discount factor. If you are completely certain of the initial forecast being right, $p = 1$,and the analysis is the same as if there were no uncertainty. If the previous estimation is entirely wrong, $p = 0$, making the right hand side negative making high levels of harvest the preferred course of action. Therefore, as expected, increases in the probability of being wrong about our future estimates work toward making high levels of harvest the preferred option.

Similarly, we can include uncertainty for the continuous harvest version of our problem. Suppose that despite your knowledge of the stock, your prediction of how much the stock will grow after it gets harvested is not accurate due to environmental factors. That is, the theoretical net growth rate of the stock will shift around according to the characteristics of the new year. The fisheries scientists tell you that their theoretical estimations of the net population growth are within a certain range, θ. Thus, it is more likely that the net growth will be on the bottom end of the range.

The policy function for this problem is shown in figure 15 for two different theoretical populations. Bearing in mind that it is more likely for the population to be on the bottom part of the range; as the uncertainty range increases, harvest becomes more aggressive (same level of stock and increasing θ). Moreover, if we switch from low to high growth rates, uncertainty still encourages more harvest during the first period. The only difference, is that higher net growth rates give the stock the possibility of faster recovery from intense fishing, and therefore, it is optimal to harvest more aggressively.

As seen in the two previous cases, optimal decision making under uncertainty will overcome a dark future by enjoying all the benefits today rather than risking uncertain future benefits. Yet again, we can see how time preferences play a huge role for economic problems. As we discussed in the first module, reference points usually leave time dynamics aside and focus on the equilibrium of the fishery. Obviously, there are many advantages to thinking about static problems rather than dynamic ones. Accordingly, we can convert a dynamic problem into a static one. This idea is called *steady state.*

2.2.4 Steady state

Our dynamic problem has considered only two periods, today and the end of times. But despite the fact that our planet will be destroyed by a dying sun in about five billion years [21], if not earlier, our management problems usually involve more than two periods. It is customary for economic analysis of fisheries to involve at least several decades, and some of them actually deal with infinite

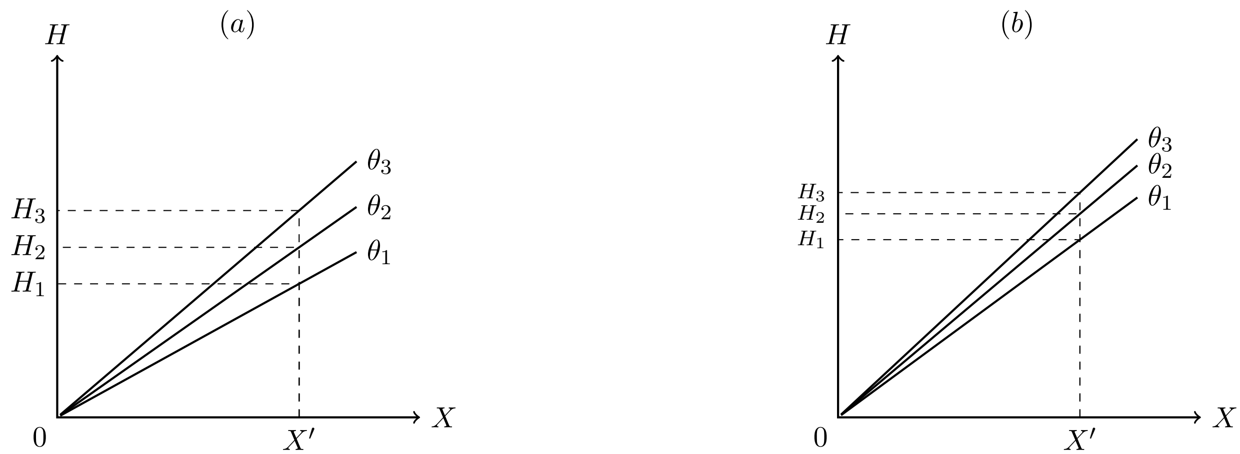

Figure 15: Two period fishery with continuous harvest decision and uncertainty. The plot shows optimal harvest decisions in the first period, H, as a function of the available stock, X', and different levels of uncertainty, θ. Uncertainty ranges are numbered in increasing order with θ_1 being the lowest and θ_3 being the highest. Each plot shows a different net growth rate, with plot (a) being a low and (b) being a high net growth rate, respectively.

time horizons. The interesting part is, that as soon as we start expanding our time horizon far enough so there is no need to extinguish the fish stock before the end of times, we can start thinking about the concept of equilibrium again. Specifically for dynamic problems, we refer to this special equilibrium as the steady state:

Definition 2.9. In a dynamic problem, steady state is the equilibrium point at which the state of the world does not change over time. [22].

Consider our simple fishery problem, but instead of lasting only two periods suppose that we are very far away from the end of times. This problem is not trivial, recall that payments lose value as they move into the future, and whatever we will get in future is also a function of our actions today. I will spare you the math required to find the policy function for this problem, but let me tell you that it is a linear function of the stock. In other words, the optimal course of action at every point in time and for every level of stock, is to always harvest a constant share of the stock, let's call it α.

Going back to our first module, remember that the sustainable catch was defined as the harvest level that was equal to the growth of the stock at equilibrium. Therefore, the level of sustainable catch and growth are the same in equilibrium. If we graph that relationship we would get an inverted parabola. The policy function is a straight line with slope equal to α, so we can graph it as well. Figure 16 shows both relationships, and how the idea of steady state arises from the combination of the stock dynamics and the optimal response in terms of fishing: the intersection of both functions. If we look at the plot, we can find two different intersections: i) no stock and no harvest, and ii) stock at $\bar{X}$ with harvest $\bar{H}$. At the latter, the system reaches an equilibrium after following all the actions required to maximize the net present value of the fishery. Despite the similarities between the concepts from module one, it is useful to remind yourself that this solution considers our time preferences as well as the stock dynamics in a cohesive framework. In a sense, it can be thought of as more rigorous version of equilibrium when compared to the static model.

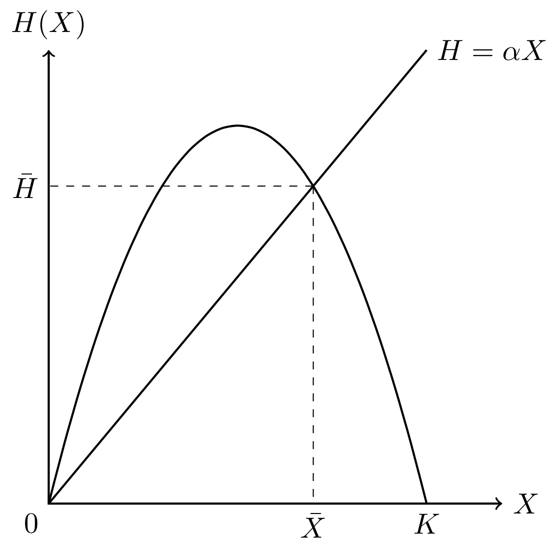

Figure 16: Steady state for a linear policy function. X is the stock size, $H(X)$ is the sustainable catch as a function of X, and K is the environmental carrying capacity. α is the optimal fraction of the stock that is harvested every period. $\bar{X}$ and $\bar{H}$ are the steady state levels of stock and harvest, respectively.

We have covered an array of advanced topics that are important when thinking about fisheries in a time dependent context. Nevertheless, the contents covered here barely scratch the surface of these expansions. I invite you to do more research regarding the applications of game theory to fisheries and how economists have dealt with uncertainty. Below I list some questions that should help you familiarize yourself with this module:

- Can you expand our two country game to consider three possible actions by each country?
- Can you make any predictions for how the optimal policy would change as a the two period game extends to three, four, and so on?
- Can you frame our discrete uncertainty problem as a closed form game where you play against the future state of the world (nature)? Can you include another player (country) besides nature?
- Keeping the inverted parabola, how would different policy functions work if they are not linear? How do you expect them to look like? Which equilibrium points do you think will arise?

3 The Spatial Model for Fisheries

So far, we have been thinking about fisheries in a very stylized way. Recall for instance, that our fish model is one homogeneous population that grows until it converges towards a theoretical carrying capacity, or when we had two countries, they were identical to each other in terms of the payoff scheme. It turns out, obviously, that the real world is far from being homogeneous. In this section we will start thinking about how to implement the notions of heterogeneity from a fisheries management perspective. In particular, we will explore two sources of complexity: spatial distribution and user heterogeneity.

3.1 Spatial dynamics for fisheries

3.1.1 Spatial distribution of fish stocks

When talking about living creatures that inhabit water bodies, and in particular the ocean, we have to keep in mind that these organisms usually have very complex life cycles [23]. This complexity often manifests in migration patterns, spawning behavior and inner population dynamics that make fisheries management more difficult. Additionally, as large scale weather patterns also influence these factors. Consequently, simple models need to be improved in order to capture these dynamics appropriately [24].

One of the approaches that economists follow to think about these sources of complexity is to include them explicitly from the user's perspective. For instance, consider two type of fish stocks. The first one is a species that reproduces once a year with no spatial preference for spawning, although it migrates long distances chasing for food. The second one is a species that congregates to spawn in one specific place and spends its adult life in a completely different region. These two examples will be the core of this module. We will try to understand the set of incentives that arise in each of them, and their significance in terms of efficient management.

Personally, I think the easiest way to represent these dynamics is to use diagrams. Figure 17 shows two diagrams for each of the examples described above. Diagram (a) shows a population that migrates between two locations, L_1 and L_2, where there is a fraction that stays (looped arrows) and another that migrates across locations (cross location arrows). Additionally, each location may present different environmental characteristics, allowing for natural mortalities to differ in both of them. Diagram (b) on the other hand, shows the idea of the population having two different habitats: one for spawning, where juveniles, J, spend some time until they are recruited to the fishery and become adults, A, that inhabit a different region.

