El Nino and the Peruvian Anchovy Fishery

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I. The Finite Resource

> *For it is a universal law that the sea and its use is common to all . . . . For every one admits that if a great many persons hunt on the land or fish in a river, the forest is easily exhausted of wild animals and the river of fish, but such a contingency is impossible in the case of the sea. (Hugo Grotius,* Mare Liberum, *1609)*

People have been catching fish from the sea for millennia, and until fairly recently everyone assumed that the fish supply was almost inexhaustible. This point of view may have been reasonable in the time of Hugo Grotius, when primitive fishing methods made it impossible, for example, for humans to exploit more than a small fraction of the huge stocks of herring and cod that inhabited the shallow seas adjacent to the European coastline. However, the advent of modern techniques for locating and catching fish haws forced a dramatic change in our attitudes. The use of echo sounders and aircraft for locating schools of fish, the construction of nets from synthetic rather than natural fibers, the use of fossil fuels rather than wind and manual labor to move ships and haul nets, and the use of factory ships rather than shore-based facilities to process the catch have combined to vastly increase our ability to exploit the fish resources of the sea.

Because of these technological advances, we must now take special care to manage fisheries in a sustainable way and in particular to ensure that the stocks are not overfished to the point where little or nothing is left for future generations to exploit. The dramatic decline in the numbers of great whales during the 20th century is one clear indication that we now have the capability to reduce some stocks to the point of near extinction. With such a potential to exploit the ocean's resources, we must ask how many fish we can reasonably expect to take from the sea on a sustainable basis.

The present total world catch of fish amounts to about 130 million metric tons (Mt) per year. (A metric ton, sometimes called a tonne, is a thousand kilograms, or 2,200 pounds.) Of this total, about 100 Mt come from marine waters. Of the marine catch, about 85 Mt are accounted for by traditional capture fisheries, with aquaculture making up the difference (15 Mt). For comparison, capture fisheries amounted to about 20 Mt in 1950. Although the increase in capture fisheries since 1950 is remarkable, the fact is that the yield from capture fisheries has been almost constant since about 1985. Fisheries biologists now estimate that roughly 25% of marine fish stocks are overexploited or seriously depleted, about 50% are being fully exploited, and only 25% are underexploited or moderately exploited. This assessment accounts for the yield from marine capture fisheries and has not changed substantially since 1985. The harvest might be increased substantially by reducing the discarding at sea of less preferred species and by fishing unconventional species such as squid, krill, and lantern fish. However, the technology required to catch many of these species is probably too expensive for anyone other than major fishing nations such as Japan and the United States. Hence most of the world, including those countries whose populations suffer serious malnutrition, may benefit very little from the unconventional catch.

The Anchovy Fishery

"Fishery" is the term used to describe the industry that revolves around catching, processing, and selling fish. Although the catch fluctuates from year to year, in general terms the Peruvian anchovy fishery has been the leading fishery in the world since 1960, at least in terms of tonnes of fish caught. During that time, this single species has accounted for about 10% of the total world finfish catch. Since 1960 the catch of Peruvian anchovies (also known as anchoveta) has exceeded the total U.S. catch of all species by about 60%, although the value of the U.S. catch is much higher. In 2001, a typical year, the U.S. and Peruvian capture fisheries harvests were 4.9 and 8.0 Mt, respectively. In that year, 74% of the value of Peruvian fishery exports was accounted for by fishmeal, which was worth about $430 per tonne. In the same year 64% of the value of U.S. fishery exports was accounted for by fresh, chilled, or frozen fish, which was worth about $2,500 per tonne. Overall U.S. and Peruvian fishery exports were worth $3.3 and $1.1 billion, respectively.

In the eastern equatorial Pacific Ocean, both Peru and Chile catch anchovies, with Peru taking the great majority of the fish. Although the economic value of the catch is modest compared to that of fisheries in some other countries, the impact of the anchovy fishery on the economy of Peru has been enormous. Virtually all the anchovies are converted to fishmeal, which is marketed in developed countries such the United States as a component of feed for animals like pigs and chickens, and, perhaps ironically, as an ingredient in aquaculture feeds. The sale of this fishmeal accounted for 25-30% of Peru's foreign exchange in the 1970s. Only the Peruvian copper industry rivaled it as a source of foreign revenue. The anchovy fishery employs about 12,000 people, 10,000 in full-time fishing and the remainder as factory workers. (By way of comparison, Disney World employs 30,000 people.) Although 12,000 people is a small percentage of Peru's population of about 28 million, many of these workers have come from slum areas surrounding Lima and other major Peruvian cities, and the improvement in their standard of living as a result of working in the anchovy industry has been considerable.

Nutritional Value of the Peruvian Anchovy

Peru is a Third World nation, and many of its people are malnourished, with diets deficient in protein. Anchovies are an excellent source of protein, which accounts for more than 40% of the calories in the fish. For comparison, protein accounts for only 15%, 25%, and 35% of the calories in pork, chicken, and eggs, respectively. Furthermore, the amino acid composition of fish protein closely matches the requirements of human beings. Only egg protein is utilized with greater efficiency by humans (see Table 1). Why, then, does Peru convert almost all of its anchovy catch to fishmeal rather than using the fish to feed its people? The answer is that when the anchovies are converted to fishmeal, the value of the catch increases by about 300%. From a strictly economic standpoint it makes more sense to feed the catch to chickens and pigs than to humans. There are also distribution problems. Many of Peru's malnourished people live in mountainous regions or in slums and do not buy their food at commercial markets. Introducing anchovies into their diets would be difficult. If the entire anchovy catch were fed to humans, it would on average provide the minimum protein requirement for 37 million people. In fact there were attempts in the

1960s to convert fish catches into fish protein concentrate, to be added to a variety of products such as soft drinks, toothpaste, and snack foods.

The minimum per capita protein requirement for humans is about 30 grams per day. In developing countries people get about 80% of their protein from grains and vegetables. The percentage of protein in a particular food that is retained by healthy humans is known as the protein utilization efficiency. As Table 1 demonstrates, grains and vegetables have low protein utilization efficiency. The nutritional status of people in developing countries could be greatly improved merely by supplementing their diet with fish protein. The potential nutritional impact of the Peruvian anchovy fishery is enormous. However, the proper economic incentives need to be established before that potential can be realized.

