3.3 How stocks are at the heart of causality: the case of overfishing

Let's work on an example to illustrate the role of stocks, feedback loops and nonlinear relationships in a systemic structure.

There is rising concern about overfishing in our oceans and seas. Overfishing occurs when more fish are caught than the population can replace through natural reproduction. Today, it is estimated that more than 85 percent of the world's fisheries have been overfished.

We will use an approach to modeling that is espoused by the founder of the system dynamics field, Jay Forrester. We begin by identifying the main stocks and we then build the rest of the systemic structure around them.

Overfishing involves two main stocks: the fish population and the fleet of ships. Now, what makes the fish population increase? Births of course! The number of births per year depends on the size of the population and the hatch rate. The more fish there are in the population, the greater the number of births. The fish population decreases with the number of deaths per year and the catch per year. These are the outflows. The number of deaths per year also depends on the size of the fish population and the death rate. The death rate is higher when the fishing zone is overcrowded or saturated. The level of saturation is simply the ratio of the fish population to the "carrying capacity" of the fishing zone. The carrying capacity is the maximum population size that the environment can sustain indefinitely, given the food, habitat and other necessities available in the environment.

For example, if the zone only has enough food and space to "carry" 100 fish and the population is 80 fish, then the saturation is 80%. When the fish population goes beyond the carrying capacity, the zone gets overcrowded, there is less food and oxygen to share around and the death rate increases. This is a nonlinear relationship.

The catch per year is the total number of fish caught per year. It depends on the average catch per ship and the number of ships in the fishing fleet. The catch per ship depends on the density of the fish population. The more fish there are in a given area, the easier it is for ships to catch them. The density of the population is calculated as the number of fish per square kilometer.

When the catch is sold it generates revenues that allow companies to cover running costs and make profits that they can then reinvest to buy more ships, to catch more fish and to make more profit. The number of new ships purchased depends on the percentage of profits reinvested and the cost price of each ship.

There are two stocks, two nonlinear relationships and six feedback loops in this systemic structure.

Let's look closer at the structure to better understand how overfishing comes about.

We'll start by looking at the top half of the structure. The level of the fish population depends on the net flow of fish into or out of the stock. If births are equal to deaths and the catch per year, then the net flow will be zero and the fish population will remain stable. This is called "dynamic equilibrium", when inflows and outflows are equal. But as soon as the catch and deaths exceed births, the net flow will be negative and the fish population will fall. As the fish population falls, the catch, the saturation, the death rate and the deaths per year also fall.

The catch per year depends on the bottom half of the structure, and in particular the size of the fleet. Two loops influence investment in new ships: a reinforcing loop of revenues from fish sales and a balancing loop of costs from operating the fleet. So long as the industry is making a profit, the reinforcing loop will dominate the balancing loop and new ships will be purchased. The reinforcing loop pushes the growth of the industry. The more money companies make, the more they invest to make even more money. The increase in ships will no doubt push the catch per year higher and higher and lead to overfishing.

Another way for companies to increase or maintain their catch is by using new technologies to "bend" the density-catch curve in their favor. Today, fishermen use under-water radar and other state-of-the-art technology to increase their catch for a given level of fish density. While the curve for traditional fishing technology would look like this, new technology bends the curve like this. The introduction of the diesel engine and the use of refrigeration technologies in the 1940s for example enabled Californian sardine fisherman to follow schools of sardine for much longer periods and further from harbor. These technologies dramatically increased the catch but also accelerated the collapse of the fish stock. We can see the impact of technology on the catch of California sardines. The annual catch increased every year until it went beyond a sustainable level for the industry.

A fishing zone is sustainable when inflows into the stock are equal to outflows. When outflows are greater than inflows, the stock will fall. If this gap gets wider every year with an increasing catch, then the fish stock will decline at an accelerating rate. We'll learn more about these bathtub dynamics in a later unit. The question remains, what can we do to maintain the annual catch at a sustainable level?

We can use computer software to simulate how a complex system may evolve over time and the impact of alternative courses of action. Here I have used a free online software program from insightmaker.com to simulate the fishing model. Let's start with a fish population of one thousand fish and ten ships and run the model over twenty years. When we run the simulation the catch per year increases linearly until the twelfth year when it levels off and then collapses. We can play with our model and test different policy decisions. What if we added a 33% tax on boat purchases to try and slow down the growth of the total fleet? This would increase boat prices from 300 to 400. We can simulate the model once more and see that the stock doesn't collapse until the sixteenth year. There is a link to the online model below. Feel free to play with the model and test alternative actions.

Simulating is fun and necessary to understand how complex systems work. We will learn how to build a simulator in our next unit.