Figure 17: Population dynamics with spatial heterogeneity. Diagram (a) displays the dynamics for a migratory stock that moves between location L_1 and L_2, respectively. D_{11} and D_{22} denotes the fractions of the stock that remain in each location, while D_{12} and D_{21} denote the fractions that move across each location. z_1 and z_2 denote the natural mortalities in each location. Diagram (b) displays the dynamics for a stock that migrates to reproduce. A and J stand for adults and juveniles, while E and R stand for eggs and recruits, respectively. z_A and z_j denote the natural mortality rates in each life stage.

The benefit of having a graphical representation is that we can track the influences across locations easily. For instance, in our examples we can clearly see that there is an interrelation between locations and life stages that conditions the overall level in each of them. Hence, any management approach should take into account those dynamics accordingly. But before we do that, let's bring fishing into the picture. Recall that in module one, we introduced fishing as another form of mortality. We will do the same in this case by limiting fishing mortality to just one location, L_1 and A, respectively.

Figure 18 shows the updated version of our diagrams by denoting fishing mortality with the letter f. For the time being, we will say that there is only one user (country) fishing these populations, and the region under the control of such user (country) is the dashed box, where the only variable up to choice is how much to fish, f_1 and f_A in the diagrams below. Despite their graphical similarities, both cases have contrasting incentives. For instance, suppose that the region outside the control area is heavily polluted and no fish can survive. If we were facing the two period fishing game we played before, it would be optimal to leave some fish in the water for (a), while it would be optimal to extract down to the last fish if we were in case (b). The difference between the two cases is that, as long as the area under control is able to produce or renew the stock, D_{11} in case (a), there is an incentive to leave fish in the water.

Figure 18: Population dynamics with spatial heterogeneity and fishing by one user (country). Diagram (a) displays the dynamics for a migratory stock that moves between locations, and diagram (b) displays the dynamics for a stock that migrates to reproduce. The fishing mortalities are denoted as f_1 and f_A, respectively. The region controlled by user (country) 1, C_1, is enclosed in the dashed box.

Obviously, this problem -at least in spirit- is not new compared to what we have previously covered. So far, all we have done is add the sources of fishing mortality and growth in a more explicit way. But that is exactly what we were trying to do, add the spatial dimension specifically to our fishing framework, and despite the simplicity of these two hypothetical worlds, we already have some insights. As soon as the control over the population renewal diminishes, fishing becomes more aggressive. This is a common result that shows up not only in the proposed model, but also in the cutting-edge heavy theoretical economic models that economists have developed for this field. How these incentives change when there is one or more players involved is the topic of our next section.

3.1.2 Spatial distribution of fishers

As soon as we start taking into account the spatial distribution of fish, we have to consider that fishers fishing the stock will also distribute across space. In the previous module, we made the implicit assumption that fish were uniformly distributted, like water in a pot, where the strategic responses had an effect over the entire stock rather than localized effects. By including spatial dynamics we recognize the mechanics, at least in a very stylized way, behind the actions of one user, their effect on the stock, and how the ripples of those actions will condition other users as well.

Building on the same ideas, we can incorporate an additional user for each of the cases considered earlier. Figure 19 shows a graphical representation of both examples, where two users (countries), C_1 and C_2, can fish in their respective controlled regions (dashed boxes). The spatial dynamics of the stock, however, connect the actions of each of them in terms of how the stock reproduces and transitions across locations. Case (a) assumes that in both locations the stock can grow, stay, or migrate to the opposite location. Case (b) on the other hand, suggests a cycle-like pattern where adults in C_1, A_1, are fished by that country, and then the remainder of the stock moves to C_2. After being fished in that country, the remainder of A_2 will reproduce and eventually recruit to be available as adults for C_1 again.

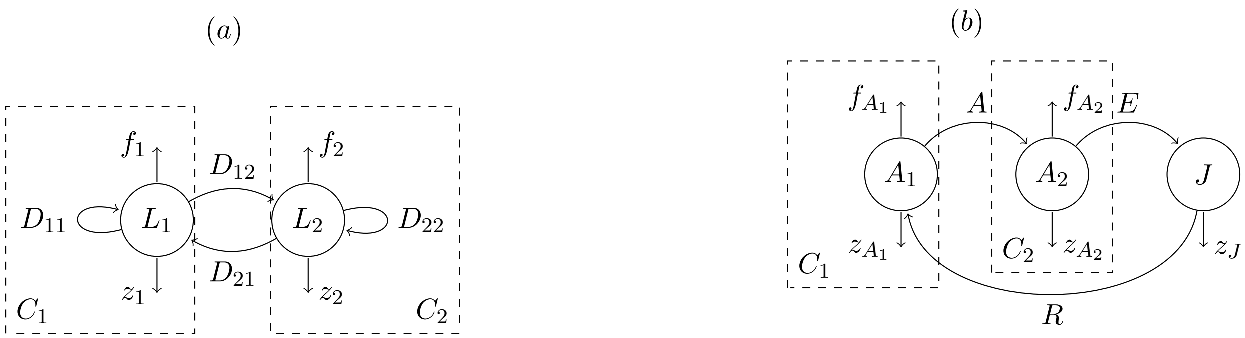

Figure 19: Population dynamics with spatial heterogeneity and fishing by two countries (users). Diagram (a) displays the dynamics for a migratory stock that moves between locations, and diagram (b) displays the dynamics for a stock that migrates across countries to reproduce. Fishing and natural mortalities are denoted by the letters f and z, respectively. The regions controlled by each user (country) are enclosed in the dashed boxes.

By now you should be able to infer how different incentives will condition behavior in each case. First, recall that the value of having a payment in the present is more valuable than the same payment in the future; furthermore, the further down the road that payment is made, the less valuable it becomes. For case (a), the fact that each user (country) is partially responsible for the availability of stock in the future, as there is a fraction that stays within their own boundaries, means that there would be an incentive to preserve those future payments over time. How valuable they are, would be a function of how much the stock can grow in the future and what are the benefits harvesting it in the current period. For case (b) on the other hand, the actions of each user (country) are deeply interconnected. Any future rents that can be obtained from this stock are conditional on both countries leaving some fish in the water for reproduction. It is only natural to suggest that the order in which they get to make their fishing decisions will play an important part when they behave strategically.

Despite of having covered only two cases, this approach can help you think about these and many other potential examples where space is important. The bottom line, however, is to conceptualize the role of the spatial dimension for your management problem, if any. As we saw before when we had only one user in a spatial context, the decisions were straight forward because space was not adding any additional insight other than higher detail of the stock dynamics. From an economic perspective, spatial extensions are relevant, if and only if, they help contribute to the quest for increasing efficiency in the fishery. More specifically, if spatial dynamics have something to contribute to an increase in the rents received by a given user (country) from the resource. In the next section, we will see how these spatial dynamics are included in strategic behavior by using the insights we learned from game theory.

3.2 Strategic response to spatial dynamics

After including spatial dynamics explicitly in our decision making problem, the fact that we are playing a game (competing) with another user (country) should raise several questions about strategic responses. If you recall from our discussion about dominant strategies and Nash equilibrium, we started by fixing the actions of our opponents to identify what was the decision for each possible action they could take. The linkage between our responses and theirs, comes from the transition of the stock across space and time. Intuitively, best responses have to be dependent on the mechanics of that spatial and temporal interconnectivity.

Let's start with case (a) in a two-period fishery, now and at the end of times. Suppose country 1 and country 2 can choose high or low levels of catch now, but in the next period they will catch everything they have in their waters because it is the end of times. The interconnectivity between countries means that a fraction of the stock will flow across countries, while some other fraction will stay in each jurisdiction. How much stock flows across space is a function of the distribution patterns across countries and how much stock there is in each location.

Figure 20 shows a graphical representation of this problem from country 1's perspective. To read this figure, we can start from top to bottom. If country 1 chooses a high level of harvest during the current period, then growth will be low for next period. A fraction of that low growth will move towards C_2, and only fraction D_{11} will stay to be harvested by country 1 in the last period. If country 2 chooses a high level of harvest, then growth will be low in its territory, while the opposite is true for high levels of harvest. Country 1 will receive fraction D_{21} of that growth in the final period. The problem is analogous for country 2.

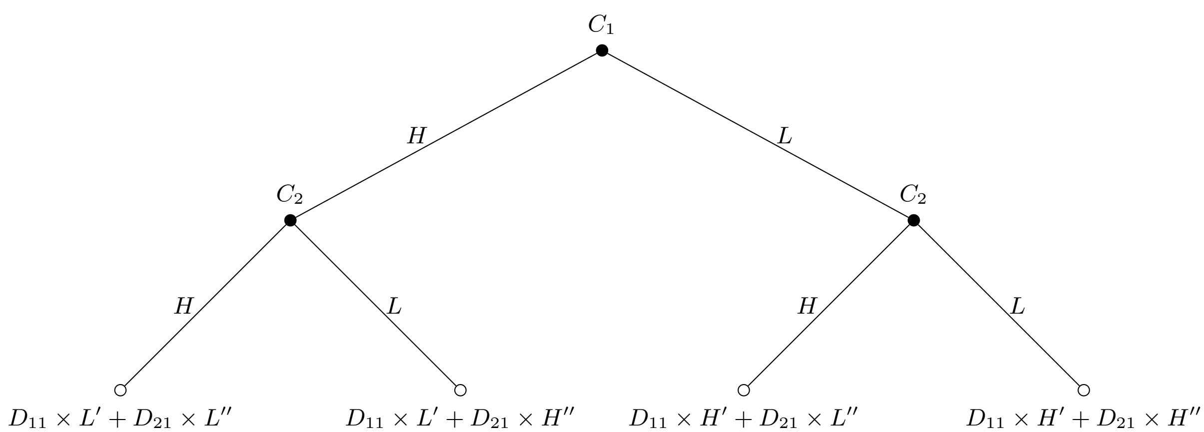

Figure 20: Two period fishery problem with two players from C_1's perspective. H and L stand for high and low levels of harvest now, respectively. H' and L' stand for high and low harvest next period derived from growth in C_1's territory, while H'' and L'' denote the same magnitudes but derived from growth in C_2. D_{11} is the fraction of growth that stays in C_{11}, while C_{21} is the fraction of growth in C_2 that moves towards C_1's territory. The first node from top to bottom shows the set of actions available for C_1, while the second one shows the actions available for C_2.