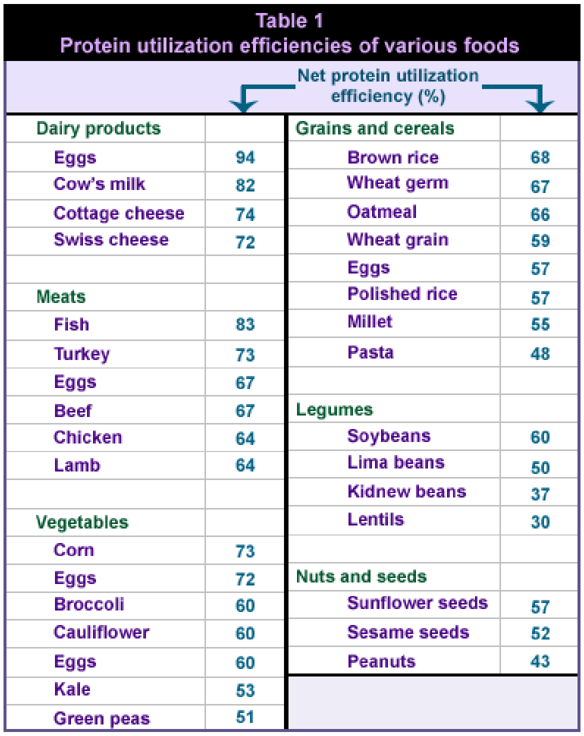

Table 1
Protein utilization efficiencies of various foods

	Net protein utilization efficiency (%)		Net protein utilization efficiency (%)
Dairy products		Grains and cereals	
Eggs	94	Brown rice	68
Cow's milk	82	Wheat germ	67
Cottage cheese	74	Oatmeal	66
Swiss cheese	72	Wheat grain	59
		Eggs	57
Meats		Polished rice	57
Fish	83	Millet	55
Turkey	73	Pasta	48
Eggs	67		
Beef	67	Legumes	
Chicken	64	Soybeans	60
Lamb	64	Lima beans	50
		Kidnew beans	37
Vegetables		Lentils	30
Corn	73		
Eggs	72	Nuts and seeds	
Broccoli	60	Sunflower seeds	57
Cauliflower	60	Sesame seeds	52
Eggs	60	Peanuts	43
Kale	53		
Green peas	51		

II. The Limits of Marine Productivity

Light and Nutrient Limitation

Why have the Peruvian anchovy fishing grounds been so productive? To answer this question one must first understand why most parts of the ocean are much less productive. Almost all food chains in the ocean depend on the photosynthetic activities of plants to convert carbon dioxide into organic carbon, which is the basic building block of organic matter. Photosynthesis requires energy from sunlight to drive the chemical reactions that produce organic carbon. All photosynthesis in the ocean is confined to the sunlit portion of the water column called the euphotic zone. This is somewhat arbitrarily defined to be the portion of the water column above which the irradiance is greater than 0.1–1.0% of the surface irradiance. In the clearest ocean water, the euphotic zone may extend to a depth of about 150 meters. However, dissolved substances and solid particles absorb and scatter light, and in coastal regions the high concentration of these substances causes light to be attenuated rapidly with depth. In such areas the euphotic zone may be only a few tens of meters deep or less. Since the average depth of the ocean is about 3,800 meters, it is obvious that the potential for photosynthesis is restricted to a tiny fraction of the ocean's volume.

In addition to light, plants require certain essential nutrients to carry out photosynthesis. The biomass of marine plants is dominated by microscopic cells called phytoplankton, which must obtain all their essential nutrients directly from seawater. Some of these nutrients are derived from the bacterial breakdown of particulate waste material, or detritus, produced by marine animals. As the detritus sinks through the water column it provides food for other organisms and is eventually broken down into nutrient forms that phytoplankton can use. Although almost all the detritus is broken down into potentially useful forms before it reaches the bottom of the sea, the regenerated nutrients are of no immediate use to plants below the base of the euphotic zone, since there is inadequate light to support photosynthesis. Thus from the standpoint of biological productivity most of the ocean consists of two layers: an upper, sunlit, euphotic zone, where photosynthesis is limited by the supply of essential nutrients, and a lower, dark, aphotic zone, within which nutrients are abundant but photosynthesis is limited by the lack of light (Figure 1).

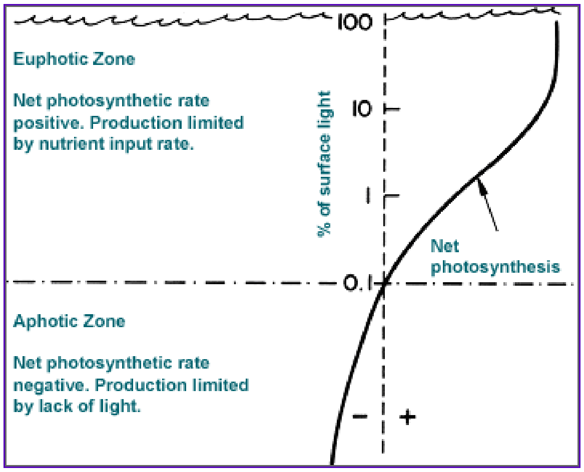

Figure 1. The two-layer ocean model. In the euphotic zone, above the dash-dot line, net photosynthetic rates are positive, that is, the metabolic activities of the phytoplankton lead to a net production of oxygen and organic matter. A typical curve of net photosynthesis is to the right. The base of the euphotic zone is shown here at a depth where the light intensity equals 0.1% of the surface light. In fact, the base of the euphotic zone may vary between approximately 0.1% and 1.0% of surface light, depending on the season and latitude

Nutrient Cycling

Some nutrients that sink into the aphotic zone are buried in sediments at the bottom of the ocean for millions of years, but most are returned to the euphotic zone by advection (i.e., currents) or mixing. Mixing can result from wind-generated turbulence or from cooling of surface waters during the winter. In shallow coastal areas these mechanisms can mix the water column from top to bottom. As a result nutrients are rather efficiently returned to the euphotic zone, and production is generally high. However, in the open ocean beyond the edge of the continental shelves, surface cooling and wind mixing seldom mix the upper water column to depths greater than 500–1,000 meters (Figure 2). Essential nutrients that sink below the depth of mixing are transported slowly throughout the ocean basins of the world as part of the deep ocean circulation, taking 500 to 1,000 years to return to the surface waters.

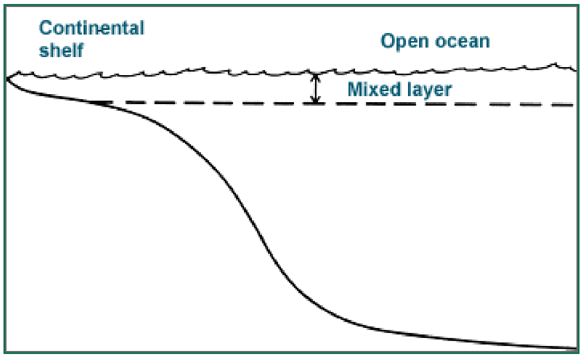

Figure 2. A cross section of the ocean from the seashore to the open ocean. Over at least a portion of the continental shelf the mixed layer extends to the bottom, while in the open ocean the mixed layer rarely accounts for more than a small fraction of the water column.