When we studied games in a reduced form, we analyzed the best courses of action by fixing the opponent's choice. We can follow a similar approach to study this problem as well. To do so, we will first analyze the existence of a dominant strategy. First, fix country 2 to always choose high levels of harvest, denoted as H_2, then the payoffs for country 1 for choosing H_1 or L_1 are:

$$NPV_{H_1|H_2} = H + \beta(D_{11} \times L' + D_{21} \times L'')$$
$$NPV_{L_1|H_2} = L + \beta(D_{11} \times H' + D_{21} \times L'')$$

Now we do the same for the case when country 2 always chooses L_2:

$$NPV_{H_1|L_2} = H + \beta(D_{11} \times L' + D_{21} \times H'')$$
$$NPV_{L_1|L_2} = L + \beta(D_{11} \times H' + D_{21} \times H'')$$

Choosing a high level of harvest would be a dominant strategy if it is strictly more beneficial than choosing low levels of harvest instead. In other words, if choosing high levels of harvest renders a better payoff regardless of the actions of country 2. Translated into math, this statement is analogous to the following inequalities:

$$H + \beta(D_{11} \times L' + D_{21} \times L'') > L + \beta(D_{11} \times H' + D_{21} \times L'')$$
$$H + \beta(D_{11} \times L' + D_{21} \times H'') > L + \beta(D_{11} \times H' + D_{21} \times H'')$$

Rearranging terms, we get that both of these expressions are equivalent to:

$$\frac{H - L}{H' - L'} > \beta \times D_{11}$$

That is to say, we only need the condition above to make high levels of harvest the preferred course of action. Once again, we get the inter-temporal ratio of the difference in harvests levels, where the actions of country 2 do not matter at all. What matters, for our decision, is the discount factor and how much of the stock remains in the country's territory after it grows. The less of the stock that stays in its territory (lower values of D_{11}), the more likely that high levels of harvest will be preferred over the alternative, where country 2 faces exactly the same problem. Therefore, if the discount factor is low enough, and the fraction of the stock that stays in each country's territory is low enough, both of them will have high levels of harvest as a dominant strategy, creating a Nash equilibrium where both countries choose to fish aggressively.

Despite the basic level of complexity of our problem, its insights are quite remarkable and consistent with many explicit theoretical models. Spatial distribution creates perverse incentives that often lead to over aggressive behavior. The lower the degree of control we have on how much stock stays in our jurisdiction, the more aggressive we will behave when making the decision. We can expect similar insights from this model if we were to make the harvest decision a continuous variable.[6] Figure 21 shows a graphical representation of the optimal harvest level in the current period for different levels of site fidelity, or as we denote it before D_{11}/D_{22}. Notice that given a stock level, X, as the site fidelity increases, the intensity of harvest in the current period decreases. Moreover, as the growth rate of the stock increases, it becomes optimal to leave more and more stock in the water for next period.

[6]This model is a two player application of the model proposed by Costello and Polasky (2008) [25].

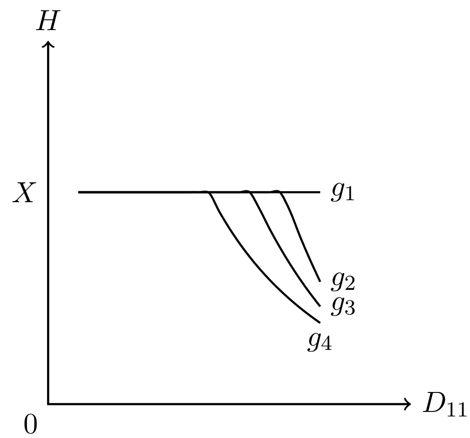

Figure 21: Two-period fishery with two players and continuous harvest decision. The plot shows optimal harvest decisions, H, in the first period as a function of the available stock, X, different net growth rates, g, and the site fidelity of the stock, D_{11}. Net growth rates are numbered in increasing order with g_1 being the lowest and g_4 being the highest.

Now that we have covered case (a) from the previous section, we can move to case (b). Recall that our simple analysis suggested that incentives were different in this case, where the order in which the decisions were made would be very important. First, and as we have done before, let's condition this problem to last only two periods. In the last period, however, both countries agree to split the resource where fraction α goes to country 1, while fraction $1-\alpha$ goes to country 2.[7] This arrangement implies that whatever both countries get in the last period is a function of both of their actions in the current period. Moreover, the actions in country 2 will be conditioned by the actions in country 1, as the stock flows from the former toward the latter. If both countries choose to have high levels of harvest in the first period, the stock will be depleted in the next period, an outcome that is undesirable for both of them. This game is illustrated in figure 22, with the respective second period payoffs shown at the end of each possible path.

As we did before, we should be looking for dominant strategies for each player. This time, however, country 1 is aware of the advantage of choosing harvest before country 2. If a depleted stock is strictly inferior to any other outcome, the only rational response for country 2 when country 1 chooses H, is to choose L. If country 1 were to choose L, however, country 2 will have to compare the two net present values to justify its decision. Analogous to our previous analysis, country 1 choosing H_1 gives the following payment:

$$NPV_{H_1} = H + \beta \times \alpha \times L'$$

When country 1 chooses L_1, the respective payoffs for country 2 are given by:

$$NPV_{H_2|L_1} = H + \beta \times (1-\alpha) \times L'$$
$$NPV_{L_2|L_1} = L + \beta \times (1-\alpha) \times H'$$

[7]Can you think of a reason for why we need this condition? It would be beneficial for you to think about this problem when this arrangement does not exist.

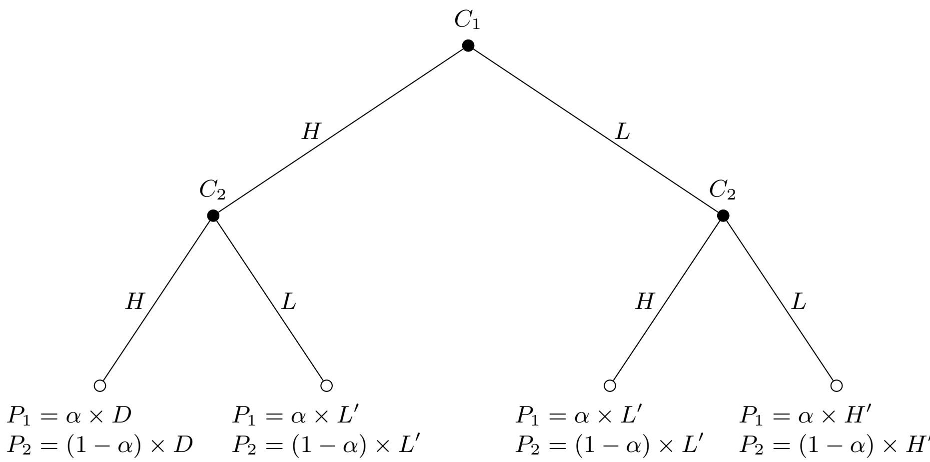

Figure 22: Two period fishery problem with sequential decisions. H and L stand for high and low harvest now, while H', L' and D stand for high, low and depleted next period as a function of how hard the stock is fished in the current period. α is the fraction of the stock that goes to country 1 in the second period. P_1 and P_2 denote the payments in the next period for country 1 and 2, respectively.

In this case, country 2 will choose H_2 if the following inequality is satisfied:

$$H + \beta \times (1-\alpha) \times L' > L + \beta \times (1-\alpha) \times H'$$

Rearranging terms, we get that for high harvest to be the preferred course of action when country 1 chooses L_1, the following condition must hold:

$$\frac{H-L}{H'-L'} > (1-\alpha)\beta$$

Now we are ready to solve the game. If country 2 was to choose H_2 (the inequality above holds), country 1 chooses H_1 if:

$$H > L$$

Which is always true by design. Moreover, if country 2 was to choose L_2, country 1 chooses H_1 if:

$$\frac{H-L}{H'-L'} > \alpha\beta$$

Notice that, for two of the conditions, the equalities on the left hand side are equal for both countries. The right hand side, however, is different. To see how these conditions will dictate the choice for each country, we can play around with the distribution fraction, α. As α (the share that country 1 gets of the stock in the final period) increases (decreases), the more likely country 2 will be to choose H (L) if country 1 was to choose L, which in turn leads to country 1 choosing H, forcing country 2 to choose L instead. In other words, as the share that a country gets in the final period increases, incentives line up to conserve the stock for the associated payments next period. Moreover, given the advantage of moving first, country 1 conditions the game by effectively restricting the feasible set of actions available for country 2. This effect is known as the *first mover advantage*, although it is not always true that moving first is advantageous.

As we did earlier, we can now work with a more complicated version where the harvest decision is a continuous variable in a infinite time horizon. The timing of the problem remains the same, with country 1 choosing its harvest first, then country 2, and then the stock reproduces to re-start the cycle. If each country seeks to maximize its net present value of fishing, the policy function that achieves this objective is linear in the stock. In other words, it is optimal for both countries to harvest a fixed fraction of the stock every period. Those fractions, however, are different across countries.[8] Figure 23 shows a graphical representation of those differences in terms of harvest.