The distribution in the water column of the essential nutrients nitrogen (N) and phosphorus (P) is illustrated in Figure 3 for a typical open ocean location. Until the development of highly sensitive analytical techniques in the 1980s, the concentrations of N and P in the surface waters of roughly half the open ocean were so low that they were below the limit of accurate measurement. This fact reflects the remarkable nutrient-scavenging ability of phytoplankton cells provided with adequate light. However, nutrient concentrations

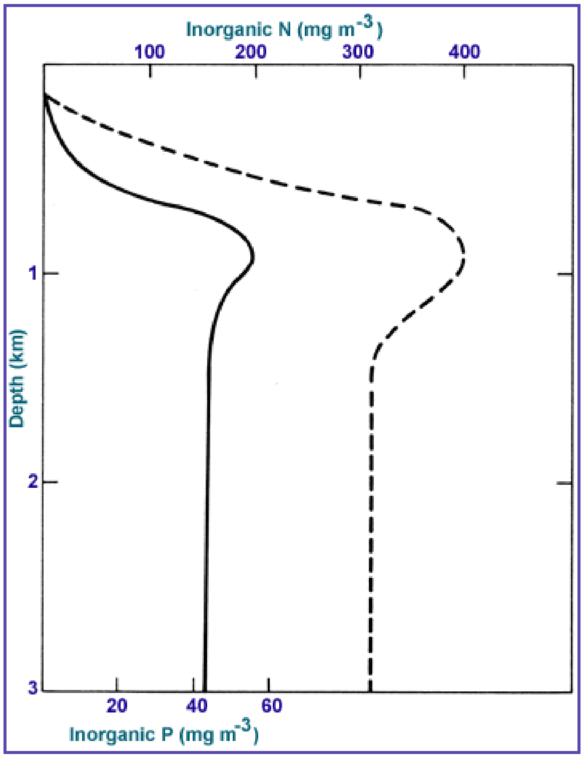

Figure 3. Illustrative profiles of concentrations of two essential nutrients in the ocean, nitrogen (N) and phosphorus (P). Concentrations of inorganic N (dashed line) and P (solid line) in the euphotic zone are often imperceptible on this scale. Deep water concentrations are rather uniform, with the ratio of N to P being about 7.0 by weight or 15–16 by atoms. The peak in the inorganic N and P concentrations at depths of 800–1,000 meters reflects the breakdown of sinking detritus from the upper water column.

begin to increase dramatically near the base of the euphotic zone, where photosynthetic rates and hence nutrient uptake rates become severely light limited. Concentrations of N and P in deep ocean water are several orders of magnitude higher than in surface water.

There is often a sharp gradient in nutrient concentrations, called the nutricline, between the base of the euphotic zone and the uniform deep water concentrations. In many parts of the open ocean nutrients do not diffuse or mix very effectively across the nutricline, and the result is that the mass of living matter (i.e., the biomass) at most open ocean locations is quite low. It is for this reason that most open ocean water is so clear.

The Peruvian Upwelling System

The highly productive Peruvian anchovy fishing ground is located in a coastal area where the sea bottom drops off very rapidly. There is no broad continental shelf to trap nutrients, as is the case along the eastern seaboard of the United States. Therefore the productivity of the anchovy fishing grounds cannot be attributed to shallow coastal water. In fact, along the coast of Peru a process called coastal upwelling dramatically increases vertical water movement, which, in turn, supplies nutrients to the euphotic zone (see Appendix). It is one of the five major coastal upwelling regions in the world, along with those centered along the coasts of California, Namibia, Mauritania, and Somalia. About half the world’s commercial fish come from these areas, even though they make up only about 0.1% of the ocean’s surface area. Upwelling may occur in the open ocean, along the equator, for example, but most important upwelling fisheries are associated with coastal upwelling caused by the effect of surface winds on ocean currents.

The current system off the coast of Peru includes two northward-flowing currents, the Peru Oceanic Current, or Humboldt Current, which extends to a depth of about 700 meters and may be as much as 500–600 kilometers wide, and the Peru Coastal Current, which runs close to shore, seldom exceeds a depth of 200 meters, and is typically no more than 100–200 kilometers wide (Figure 4). Beneath these two currents is the southward-flowing Peru Undercurrent, and to the north is the Peru Countercurrent, an extension of the Equatorial Countercurrent.

Along the coast of Peru the southeast trade winds usually blow parallel to the coastline or offshore at an angle to the coastline. The Coriolis force, caused by the rotation of the Earth, deflects surface water to the left of the wind direction in the Southern Hemisphere and causes surface water to move offshore along the entire Peruvian coastline. The surface currents move at an angle of roughly 45 degrees to the direction of the wind, and the associated movement of water is called Ekman transport. A more detailed discussion of the Coriolis force, Ekman transport, and the global circulation of winds and currents appears in the Appendix.

As surface water moves offshore, it is replaced by water from a depth of 40–80 meters. The upward movement of this subsurface water is slow, about 1–3 meters per day, compared to the speed of the Humboldt Current, which travels about 10 kilometers per day. However, since the top of the nutricline in this area of the ocean is no deeper than 40 meters, the subsurface water brought to the surface contains a high concentration of nutrients, typically a third to a half of the highest values found in deep ocean water. This upward movement of water from depths of 40–80 meters at speeds of a few meters per day is what is meant by upwelling. When upwelled water comes

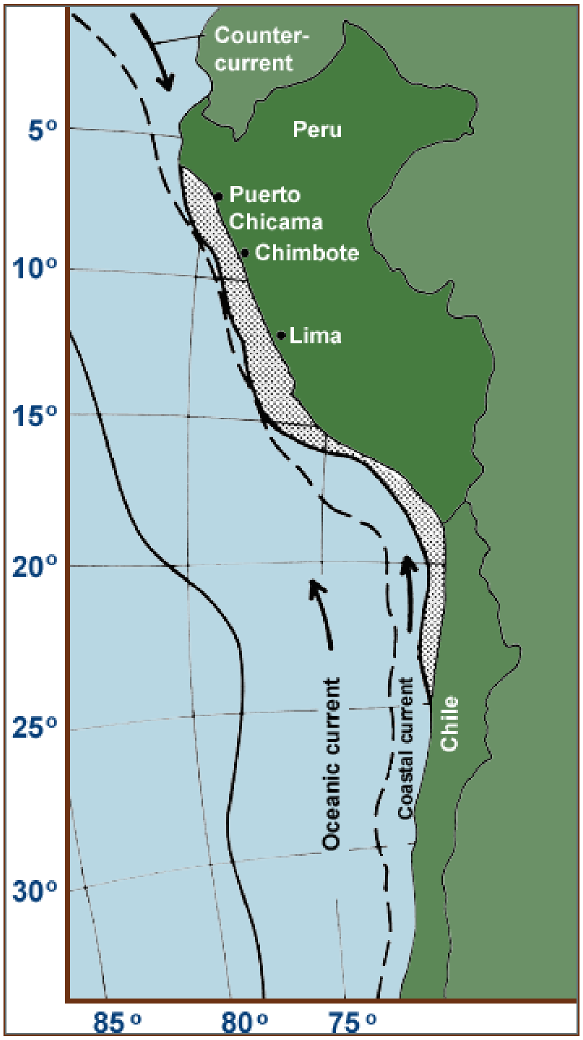

Figure 4. The surface current system off the coast of Peru. The dashed line marks the approximate boundary between the Peru Coastal Current and the Peru Oceanic Current (Humboldt Current). The countercurrent rarely extends more than a few degrees south of the equator except during El Niño. The shaded area is the approximate area of the Coastal Current system occupied by the Peruvian anchovy stocks. The distribution of the anchovy as well as other information suggests that there may be separate northern and southern stocks. Redrawn from Idyll (1973).

from below the nutricline, the result is a remarkable stimulation of biological productivity. In the case of Peru, most of the upwelling occurs within 50 kilometers of shore. It is this upwelling that accounts for the spectacular yields of the Peruvian anchovy fishery.