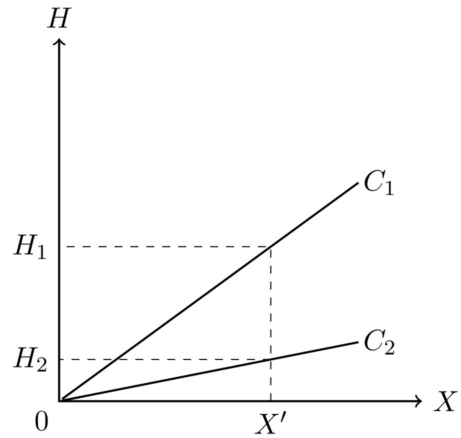

Figure 23: Two country fishery with sequential decisions. The plot shows optimal harvest decisions in the current period, H, as a function of the available stock, X', for both countries, C_1 and C_2.

Unlike the previous cases, where decisions by all agents were implicitly assumed to be simultaneous, country 1 now has the advantage of moving first, which allows it to predict country 2's response to its actions. Country 1, by having high levels of harvest, conditions country 2 to behave more conservatively if it wants to have any rents in the future. Hence, country 2 will always harvest less than country 1 for any level of stock available. In line with our previous insights, time dependent decisions will generate opposite incentives depending on the order and nature of the decision.

In this module, we have covered the principles behind strategic decision when the spatial dimension affects the resource dynamics. By now, you should have all the tools to start thinking about problems of this nature, as well as the associated incentives that arise in each case. More specifically, how distribution dynamics and timing can affect optimal decisions for a given user (country). In the next module, we will see how the concepts we have covered so far are applied in real world experiences and how or why they succeed or fail. Finally, to sharpen your intuition around the role of space in fisheries management, I invite you to try to answer the questions listed below:

- Can you think of some species that fit the characteristics described by cases (a) and (b)?
- From figure 22, what would happen if you extend the length of the game for three periods?
- Using diagrams, can you expand cases (a) and (b) to include a third and fourth agent?

[8]This problem is the Stackelberg competition version of the standard Cournot competition proposed by Levhari and Mirman (1980) [18].

- Can you frame cases (a) and (b) as a closed form game? Can you add uncertainty?
- Can you predict how incentives change as the number of agents increase for cases (a) and (b)?
- Can you think of any mechanism that could alleviate the incentives created by the spatial dimension? Can you add the mechanism into the diagrams?

4 Managing Fisheries

In the previous modules we covered the main concepts behind fisheries models. The main idea is that incentives matter; they matter a whole lot. In any management problem, the users will play according to the written rules and adapt in the best way they can [26]. These management rules and the entities that oversee them are called institutions.

4.1 The role of institutions

From an economic perspective, institutions are the foundations where human behavior takes place. Formally, we can define them as:

Definition 4.1. Economic institutions are the human-devised constraints that shape economic interaction in society [27].

Going back to our first section, our definition of property rights made reference to the ability a certain individual has to consume or transact a certain good or service. Bearing this definition in mind, we can link the concept of property rights directly to the idea of economic institutions: property rights are the fundamental building block of any economic institution [28]. Therefore, when it comes to fisheries, whenever we refer to economic institutions for fisheries, we are referring to the property rights associated with the resource.

When we introduced the static model, we talked about two possible open access reference points: i) economic open access and ii) social open access. The difference between those two was that the first took place in a competitive system where wages in the fishery were equal to the opportunity cost of doing something else, while the other one assumed high levels of unemployment, where the opportunity cost converged towards zero, sinking the wage levels with it. The overarching characteristic, however, was that in both cases of open access, there were no economic or social profits. The incentives behind open access equilibrium, we said, were that as soon as there are rents available in the fishery, individuals would capture them. These actions translate into an increase in effort until there are no more rents left for distribution, making the overall value of the resource equal to zero. Thinking about this problem in terms of property rights means that everyone has the right to enter the fishery, but no one gets an explicit property right over the resource: the fish is yours if you capture it; hence the name open access.

From society's perspective, however, open access may be the least desirable outcome if the rents of the fishery want to be maximized. Intuitively, the first measure to control for this problem is to avoid open access by closing it (i.e., keep some fishers out of the fishery). The extent at which this measure is conducted varies from case to case, but in practice it is hardly ever successful by itself. For instance, fishers are rarely focused on one species only; they tend to diversify their production matrix with all that is available for harvest, and controlling for how fishing effort is distributed across all target species can be practically unfeasible or prohibitively expensive. Even after controlling for effort levels, the property rights associated with access to the resource may still create the perverse incentive to capture all available rents before others, leading to what is known as the *race for fish* [29].

The usual stand for fisheries economists is to maximize the value of the fishery. Nevertheless, it is significantly harder to achieve in practice than to just reduce effort down to the maximum economic yield (MEY) level [30]. This problem often stems from two sources of imperfect information: i) the lack of knowledge with respect to the resource, and ii) the lack of knowledge about the fishing industry itself. Otherwise, the management agency will be able to perfectly oversee and control the fishery towards any desired objective. How to -at least partially- solve these sources of inefficiency is the main goal of the institutional approaches we are going to go cover in the next sections.

4.1.1 Individual Transferable Quotas

Individual transferable quotas (ITQ) are an incentive based measure to control for the inefficiencies that arise from fishing incentives [31]. That is, the incentives for the race to fish when effort control is in place. Analogous to that idea, recall that in our static model the point at which harvest was maximized, MSY, was to the right of MEY. We can think -as many countries do- that maximizing harvest is the desired national policy for its fisheries. Every cycle, the fisheries scientists will inform about the recommended levels of catch for a given stock, the authorities will set the total allowable catch (TAC) for that stock, and as soon as the reported landings meet the ceiling, the fishing season will end. This approach, if followed appropriately, should ensure the sustainability of the stock while ensuring maximum levels of harvest every period.

The problem with a TAC, however, is that it carries the same type of incentives of effort control. Under a pure TAC system, every fisher allowed to fish can fish as much as he wants as long as the season is still open. But every other fisher faces the same incentive as well. From an strategic point of view, it is rational for every individual to take all the necessary measures to outcompete all the other fishers in the system. Usually, these incentives translate into buying bigger and faster boats, or top of the line technology, or any other upgrades that could give individuals an advantage when it comes to fishing [31]. Despite being a rational decision from an individual's perspective, this response usually has negative consequences (i.e., demand for higher quotas, increased fishing costs, extremely short seasons, and a decrease in diversity in the products derived from fishing) [32–34].

When we talk about ITQs on the other hand, we refer to the assignment of a property right over the resource itself, not just the chance to get it (i.e., effort control and TACs). After the TAC is assigned, shares of that total allowable catch are assigned to different members of the fishery, so they can harvest them at their own convenience. By securing the amount of harvest by fixed shares, incentives for the race to fish are diminished, and every individual can choose the best methods and timing to capture their respective share [31]. Moreover, by assigning shares in the form of a property right that continues throughout time, each individual has the incentive for the stock to be in the best shape possible, so that his shares are maximized through time as well. One of the most appealing characteristics of this system, however, is the fact that the value of resource increases with the possibility of transactions between users.

To see how this creation of value works, suppose there are two agents in a given fishery. Fisheries scientists suggest a TAC of T. For starters, let's assume you divide the TAC into two equal parts among agents. The agents, however, are not homogenous when it comes to efficiency. In other words, one of them is able to fish at a lower cost or maybe sell its harvest for higher price. Under these circumstances then, the overall value of the resource will not be maximized if agents cannot trade. Instead of the resource flowing to those who can create the most rents out of it, the resource is locked into whatever distribution the manager decides, in this case half and half. As agents are able to trade, they are expected to ponder on how much to harvest and how much to sell given that they know how efficient they can be. If it is more beneficial to sell or buy a given amount of quota, they will act accordingly.

To illustrate this example, we can make use of a two-sided plot. Figure 24 shows the canonical illustration for the ITQ mechanism when it comes to trading. To read this figure, you have two y-axes: one for agent 1 (left hand side), and one for agent 2 (right hand side). The x-axis, however, shows the quantity of harvest each agent extracts, where the far left (right) extreme would mean agent 1 (agent 2) harvests nothing, and the far right (left) extreme means agent 1 (agent 2) harvests the entire TAC. All points between the extremes would be all possible mixes of harvest between the two agents. MB_1 and MB_2 are the marginal benefits (benefits of harvesting one additional unit of harvest) at any level of harvest for both agents. Both of these relationships tell us that marginal benefits decrease as agents increase their harvest. This condition is analogous to saying that the first units of harvest are very valuable because they are easier to find, that there is a comparatively high willingness to pay as the season opens, or that it becomes very costly to harvest the entire quota by just one agent.

The initial allocation was half and half for each agent. In our figure that point is right at the center of the plot, where each agent gets $T/2$ (figure 24). At that point, however, the marginal benefits that agent 1 receives are far greater than those perceived by agent 2. In that situation both agents will benefit from agent 2 selling quota to agent 1, where the former would be willing to accept any price above his marginal utility at that point, while the latter will be willing to pay any price below his marginal benefit at that level of harvest. Similar to what we observed with the market equilibrium, the point at which the marginal benefit of the two agents intersect will determine the optimal quantities harvested by each agent, Q_1^* and Q_2^*. Furthermore, the price at which they would trade is given by p. This allocation is the one that maximizes the rents of fishery.

The theoretical appeal of this idea is evident. The responsibility of the management agency, besides having the appropriate management institutions in place that ensure the security of the property right, is to establish the TAC every season. Later, the users will trade among themselves seeking their own benefit, and increasing the overall value of the fishery as a result. This outcome, which aligns with our social objective of maximizing the rents of the fishery, is achieved solely out of incentives, and not by the manager actively controlling the level of effort. In our case, we make a couple simplifications, which include having only two users and the condition that the entire TAC should be harvested. Relaxing both restrictions, however, has no implications for the performance of the institutional approach; the total rents of the fishery will always be maximized.

ITQs are very attractive as an intellectual exercise. Nevertheless and away from the white board, they are far from an ideal system. As the spirit of the institution is to establish a property right over the TAC, as soon as factors increasing the difficulty of transfer, capture and protection of the property right over the shares start to arise, the more difficult it will be to achieve and maintain the theoretical benefits discussed above. For instance, this type of institution requires proper stock assessments every season, the legal certainty over the property right throughout time,

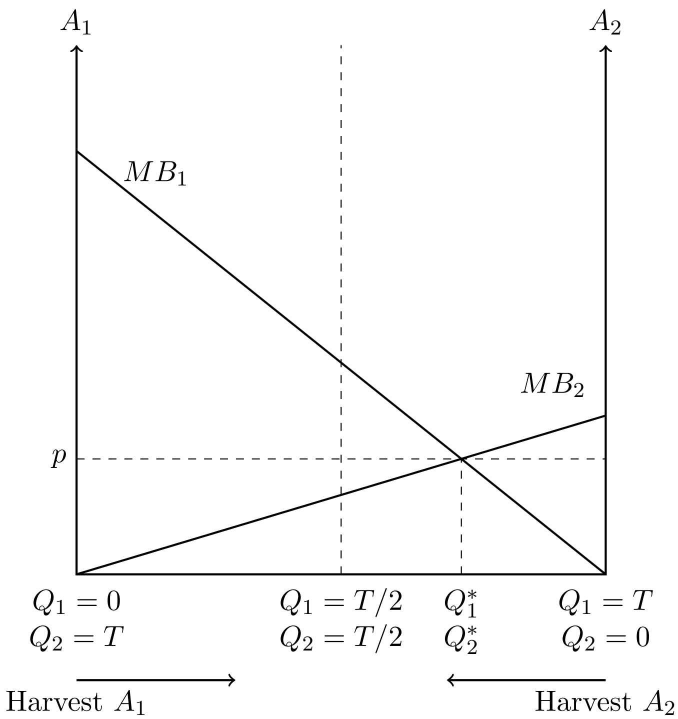

Figure 24: Trade of catch shares between two agents. The plot shows marginal benefits for each agent (A_1 and A_2) on two different y-axis, plotted against the amount of quota each agent harvests, where agent 1 increases harvest to the right and agent 2 increases harvest to the left. T denotes the total allowable catch, while Q_1 and Q_2 denote the respective levels of harvest for each agent. p would be the equilibrium price point at which shares are traded.

and the flexibility for transactions to occur normally. In cases where there are large numbers or extremely heterogenous fishers involved, or when stocks are hard to assess or highly volatile across fishing seasons, the property right granted by the shares weakens, diminishing the overall benefits of the institution.

Another feature that we haven't discussed yet is the issue of inequality. In our market equilibrium example, even though the equilibrium is Pareto optimal, the provision of goods will go to those that value them the most, or those that have the highest willingness to pay for it, while the ones that supply them will be those able to produce them for cheaper. In our ITQ case, trading among individuals will take the resource from those that extract the fewest rents to those that get the most rents out of the same product. More often than not, this flow translates into the rights flowing from small-medium scale fishers toward the high-technology industrial sectors. As most fisheries in the world are thought to be a public good, that in principle belongs to all citizens of a given country, the concentration of fishing permits in the hands of a few members of society can be problematic, and, in some cases, politically unfeasible.

Finally, our example assumes that the initial allocation was to split the resource in half. There are, however, an infinite number of possibilities to distribute ITQs among fishers. The most prominent method is what is known as *grandfathering*. This type of allocation recognizes the history of the fishery before ITQs are implemented, and favors those with a bigger participation by giving them bigger initial shares of the quota. Another potential allocation method is *auctioning*, in which the highest bids get the respective shares of the TAC. The final distribution of the shares is expected to be the same, regardless of how the initial allocation is executed, but grandfathering has three main advantages over the auctioning system: i) rents generated by industry before ITQs will remain within the firms; ii) it lowers the investment levels required to extract the rents from the fishery after the allocation; and iii) it encourages cooperation by those involved in the fishery, effectively reducing costs and information asymmetries [35].

As previously mentioned, ITQs may not be a good fit when we are in the presence of highly heterogenous systems, either in terms of fishers or the resource itself. These characteristics increase the level of transaction costs that may render the establishment of property rights over catch practically impossible. All is not lost, however, because we can still use incentives to guide behavior in a more desirable way. This point brings us to our next topic, TURFs.

4.1.2 Territorial user rights for fisheries

Territorial User Rights for Fisheries, also known as TURFs, have been gaining a lot momentum over the last few years. Two remarkable cases have contributed to this popularity: the experiences in Chile and Japan [36–38]. Far from perfect, both experiences were very successful in taking into account all the sources that increase transaction costs into features that helped the institutional reform: assigning property rights over space for highly heterogenous systems.

The core idea behind the assignment of TURFs, is to allocate exclusive access to individuals (or groups of individuals) to certain geographical areas where they can fish the species of interest. Figure 25 shows a stylized graphical representation of this idea, where the dashed boxes represent a different exclusive access patch (TURF) across the fishing grounds. Notice that not all fishing grounds have to be assigned for exclusive access nor do the TURFs have to be homogenous.

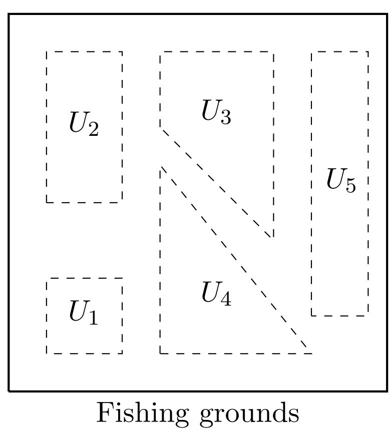

Figure 25: Graphical representation of the territorial user right scheme. The outer box denotes the species habitat, while each of the dashed boxes denotes a exclusive area assigned for a different user, U.

This institutional approach is basically an intent to take concept of land-property to ocean-property. This exercise, however, is not straightforward, as translating the idea of land ownership to the ocean is fairly complicated. When delimiting a certain TURF, we have to take into account that water bodies are not a unified matter: water and many of the organisms in it are constantly flowing in and out of that TURF. Obviously, as the size of the TURF increases, this effect gets reduced accordingly.

Intuitively, this type of institution should be analyzed using our spatial model of fisheries. Recall that according to our findings, spatial distribution of the stock and the timing of movement throughout space create perverse incentives from a fisher's perspective. For instance, the less control a user has over the stock over time, the more intense he will fish the stock. It is only natural then, to suggest that a TURF system will be the most effective for species that have a high degree of site fidelity, or that do not move that much. This is one of the key factors for the success of both the Chilean and Japanese experiences. They effectively granted rights over resources that live in constant contact with the bottom. For fish on the other hand, at least in the Japanese case, co-management is implemented through a series of organizations that ensure the overall stock is exploited sustainably.

TURFs, when designed properly, provide fishers with enough incentives to harvest the resource to maximize benefits, rather than to outcompete other fishers. The problem, however, is to find the best way to grant these rights such that the incentives align with that goal. Analogous to our discussion about ITQs, grandfathering has a series of benefits over alternative allocation methods. Moreover, when mixed with ad-hoc design proposed by the users, which was the Chilean experience, individual TURF design can be greatly improved by the superior knowledge fishers have regarding the resource and its distribution.

As with any experience of establishing property rights over a common pool resource, this institutional arrangement entails giving some users the ability to extract the resource, but also leaving others users without that opportunity. This selection entails that there would be winners and losers, in the sense that the losers may not have exclusive access to the resource, or that the patch that they get may not be as productive as others. Of course, this type of tradeoff would be true for any type of management that seeks to maximize the rents of the fishery, but more often than not, we cannot maximize multiple objectives at the same time [39]. How to take other factors aside from rents into account will be the topic of our last module. To finalize this section, however, you should try to answer the questions below:

- Can you identify the sources of transaction costs for fisheries that have ITQs and TURFs explicitly?
- Why do you think establishing property rights over fishing resources can be difficult from a political perspective?
- Can you think of other types of institutional reform for fisheries? Can you describe the incentives that they create?
- When thinking about ITQs, why do you think freezing facilities oppose this measure?

5 Managing Fisheries, People, and the Environment

In the previous four modules, we talked extensively about how economists rationalize fisheries problems. Up to this point, you should be able to identify the sources of conflict and their associated incentives from the user's perspective. The problem with staying at that level is that we need to consider that reality is far more complex than our theoretical models. The difficulty of establishing proper management institutions can sometimes be either politically or economically unfeasible, hence the high percentage of fisheries that remain under de-facto open access [40]. In this module, we will cover two important issues that make fisheries management more difficult: i) government policy and ii) heterogeneity.

5.1 Government policy

When we studied the different models of fisheries, we made a very important assumption, that the managing entity was benevolent and could easily oversee the fishery. In reality, however, government agencies are highly dynamic organizations for which operations are costly and, at many times, highly politicized. These characteristics imply that management approaches are flexible and will continue to evolve as a function of those those being managed and those who manage. Below, we discuss how to think about these problems and how they translate into the economic performance of the fishery.

5.1.1 The cost of science and enforcement

If you noticed, all of our models took population dynamics and the current stock status as known to both the manager and users. In reality, however, population dynamics are very complicated, and it is virtually impossible to count and measure every fish in the water. Nevertheless, we can still rely on science to gather information that brings us closer to this ideal set of knowledge. The problem, however, is that such information is not free [41]. From basic scientific studies to state-of-the-art stock assessments, all information and studies have a certain cost that is often covered by the government.