III. El Niño

Since 1960 the total catch by weight of Peruvian anchovy has exceeded that of any other single fish species in the world, but the annual catch has varied considerably (Figure 5). In the decade between 1962 and 1971, annual yields averaged 9.7 Mt, but the catch dropped dramatically in 1972 and averaged only 1.3 Mt in the decade between 1976 and 1985. Such large variability in fishery yields makes economic planning very difficult in a country that relies heavily on the foreign exchange from this one source.

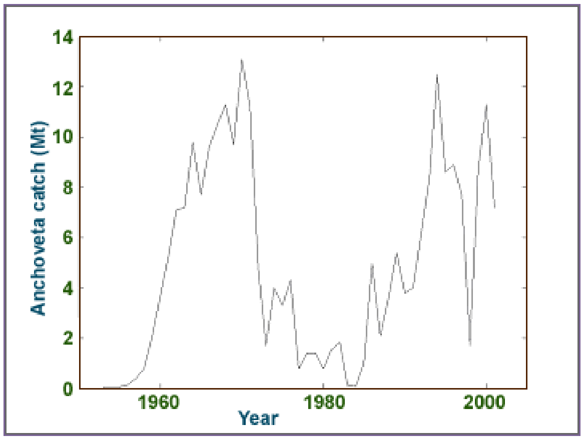

Figure 5. The annual catch of Peruvian anchovy, by weight, since 1953.

One cause of the large fluctuations in anchovy catch is a phenomenon called El Niño, an intrusion of warm, nutrient-poor water from the vicinity of the equator southward along the coast of Peru. The water is transported by the Peru Countercurrent, and in extreme cases may extend as far as 12 degrees S latitude. The intruding water is less dense than the Peru Coastal Current, both because it is warmer (sometimes by as much as 10 degrees C) and because it is less saline (contains a lower concentration of dissolved salts). This lighter water overrides the Coastal Current water in a nutrient-poor layer up to 30 meters deep. During El Niño the coastal wind system sometimes slackens, and upwelling may cease. Alternatively, the coastal wind system and upwelling may continue as usual, but because the nutrient-poor upper layer is so much deeper than usual, the upwelled water comes from above the nutricline and is therefore low in nutrients. From a biological standpoint, upwelling has become ineffective. El Niño conditions have been known to persist for as long as 12 to 18 months. These events usually begin during the Christmas season; hence the name El Niño, which means "the Child" in Spanish.

Biological Effects

During El Niño there is a dramatic drop in photosynthetic rates in the coastal current system, in extreme cases by more than an order of magnitude. This decline in photosynthesis impacts the food supply of virtually all organisms in the coastal current ecosystem. However, not all scientists agree on the impact of El Niño events on the anchovy population. Some scientists feel that the anchovy schools do not die but simply disperse, i.e., the anchovies swim farther offshore and/or into deeper water, beyond the reach of the fishing nets. Either way, fewer fish are caught during El Niño events.

Fish-eating birds are significant and highly visible predators of the anchovy. These birds, regionally known as guano birds, sometimes number in the millions and live on islands off the coast of Peru. Their droppings, or guano, are used as fertilizer. Guano birds include cormorants, gannets or boobies, and pelicans. Anchovies account for 95% of the cormorants' diet and 80% of the diets of gannets and pelicans. Guano birds have a limited ability to fish at depth, so when El Niño occurs, the guano bird population is seriously impacted. The weaker swimmers and divers are unable to find food even if the schools of fish do nothing more than disperse into deeper water. Census data confirm that weak, immature guano birds are decimated by El Niño. In mild or moderate El Niño events, the adult guano birds are still able to find enough food for themselves but not enough to sustain their young as well. They abandon their nests, and their nestlings starve. This may be appropriate evolutionary behavior for relatively long-lived birds, because it allows the adults to use available food for survival rather than reproduction. However, in severe El Niño events, significant numbers of adult guano birds die as well. After the severe El Niño of 1957 the guano bird population, then estimated to be about 27 million, dropped to 6 million. Millions of dead birds washed up on the Peruvian coast. The population gradually recovered in subsequent years and had reached 17 million just prior to the El Niño of 1965 (Figure 6). The population dropped to fewer than 5 million in 1966 and to a few hundred thousand after the 1972–73 El Niño. The population slowly increased to a peak of 6.8 million in 1996, but the birds were decimated by the very strong El Niño of 1997–98. As of 2002 the population stood at 1.8 million individuals.

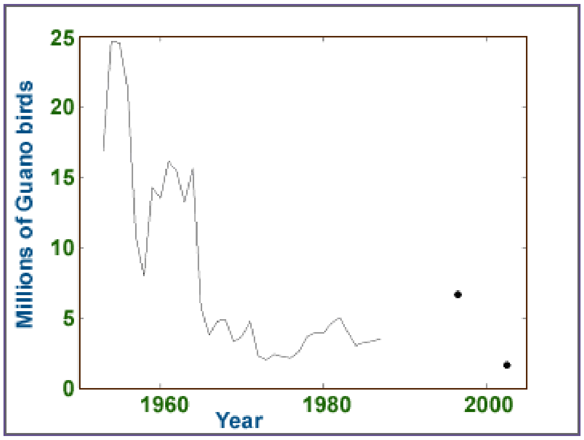

Figure 6. The continuous record of guano bird numbers from 1953 through 1987 and individual data from 1996 and 2002.

During a strong El Niño large numbers of marine organisms also die off the coast of Peru, including fishes, squids, and even turtles and small sea mammals. In some years the decomposition of all these dead bodies may consume the oxygen in the water, and as a result toxic and foul-smelling hydrogen sulfide gas bubbles up through the water and blackens the paint on boats. Although some geographical redistribution of the Peruvian anchovy population may occur during El Niño years, the catch of anchovies by Peru's southern neighbor Chile does not increase during El Niño events. In years when Peru's anchovy catch has dropped below 2.0 Mt, the catch of anchovies by Chile has never exceeded 0.32 Mt. A strong El Niño drastically reduces or eliminates the fertilization of the ocean off Peru by upwelling. The result is a radical drop in the supply of food for all animals in the ecosystem. It seems improbable that a compensatory food supply would be waiting to the south.