Generally speaking, costly fisheries science would not be a problem if the government had an unlimited budget. Nevertheless, governments usually have a very limited budget and an oversupply of social issues for which they are responsible (i.e., health, education, and national security). The importance of fisheries in this realm, is a function of how important fisheries are in a given country's overall economic activity. For most countries, fisheries rank pretty low when compared to other industries (i.e., housing development, commerce, and agriculture).

On top of these issues, we also need to recognize that the natural state of fisheries is open access. As soon as rents become available in the fishery, there will be incentives for users to go and capture them as soon they get a chance. The higher the level of these rents, the bigger the incentive for pursuing the available rents. Having recognized these incentives, the natural course of action is to establish enforcement mechanisms to keep the fishery centered around the management goal. The problem in this case, is that enforcement is not free either, thus further increasing the budget requirements to properly manage the fishery.

Now that we have talked about costs, it is only natural to wonder about the key determinants that make a government decide on necessary measures to manage a fishery. Just looking at pecuniary benefits, it won't make sense for any government to implement any measures that would push the costs beyond the levels of derived benefits. But, if you remember our static model of fisheries, benefits are not constant: instead, they are concave in the level of effort. Moreover, we can use the same model to include the notions of management cost. Figure 26 illustrates these ideas using a graph. In this case, we have assumed that there is a certain management cost (i.e., science and enforcement), TCM, that is independent of the amount of effort; hence, it is a horizontal line.

Total cost of fishing effort, TCE, is assumed to increase linearly with effort, thus it has a positive slope and starts from the origin. The total operational cost in the fishery, TCF is given by the sum of both management and effort costs, adding a positive intercept to the cost relationship in the original static model.

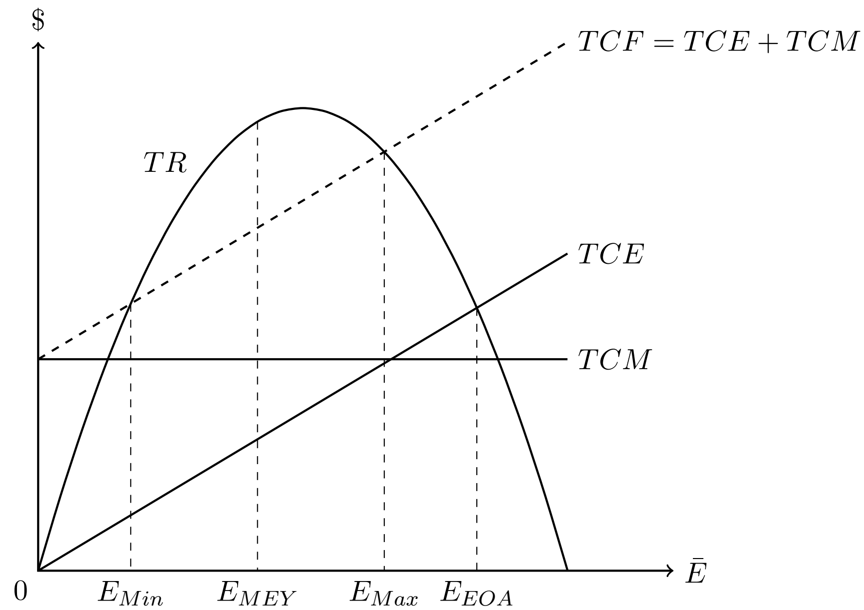

Figure 26: Static fisheries model with management cost. The graphs plot monetary units against effort at equilibrium. TR is total revenue, TCE is total cost of fishing effort, TCM is total cost of management, and TCF is total operational cost of fishery.

Keeping in mind our previous reference points, E_{OA} and E_{MEY}, notice that if the government is to implement management, it will cover the associated costs without ever leaving effort to reach the open access equilibrium point, E_{OA} (figure 26). Instead, the upper bound for effort will be given by the point at which the total operational costs of fishing meets with total revenue, E_{max}. Conversely, it won't be beneficial to have effort levels below E_{min} either, as the costs of management alone exceed any rents generated at such low levels of fishing effort. Notice, however, that since management cost are independent of the effort level, the point at which the pure economic benefits are maximized, E_{MEY}, would be the same point at which the overall benefits of the fishery are maximized as well.

These results are very intuitive. If the government is to fully take into account the pecuniary benefits of the fishery along with its required management costs, it would still choose the level of effort required for MEY. Moreover, these management costs also force the government to maintain the fishery within the profitable range, between E_{min} and E_{max}. It is only natural to suggest that as soon as the potential benefits of the fishery decrease, expensive management from the government's perspective may be undesirable for any plausible level of effort.

This outcome is an interesting theory to explain why proper management is sometimes absent, specially for small-scale fisheries. There are many forces at play, however, and management decisions are not necessarily justified solely on budget balance. It is often the case, especially in the developing world, that authorities seek to manage fisheries for their intrinsic and demographic value.

That is to say, manage fisheries because the activity itself provides value to society and it generates employment. The latter is quite a strong argument and motivation in the political realm. Every single single management decision has to take responsibility for the jobs it creates and destroys. If you recall, open access involves the maximum sustainable amount of effort possible. If effort is to be fishers fishing in the fishery, open access maximizes the amount of jobs associated with the fishery, but no surplus is generated. To deal with the surplus problem, governments usually resort to some type of transfers to fishers, which brings us to our next topic.

5.1.2 Transfers

When we talk about transfers, we usually think about social security and unemployment insurance. Formally, however, transfers can be defined as:

Definition 5.1. Government transfers are the shifts of purchasing power from one group of economic agents to another [5].

Generally speaking, there are two type of transfers: direct and indirect. A direct transfer is basically a payment made to an individual without being a function of his output. Usually, these transfers are known as lump sum taxes/payments, and create no incentive other than to increase consumption. Indirect transfers on the other hand, are transfers that target the production process directly. In other words, these transfers are a function of the individual's actions and usually take the form of taxes/subsidies on the fishing activity. Indirect transfers, unlike direct transfers, create strong incentives that alter the behavior of fishers when it comes to acquiring physical capital and fishing.

To see how these differences arise, we can do a quick thought exercise that illustrates how to think about this problem. First, consider the case in which the government announces a big transfer of public funds to fishers, something like a one-time check of a fraction of their average yearly income. It is uncertain if the government will ever make that payment in the future, so the measure will be expected to be a one-time deal. As there is no relationship between the payment and how productive or profitable fishers are, these type of payments are expected to have minimal effect on the overall fishing activity. In other words, since fishers can still profit from the ocean, they will keep fishing because the rents of the fishery are still available for capture. Some of them may use the government payment to become more competitive (i.e., upgrade their boats), or they will simply channel the additional funds towards consumption directly, the latter being the most common of all. Now suppose that the government implements a tax on landings. Under this scheme, every unit of harvest becomes less valuable, effectively altering the rents generated by the resource, and thus conditioning fishing behavior as a result. Even when this type of tax gets returned to the fishers in the form of public services or a tax refund at the end of the fiscal year, its effect on the fishery has already taken place. Furthermore, suppose that the government decides to impose a subsidy on fuel and the acquisition of capital. This measure directly decreases the cost of fishing effort, effectively changing fishing dynamics as a result of the operation being relatively cheaper.

As we have done previously, we can evaluate the effects of indirect transfers using our static model. Figure 27 shows how a tax and a subsidy can alter the performance of the fishery. First, consider a fixed tax imposed on landings, which is analogous to a proportional decrease in the amount of revenue the fishery can sustain at equilibrium. This effect is shown by the arrows that push down TR toward TR_t (figure 27-a). Notice how the effect of the tax moves the reference points, except for MSY, to the left. In other words, the tax policy makes fishing less profitable, effectively altering the levels of effort associated with open access and MEY. On the other hand, a subsidy on production costs (i.e., fuel price and capital acquisition) effectively leads to a decrease in the relative cost of fishing for any level of effort from TC to TC_s. In turn, this decrease in the fishing cost leads to an increase in the effort required to sustain the reference points.

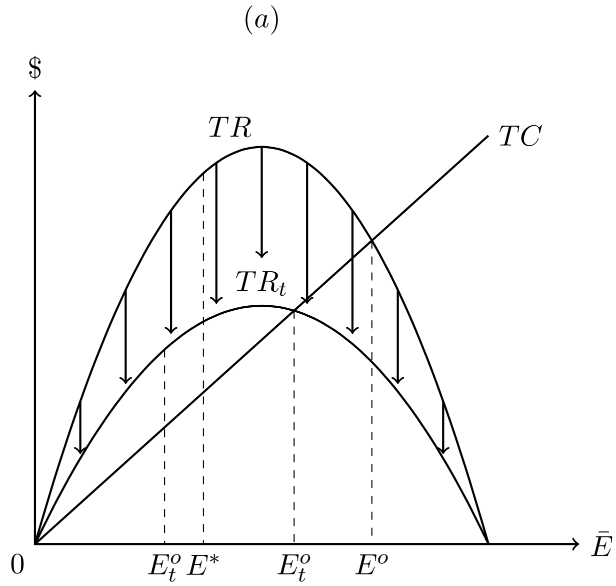

Figure 27: Static fisheries model with taxes and subsidies. Both graphs plot monetary units against effort at equilibrium. TR is total revenue and TC is total cost of fishing effort, upper-scripts (o) and $(*)$ denote open access and maximum economic yield, respectively. Sub-scripts (t) and (s) denote the equilibrium after taxes and subsidies, respectively. Plot (a) shows the effects of a tax on the references points, while plot (b) shows the effects of a subsidy.