While it seems logical to assume that El Niño adversely affects the population dynamics of the anchovy, experimental data do not support this conclusion. Scientists have estimated mortality due to guano birds, mackerel, etc., and subtracted it from the apparent natural mortality of the adult anchovies. What is left, the unexplained mortality, is called baseline mortality. In other words, baseline mortality is the natural mortality unaccounted for by known predators. The natural mortality rate of the adult anchovy from 1953 to 1981 is shown in Figure 7. The average was 16% per month. Baseline natural mortality includes the effects of starvation. During the 1953–1981 period moderate El Niños occurred in 1953, 1965, and 1976, and severe El Niños occurred in 1957–58 and 1972–73. Above-average natural mortality did occur during the El Niños of 1953, 1957–58, and 1976, but only the 1976 deaths can be attributed to

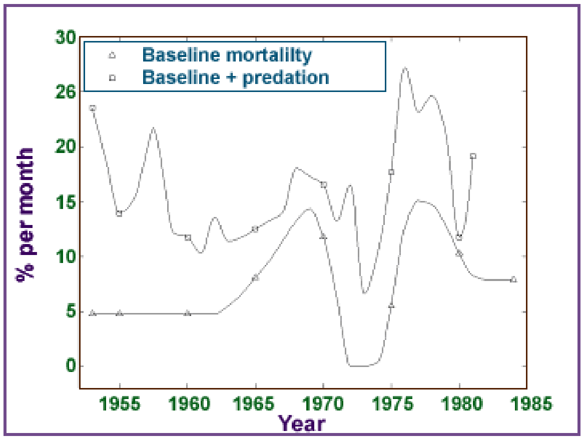

Figure 7. The mortality rate of the Peruvian anchovy from 1953 through 1981. Baseline mortality is natural mortality unaccounted for by predation.

factors other than predation. Furthermore, the lowest rate of natural mortality occurred during the severe El Niño of 1972–73, and natural mortality was below average during the 1965 event. What is the explanation for this pattern?

The high natural mortality that occurred during 1953 and 1957–58 can be attributed largely to horse mackerel, which are believed to be the principal predators of the Peruvian anchovy. The increased threat from horse mackerel may well be related to El Niño. In the absence of El Niño, horse mackerel, which prefer water temperatures of about 20 degrees C, are most likely to be found 100–150 kilometers from shore. This limits their access to anchovies, which prefer the cooler waters nearer the coastline. However, when El Niños occur, the horse mackerel move to within 50–100 kilometers of shore, and the overlap of their distribution with that of the anchovy may increase considerably. The response of the anchovy to an El Niño event depends on the event's severity. In some cases only a portion of the anchovies' habitat is overrun with warm water, and they concentrate in the remaining cold water near the coastline. In other cases the cold surface waters completely disappear, and the anchovies dive to deeper water and disperse. Obviously which way the anchovies respond can very much influence their vulnerability to human fishing as well as to horse mackerel, guano birds, and other predators. In any case, large numbers of anchovies do not seem simply to starve to death during El Niños.

One important influence on the size of the adult population is the maturation of juveniles. In fisheries management juveniles are considered to have become adults when they reach a certain size or stage of development. At that point the juveniles are said to have been "recruited" into the adult stock. Figure 8 shows the average monthly recruitment of anchovies to the adult stock, here defined as those anchovies longer than 4.25 centimeters, from June 1953 to November 1981. During this period there were two moderate El Niños (1965 and 1976) and two severe ones (1957–58 and 1972–73). Recruitment was poor during the 1976 El Niño but excellent during the 1965 El Niño, and recruitment was actually as high or higher during the severe 1957–58 El Niño as during the

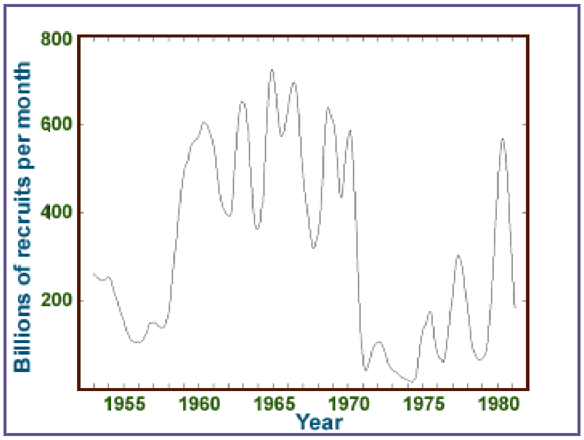

Figure 8. Monthly recruitment to the anchovy stock from 1953 through April 1982. The data have been smoothed using a 12-month running mean to filter out seasonal effects.

preceding three years. There was poor recruitment during the devastating 1972–73 El Niño, but recruitment the preceding year was even worse. There was a very severe El Niño in 1982–83, but again the decline in recruitment preceded the arrival of El Niño conditions. Thus it is difficult to support the argument that an El Niño is a major determinant of the decline in anchovy recruitment. Annual recruitment was actually rather stable (i.e., varied by less than a factor of 2, during the decade of the 1960s, and the adult population was relatively large (Figure 9). By the same token, the absence of an El Niño event is certainly no guarantee of good recruitment, the poor recruitments of 1971, 1974, and 1979–1981 being cases in point. There are reports that anchovies appear emaciated during El Niño, and they probably do not grow as rapidly as they would otherwise. However, at some stages they can survive for as long as six months to a year with a generally reduced food supply. The fact that recruitment does not show any clear correlation with El Niño means that factors other than the overall level of primary production in the Peru Coastal Current are important determinants of the survival of juvenile anchovies. The threat from predators such as other fish, birds, and humans may be as important as food supply.

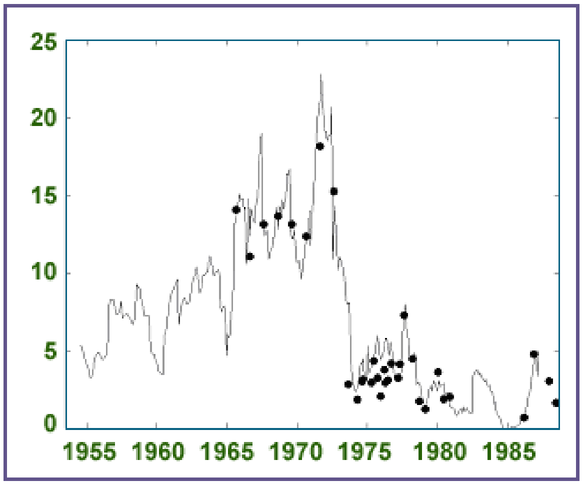

Figure 9. The biomass of Peruvian anchovies from 4–14 degrees S latitude from 1953 through 1985. The dots are estimates based on actual surveys. The continuous line was estimated from a population dynamics model.