The effects of both taxes and subsidies are fairly intuitive. although we won't discuss other versions, additional extensions can be implemented following the same logic above. The bottom line is that both policies modify the level of rents available in the fishery, thus altering the expected behavior of fishermen. Such effects can be of great importance when it comes to invigorating or regulating the industry, especially when we consider transfers from one group to another. Using our previous example, a tax means some of the rents of the fishery will be captured by the government and not by the fishermen. The decision of what to do with that revenue will be a function of both the discretionary policy of the administration and the set of regulations guiding the fiscal policy, which may or not be going back to the fishery itself. The reversed analogy applies to the case of subsidies, the only difference is that government revenue, which may be gathered form other economic activities, is being used to make the fishery more profitable than it would be without interference.

As transfer policies may be a valid way of influencing the status and trajectory of a given fishery, they need to be validated by the agents involved in the fishery. In an ideal world, those will be only fishers who are indifferent to any management decision. In reality, however, the world is much more complicated, forcing policy making to adapt to highly complex and constantly evolving management challenges. This sort of complexity is the main topic of our next and final section.

5.2 Heterogeneity

During the previous sections, we have assumed that fisheries are isolated and only fishermen are important in the decision making process. This assumption cannot be farther from the truth as any fishery is part of an ecological system supported by both land and ocean. Moreover, management decisions in fisheries are likely to influence not only fishers, but also other agents with interests in conservation, development and tourism, among many others sectors. Below we will explore some of them so you can develop the economic intuition for these sources of conflict. The first topic we will review is the case in which there are multiple species involved in a fishery.

5.2.1 Multiple species

Earlier in the notes, we mention that small-scale fishers often target multiple species in their harvesting activities, and unlike many industrial fisheries, searching for more than one species is intentional. Establishing a reference point can be complicated because the levels of theoretical effort that guarantee MSY for one species may be too high or too low for another one. The manager's decision becomes even more complicated as trophic relationships also suffer from the external effects of fishing effort, altering the species composition and its natural age structure inter-dynamics. Under such degree of complexity, and given the nature of the fishing activity, it may be completely unrealistic to expect an ideal outcome in terms of achieving the desirable reference point for every single species that is being targeted. Moreover, if you recall our discussion in section 5.1, management of some fisheries may not be feasible if their associated rents are not able to cover for the expenses that society incurs to regulate them.

A potential solution to this problem is to think about this fishery from an aggregated perspective. That is, to manage the fishery as a whole, rather than just by species. To do so, the manager would still have to collect information regarding the fishery, the relationship between its species, and the effects of fishing effort for each of them. With this information, the manager can establish the desirable goals for the aggregate and implement the required management policies that will move the system towards a certain state. Formally, this can be thought of as managing the global performance of the fishery, rather than the local species-by-species approach.

To illustrate this idea, figure 28 shows a graphical representation of a fishery comprised of three species with different biological characteristics. In this model, species 1 can sustain relatively little effort when compared to the other two. Moreover, species 3 shows the highest individual performance of the fishery. When we look at the aggregated performance (dashed line in figure 28-a), however, the MSY of the fishery does not coincide with the MSY of that single species. This misalignment between individual and aggregated performance means that the reference points will be modified for the whole system: highly productive species will create incentives for increasing fishing effort at the expense of those that are less productive. For instance, in figure 28-b we can see that the aggregate MSY will bring species 1 and 2 above their own individual MSY. Aggregate MEY on the other hand, shows the consistency of requiring less effort than MSY, although with similar effects when we look individual species.

These results are remarkable, and also validated by real world examples [42]. Highly productive species will mask the productivity of others, leading to levels of effort that cannot be supported by the less productive species. When we analyze fisheries around the world, this result is quite powerful in explaining the effect of fisheries in areas with diverse ecosystems and fishing gears with low selectivity. Managers should be wary of the incentives created by this type of dynamics, and

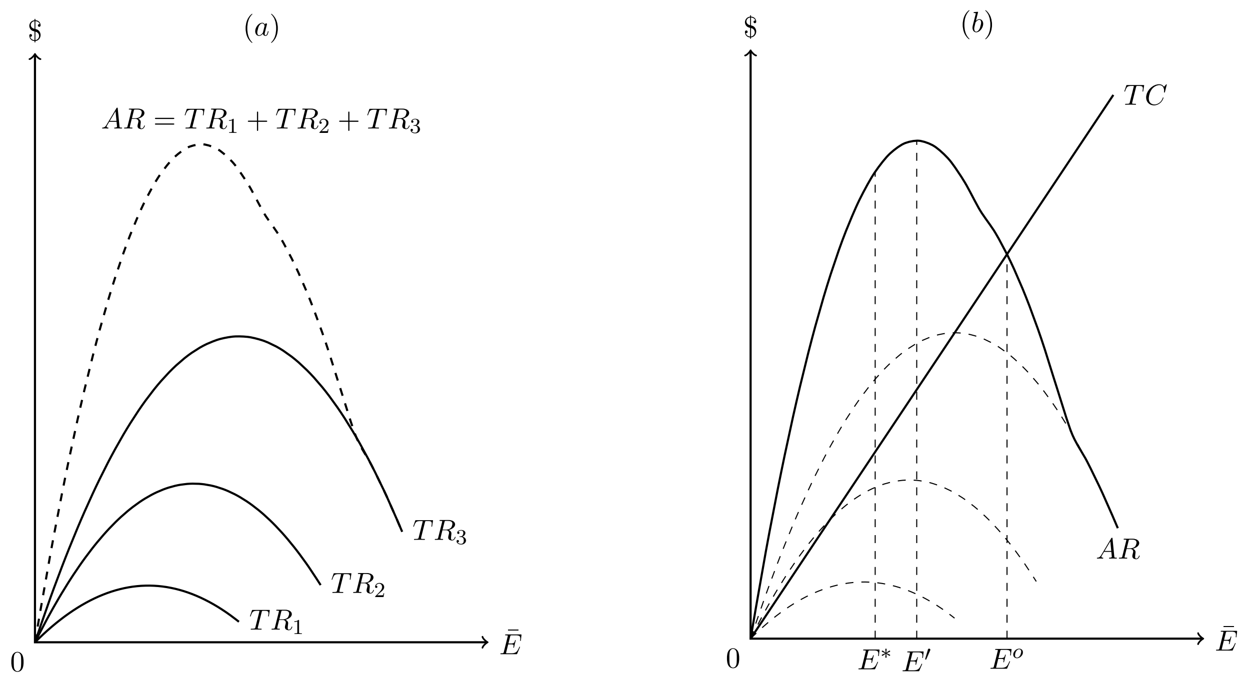

Figure 28: Aggregated revenue for a fishery that targets three species. The graphs plots the revenue sources as a function of the effort in the fishery. TR is total revenue, where the subscript indicates a different species. AR denotes the aggregated revenue for all three species, and TC is the total cost of fishing. Plot (a) shows how the aggregated revenue is constructed, and plot (b) show the reference point at the aggregate level, where the subscripts (o), $(')$ and $(*)$ denote the points of open access, MSY and MEY, respectively.

develop policies that adapt well to these circumstances. One possible approach is to induce control on the amount of harvest of those species with low productivity, either by forcing the use of certain fishing methods, or by implementing a quota system for different species.[9]

5.2.2 Multiple stakeholders

Another common problem in fisheries management comes with the presence of multiple stakeholders. So far, we have assumed that society cares about the economic benefits of fishing, and those benefits only. In reality, however, fishing activities are highly controversial across different sectors of society. Often, different interests from fishers are mutually exclusive, and the interaction with other sectors of the economy such as aquaculture, mining or housing development could facilitate conditions of social turmoil. As economists, we think about this problem in terms of the preferences that different stakeholders have over the resource, its environment, and the agents involved in all relevant activities.

The way in which economists think about the discrepancy between different agents is through the use of *utility functions*. Formally, utility functions can be defined as:

[9] If you are interested in how restrictive quotas work for species of low productivity, you can read the paper by Steve Miller and Robert Deacon for the experience of bycatch quotas in the West Coast ground fishery: `http://www.stevejmiller.com/wp-content/uploads/BycatchIFQs.pdf`

Definition 5.2. A utility function is the representation of an agent's preferences over different bundles of goods and services.

If we apply this definition to a fisheries context, agents can have a set of different preferences over the goods and services provided by both the fish stock itself and the water that it inhabits. For instance, any given fisher may not care about the total economic benefits generated by the fishery, but only about his own benefits, which lead to the strategic outcome that is open access. The manager on the other hand, may not care about the rents at all, but only about the number of jobs created in the system. A conservationist may care only about the jobs generated in the small-scale sector, or about how much of the fishing grounds are being declared as marine protected areas. The role of the manager is to take into account these differences, and to devise policy mechanisms that will induce the best use of the resource in this heterogenous context.

To see how these dynamics can be analyzed from an economist's perspective, we will cover two cases: i) government revenue vs jobs, and fishing profits vs conservation. First, let's consider the case in which a manager has to maximize the government revenue and the number of jobs generated by a given fishery. The first thing to remember here, is that it is often impossible to maximize several objectives at the same time. Nevertheless, we can still establish a set of possible combinations in the fishery by taking into account the relationship between government revenue and the amount of jobs created. Formally, this relationship is known as the *production possibility frontier*:

Definition 5.3. The production possibility frontier describes the technological possibilities between the joint production of certain goods and services in the economy [5].