There is good reason to believe that predation of adult anchovies by guano birds declines during El Niño events. It is possible that during some El Niño years reduced food supplies may be more than offset by a decline in the threat from the important juvenile predators, which include copepods (small shrimp-like crustaceans) and arrow worms (small, transparent, worm-like animals).

Since 1970 catches of adult anchovies have declined during El Niño events. In the past it was assumed that this reflected a decline in the size of the anchovy stock due to El Niño. However, the declines of the stock during both the 1972–73 and 1982–83 El Niños were caused in large part by a combination of previous heavy fishing and recruitment failure preceding the El Niños. So the catch would have been reduced even if there had been no El Niño.

The El Niño Cycle

The history of El Niño events has been reconstructed from as early as 1525 using proxy information, and the record indicates that they occur about every 4 years, with strong events separated by an average of 10 years. Unfortunately for purposes of prediction, the interval between El Niño events is very irregular. It is not uncommonly six or seven years, but some events have been separated by as little as one year. The most recent El Niños occurred in 1957–58 (strong), 1965 (moderate), 1969 (weak), 1972–73 (strong), 1976 (moderate), 1982–83 (very strong), 1986–87 (strong), 1991–92 (very strong), 1993 (weak), 1994 (weak), 1997–98 (very strong), and 2002–03 (moderate).

At one time El Niño was regarded as an abnormal event. However, scientists currently view El Niño as simply one phase of a natural cycle that occurs over several years and see it as no more usual or unusual than the conditions during any other phase of the cycle. Furthermore, they now recognize that the changes in climate observed during El Niño years along the coast of Peru are simply a local manifestation of a much larger phenomenon, which is driven by interactions between the ocean and atmosphere in the equatorial Pacific.

IV. The Ecology of the Peruvian Anchovy

The Peruvian anchovy population is confined largely to the Peru Coastal Current system (see Figure 4). The population distribution and some indirect evidence based on feeding behavior and anatomy suggest that the population off Chile and southern Peru may be genetically distinct from the fish off central and northern Peru. The northern stock is normally much larger and accounts for most of the anchovy catch. The Chilean anchovy catch averages 10–15% of the Peruvian catch.

The Peruvian anchovy has a relatively short life span that rarely exceeds four years. In the presence of the fishery, few anchovies survive beyond the third year. Although anchovy in the Peru Coastal Current spawn to a certain extent throughout the year, about 80% of the spawning occurs from July to November, with a peak in September and October. A secondary peak during February and March accounts for about 10% of spawning. The young anchovies grow rapidly and are recruited to the fishery (become large enough to be caught by fishing nets) when they are about five months old. At that time they are 8–10 centimeters long and weigh about 2 grams. A full-grown adult may be as much as 20 centimeters long and weigh about 55 grams. The new recruits to the fishery are therefore very lean compared to the adults, but they gain weight rapidly and weigh almost 25 grams by the end of their second year (Figure 10).

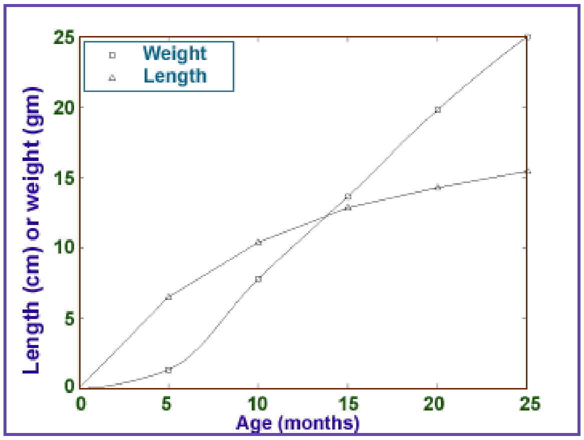

Figure 10. The length and weight of Peruvian anchovies as a function of age to age 25 months. Source of data: Paulik (1971).

Phytoplankton are minute aquatic plants on which anchovies feed. Many of the phytoplankton in the Peru Coastal Current form long chains or gelatinous masses of cells that are easily filtered from the water by the gill rakers of adult anchovies. Hence the adult anchovies are basically herbivores (plant eaters), although they eat zooplankton (minute aquatic animals), fish eggs, and larval fish.

The feeding relationships among organisms are often depicted as constituting a food chain in which functional groups of predators and their prey form successive links. At the bottom of the food chain are plants. These are consumed by herbivores, which in turn are eaten by primary carnivores, which are eaten by secondary carnivores, and so on. At each step in the chain, some food is converted to energy or excreted by the consuming organism, making it unavailable to the next organism up the chain. Aquatic organisms typically convert about 20% of the food they eat into biomass. The fact that anchovies are largely herbivorous accounts in part for the remarkable productivity of the anchovy fishery. The potential yield of the fishery would probably be at least 5–25 times smaller if adult anchovies functioned as primary or secondary carnivores, respectively.

The anchovies become sexually mature and begin spawning when they are one year old. The species is very fecund. A typical two-year-old female may produce 15,000 eggs in a single spawning and may spawn 24 times per year. However, very few of the released eggs survive. More than 99% die in the first month from starvation and predation. Many fish eggs contain sufficient yolk to nourish the larvae until they have a chance to develop their swimming and sensory capabilities. By contrast, the Peruvian anchovy's eggs contain almost no yolk, and the larval fish have only enough energy for a few wiggles before they must begin to feed. Many starve. The survivors have been fortunate enough to find themselves in a patch of food such as protozoa or zooplankton larvae. The high concentrations of plankton in the patches of upwelled water along the Peruvian coast are thus crucial to the survival of the larval and juvenile anchovies.

The anchovies that do not starve are subject to predation by a variety of zooplankton and small fish. In fact even adult anchovies will eat larval and juvenile anchovies, and predation by their own species may be one of their chief causes of mortality. As many as 2,200 anchovy eggs and 180 anchovy larvae have been found in the stomach of a single anchovy. Once the anchovies are five months old, their rate of natural mortality usually falls to about 16% per month, with horse mackerel and mackerel being the most important predators, in that order.

V. Fisheries Management

Renewable and Nonrenewable Resources

A renewable resource is one that can be replaced as fast as it is exploited. A nonrenewable resource is one that cannot. Petroleum and metal ore deposits are generally considered to be nonrenewable, because current rates of human use almost certainly exceed the rate of natural formation.

A fishery is generally assumed to be a renewable resource. If we remove a small number of fish from the population in a given year, those fish will be replaced the following year by offspring of the remaining adults. We now have the capability, however, to kill many species of fish (and other land and sea animals) faster than biological processes can replace them. Without proper management, such resources are effectively nonrenewable and may become extinct. What is the best way to manage a renewable resource such as a fishery?