In our example, the manager cares only about two things: government revenue, which is given by a tax on fishing revenue, and jobs, which are a one-to-one relationship with fishing effort. Figure 29 shows a graphical representation of the production possibility frontier, PPF. First, in plot (a) we see that the government imposes a tax on revenue, so the revenue after tax, TR_t, will be always below the total revenue before tax, TR, thus generating a different level of government revenue, GR, for every different level of effort, E. Recall, however, that the level of effort that supports open access, E_t^o, will be less when compared to the case in which no tax is imposed. Plot (b) on the other hand, shows the PPF between effort and government revenue. To read this graph, suppose that the current state of a fishery, in terms of effort and government revenue is given by point A. This point, however, is in the interior of the PPF, which means that the fishery can actually sustain more effort and generate more government revenue at the same time. It would be irrational for the manager to move point A in any direction other than the arrows depict since her objective is to create jobs and generate government revenue. Any point outside the PPF, however, is not possible. Thus the best the manager can do is to aim for a combination of number of jobs and government revenue that is on the PPF.

Every point on the PPF is different. Notice that both the maximum and minimum amounts of effort entail no government revenue (figure 29-b). Starting at the origin, as effort increases, so does the level of government revenue. Moving up to $\hat{E}$, at point C, the total amount of government revenue would be $\tilde{GR}$. Notice that the same level of government revenue can be achieved with a higher level of effort, $\tilde{E}$, at point B; meaning it would be irrational for the manager to choose point C over B given the characteristics of the fishery. Moreover, it is also irrational to choose any point of effort below $\underline{E}$, because any government revenue achieved by any of the points of the PPF below $(\underline{E}, GR^*)$, can also be achieved with a higher level of effort on the PPF.

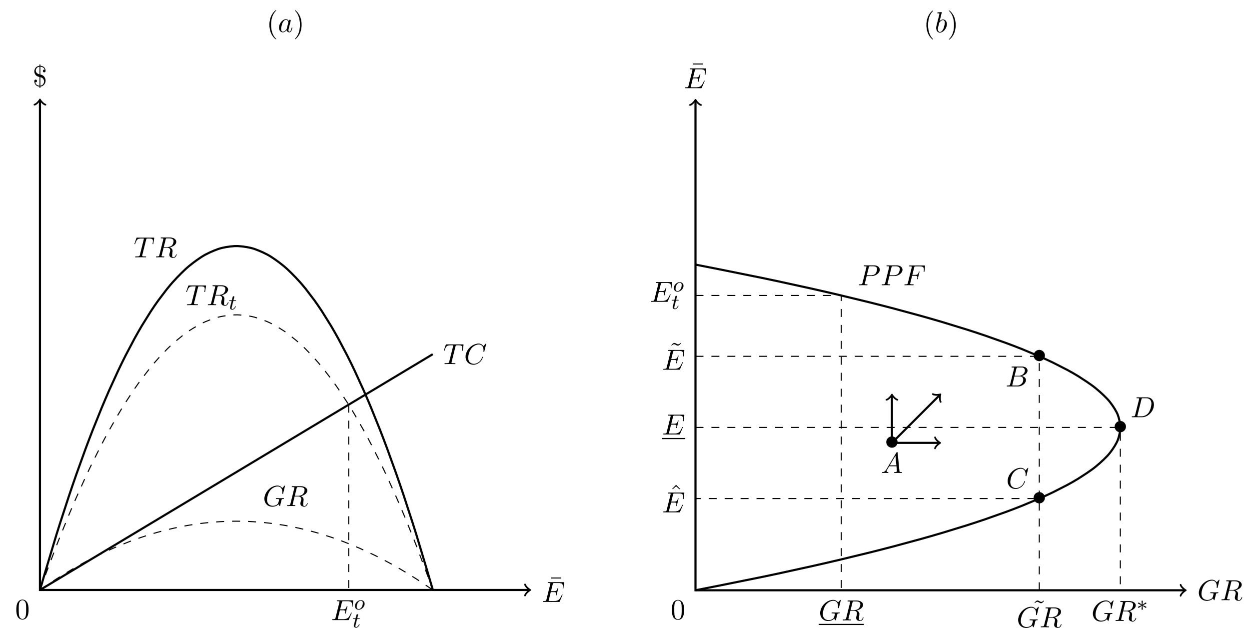

Figure 29: Production possibility frontier with effort and government revenue. GR stands for government revenue, while PPF stand for the production possibility frontier. E_t^0 and GR stand for the level of effort in open access with a tax policy and maximum government revenue, respectively.

The idea of moving along the PPF, or the sacrifice of one good or service for another due to incompatibility, is often referred to as *tradeoff*. The core idea behind this concept is that in order to achieve multiple objectives, we have to make sacrifices. In our previous example, starting from the point of maximum government revenue, D, the only way to achieve a higher level of effort is by sacrificing government revenue (figure 29-b). This need to sacrifice one type of objective for another is arguably the main challenge that any manager will face in his day-to-day activities. Maximizing inputs, in our case, jobs in terms of fishing effort, is often one of the goals that certain administrations will encourage. It would be helpful for you to think about the consequences of such policy on the: i) dissipation of the rents generated by the fishery, and ii) depressed fish stock levels. As we saw earlier, when the fishery consists of multiple species, increases in effort are subsidized by the species that are most productive, and the ones that are not as productive become overexploited or depleted.

Now we can examine our second example. Over the last decades, there has been a growing interest among governments for conservation measures, or the establishment of marine protected areas (MPA). Several advocates argue that MPAs can be used as a standalone fishing management tool, but we should always be aware that the maximization of two or more objectives at the same time is often not feasible. For instance, leaving all fishing grounds open would arguably lead to zero conservation and *vice-versa*. It may be plausible, however, that some amount of conservation may actually be beneficial for fisheries depending on how the spillover effect develops. From an economic perspective, and given that MPAs are not free, it is expected that their potential as a fisheries management tool would be limited to specific cases where other management approaches are less cost efficient (See Section 5.1.1).

Suppose, however, that society decides that there is an intrinsic value to conservation. The manager recognizes then, that there are two sources of value from the ocean: the value from fishing, FV, and the value from conservation, CV. Figure 30 shows the PPF for this example with four points of reference. The first point, FV_0, shows the performance of the system when there is no conservation. At this point, the value of fishing is maximized, but the value of conservation is zero. A law decreeing a marine sanctuary for vulnerable ecosystems will move the system to point A, where there are positive values for both fishing and conservation, where the increase in value for conservation (0 to CV_A) is significantly larger than the loss in fishing value, (FV_0 to FV_A). If more fishing grounds start to get designated as MPAs, we will transition towards point B, where the gain in conservation value (CV_A to CV_B) is still greater than the loss in fishing value (FV_A to FV_B). If we now see a more aggressive policy that pushes MPAs even further to point C, the gains from conservation (CV_B to CV_C) no longer exceed the losses in fishing value (FV_B to FV_C). The same type of analogy is applicable if we were to start from CV_0 where fishing is forbidden.

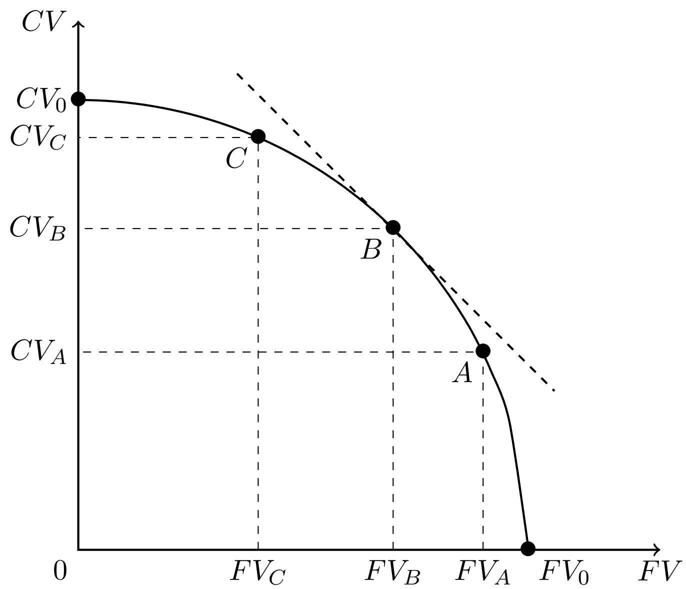

Figure 30: The production possibility frontier for fishing and conservation. The graph plots conservation value against fishing value.

You may have noticed that this tradeoff analysis has an interesting property: there are decreasing marginal returns to increasing conservation and fishing. This is a similar concept to the willingness to pay we covered with market equilibrium: as the supply increased, the willingness to pay for an additional unit supplied decreased accordingly. In this case, the marginal gains from conservation decrease as we lose value in terms of fisheries. In fact, point B in figure 30 shows the level at which the marginal rate of substitution between fishing value and conservation value is one-to-one. In other words, at that point the tradeoff between values is equal, and it would be the desired outcome if society cared about both values equally. If society had other preferences, other combinations would be desirable instead. These other combinations, however, should always take into account both the existence of the production possibility frontier as well as the tradeoffs that take place when moving over the frontier. Moreover, managers should also keep in mind that the frontier can be expanded by technological change and institutional reform.

The tradeoff analysis is a powerful tool when it comes to visualizing gains and losses from different policies. It allows us to compare apples to oranges in a way that is both credible and technically accurate. Moreover, by providing both the total set of possibilities and the individual performance of any given reference point, it informs the decision making process by providing unbiased comparisons across the board for multiple sets of criteria. The final decision, however, is a function of how society's preferences align in any given case, or as we defined it before, society's utility function with respect to the dimensions of interest. To practice these concepts you should spend some time trying to answer the following questions:

- If the cost of management is increasing in the level of effort, what would be the expected effect on the reference points?
- What would happen if the government imposes a tax on profits rather than just revenue?
- In the case of multiple species, what would you expect to happen if all species have similar relative productivity?
- Can you identify a couple reasons for why looking to maximize the number of jobs may be economically inefficient?
- Not all activities are totally incompatible, what would the PPF look like if for the initial levels of conservation there are positive effects in terms of fishing value?

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