The Concept of Maximum Sustainable Yield

There are many approaches to analyzing the exploitation of fish populations. We will focus on one of these, the concept of maximum sustainable yield, and will discuss both its merits and its drawbacks. The most common goal in fisheries management is to maximize the sustainable yield from the fishery. A sustainable yield is a yield that can be achieved year after year. For example, we could harvest 1,000 tonnes of Peruvian anchovies year after year from the waters off the coast of Peru without threatening the existence of the anchovy population. Such a harvest would be a sustainable yield. We could also harvest 2,000 tonnes of anchovies without threatening the anchovy population. Thus, while 1,000 tonnes of anchovies per year would not remove the resource faster than it could be replaced by biological processes, such a harvest would not be the maximum sustainable yield.

Figures 11–13 provide a useful way to visualize the strategy of maximizing sustainable yield. We focus our attention on the population of fish large enough to be caught in nets. In the case of the Peruvian anchovy, this would include all fish older than about five months. The number of fish in this population can change as a result of recruitment (R), natural mortality (M), or fishing mortality (F). If the population is to remain stable, the number of fish recruited to the population must balance the number of fish lost to natural mortality and fishing mortality (R = F + M). In the absence of a fishery, the population is stable when R = M. The population before there is a fishery is referred to as the virgin stock. Once the fishery begins, two changes almost always occur. First, the size of the population is reduced. Second, recruitment begins to exceed natural mortality, for reasons that are discussed below. The difference between R and M at a given population size is the sustainable fishery yield F. In other words, F = R – M. F is equal to the length of a

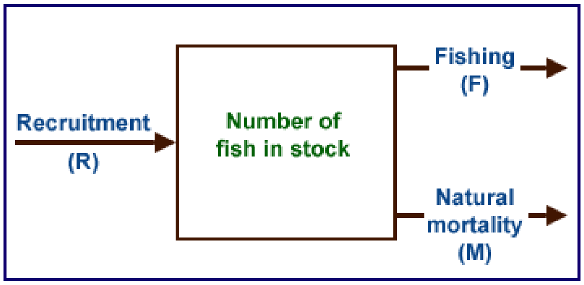

Figure 11. A model (the Schaefer model) used in the management of a commercial fish stock. The only input to the stock is assumed to be recruitment. The outputs are natural mortality and fishing mortality.

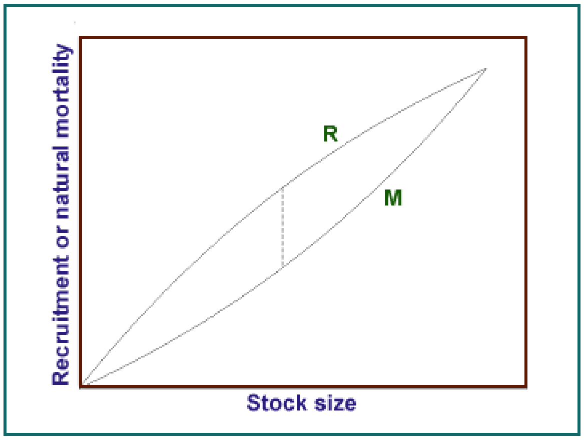

Figure 12. One possible relationship between the size of the stock of adult fish and recruitment and natural mortality. The vertical distance between the R and M curves represents the sustainable fish catch at the given stock size. The maximum sustainable catch is indicated by the dashed line.

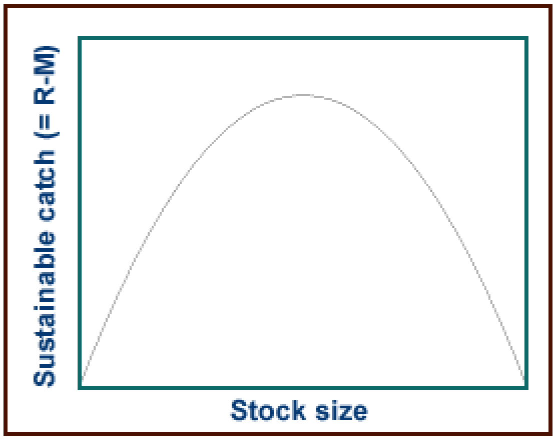

Figure 13. The sustainable catch (= R – M) versus the size of the stock of adult fish derived from the curves in Figure 12. In this case the maximum sustainable yield is attained at a stock size equal to half the size of the virgin stock.

vertical line between the R and M curves in Figure 12. Obviously both R and M are zero if there is no adult population, and the difference between R and M is zero if the size of the population equals the size of the virgin stock. Hence the sustainable fishery yield F is zero in these two extreme cases. However, as depicted in Figure 12, F is positive at all intermediate population sizes, and when F is graphed as a function of the population size, it appears roughly as in Figure 13. As a very rough guide, one can anticipate that the maximum value of F will occur when the population has been reduced to about half the size of the virgin stock.

The Resource-Limited Population

Why might one expect the R and M curves to behave as depicted in Figure 12? Let us consider the M curve first. Obviously fish that are caught cannot also die from natural causes. From that standpoint alone one would anticipate that M would decrease in the presence of a fishery. Furthermore, for many adult fish populations older fish have a greater chance of dying of natural causes than younger fish. In the presence of a fishery, the chances of a fish reaching old age may be greatly reduced. For example, assume that a certain species of fish has a life span of ten years and that virtually no fish die of natural causes between the ages of two and six. Assume that fish are recruited to the fishery at two years of age and that about 20% of the adult population is caught each year. The probabilities that a recruit will reach three, four, five, and six years of age are shown in Table 2. There is

TABLE 2

Probability of survival for a fish recruited at age 2 years and with an 80% chance of surviving each subsequent year of life

Age of fish	Probability that fish will reach the give age (%)	
2	100	
3	80	
4	64	
5	51	
6	41	

now only a 41% chance that a recruit will reach six years of age, and so the natural mortality rate is sure to drop by at least a factor of 1/0.41 = 2.4 in the presence of the fishery. The actual drop would be even greater, because the probability that a fish will reach an age of seven to ten is reduced by a factor of three to six, respectively, in the presence of the fishery. The actual drop in M would depend on the probabilities of natural mortality between the ages of six and ten. Finally, many fish populations are resource limited. In other words, the availability of food, shelter, and desirable habitat limit the distribution and biological productivity of the species. In the absence of competitors for these same resources, when the size of the population is reduced, more resources become available to the remaining fish. If some fish had previously been in marginal habitats, the population might contract into the more desirable areas. In any case, a greater availability of resources, including food and shelter, could certainly reduce the rate of natural mortality.

As the population is reduced below the size of the virgin stock, R is not expected to decline as rapidly as M, and in the case of cannibalistic fish like the anchovy, a modest drop in the population size may actually increase R. In fact, studies conducted by fisheries biologists in Peru indicate that a decrease in population leads to an increase in recruits until the population is reduced to less than half the size of the virgin stock (Figure 14). However, even if R and population size are positively correlated at all levels of population size, the same arguments about habitat and resource availability that applied to natural mortality are pertinent to recruitment. If a decline in the number of adult fish causes the population to abandon marginal habitats, and if more resources become available, then there is a greater probability that the offspring will survive the critical egg and larval periods and be recruited into the adult stock.

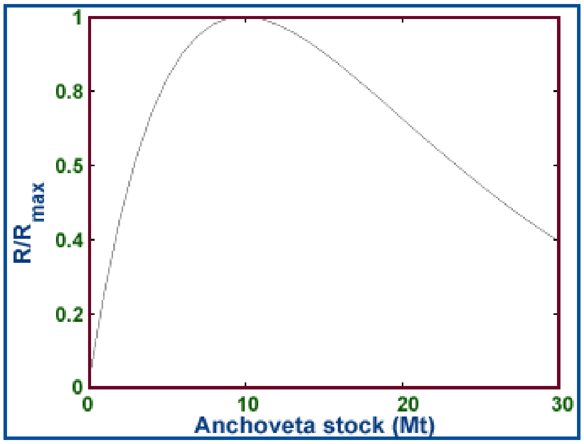

Figure 14. Relationship between recruitment and the size of the anchovy stock deduced from field data analyzed by Csirke (1980). R_{max} is the maximum value of R. The negative correlation between R and stock size at stock sizes greater than about 10 Mt reflects the cannibalistic behavior of the anchovy.

Problems with the Maximum Sustainable Yield

The Beverton-Holt and Schaefer Models. Although the maximum sustainable yield may seem to be a logically appealing goal of fisheries management, there are unfortunately significant problems with both its implementation and its theoretical underpinnings. For a start, given a real population of fish, how do we decide what the maximum sustainable yield is? There are basically two approaches. First, we can assume that we know enough about the dynamics of the population to predict R and M as a function of population size. This approach is usually associated with the names of the two fisheries biologists who pioneered its use, Ray Beverton of the

Fisheries Laboratory in Lowestoft, Engla`nd, and Sidney Holt of the United Nations Food and Agriculture Organization in Rome, Italy. The problem is that it is difficult enough to determine what R and M are under a given set of circumstances, let alone what R and M may become as the population size changes. Information from controlled experiments, in which the population size is systematically changed and the population dynamics given sufficient to stabilize, is virtually nonexistent. Therefore, in practice, one finds that application of the Beverton-Holt model to estimate maximum sustainable yield usually involves a good deal of educated guessing.

The second approach is to ignore the population dynamics and just plot fisheries yield against population, as in Figure 13. This model of fisheries management is associated with Milner Schaefer of the Scripps Institution of Oceanography in La Jolla, California, the biologist who first advocated its use. The practical problem with the Schaefer model is that because of ongoing fishing the population is virtually never given sufficient time to come to equilibrium. Hence the catch for a given year usually does not represent the sustainable yield that could be achieved at that population size.

Highly Variable Recruitment. In addition to these practical problems with implementing the maximum sustainable yield, the concept itself has been called into question. The three theoretical issues most often mentioned are the temporal variability of recruitment, the presence of competitors, and the catch of sexually immature fish. Temporal variability in recruitment is a characteristic of many of the world's important commercial fisheries, because marine fish, including the Peruvian anchovy, tend to spawn at certain seasons. This behavior is typical of the gadoids (cod, pollock, haddock, hake, and their relatives) and clupeids (anchovies, sardines, herring, and their relatives), the two groups of marine finfish that account, by weight, for the largest percentage of the world's fish catch. Although these species appear to time their spawning so as to maximize the probability that their eggs will survive and grow to become adults, the fact is that very few do survive. Predation on the eggs and larval fish is undoubtedly a major factor, but some scientists believe that a more important factor is the availability of food for the larval fish. The hypothesis is that in most years there is an imperfect match between the peak in the larvae's need for food and its availability. This mismatch may be either spatial or temporal. Unfavorable currents may cause the eggs to drift into an area where the concentration of nutrients is low. In temperate latitudes there is a burst of growth of microscopic marine algae in the spring. This phytoplankton bloom, caused by the warming of the surface waters, may easily vary by a week or two from one year to the next as a result of normal fluctuations in the weather. Many larval fish have only about a day to begin feeding once the nutrition in the egg yolk has been used. Since their swimming ability is minimal, the concentration of food in the water during this limited time can have a dramatic influence on survival and growth. A shift of a week or two in the spring phytoplankton bloom could easily account for large year-to-year variations in fish survival.

The use of this match/mismatch hypothesis to explain interannual variability in R is largely the work of David Cushing of the Fisheries Laboratory in Lowestoft, England, and is illustrated in Figure 15. Not all scientists agree with the details of

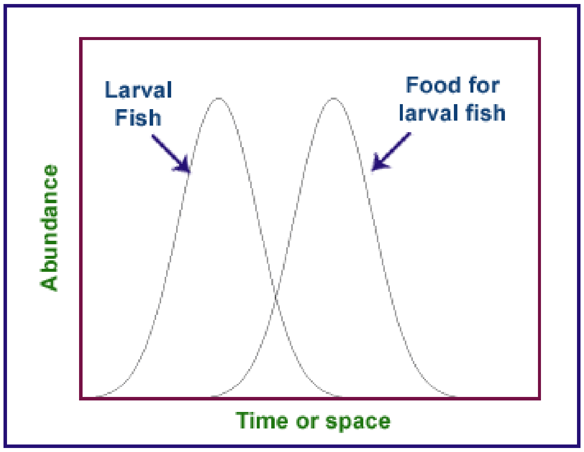

Figure 15. Illustration of the match/mismatch hypothesis advanced by David Cushing to account for the highly variable recruitment characteristic of many commercially important fish stocks. A perfect match requires that the peak in the requirement of the larval fish for food coincide with the supply of that food. Although Cushing originally formulated his hypothesis in terms of a temporal match/mismatch, the concept has been extended to include spatial match/mismatches. The theory assumes that during most years there is a poor overlap between the two peaks, and recruitment is poor. Occasionally, however, a good overlap occurs, followed by a spectacular recruitment.

Cushing's hypothesis; there is some evidence that the most critical phase in the early life of the fish is not always when the larvae begin to feed. However, most scientists agree that critical periods exist in the pre-recruitment life history of the fish and that differences in environmental conditions during those periods largely account for the interannual variability in R. While a moderate variability in R does not utterly invalidate the concept of a maximum sustainable yield, it does suggest caution in setting catch limits. For example, a perfectly acceptable catch during years of good recruitment could almost wipe out the stock of fish if recruitment were poor for several years in a row. In fact, the California sardine fishery was virtually destroyed because of heavy fishing during 1949 and 1950, when recruitment was quite low.

The life span of the fish species also affects its sensitivity to variations in recruitment. For species of fish with a long life span, the population of adults tends to be relatively stable even if recruitment is highly variable, because each year's recruitment is a small percentage of the total population. Heavy fishing reduces the average life span, so the size of the adult stock tends to undergo much larger year-to-year fluctuations. Since the anchovy has a life span of at most four years, its adult stock tends to be much more sensitive to variability in R than a species such as cod, which may live 20 years.

Although the anchovy tends to spawn at certain seasons (September–October and February–March), some spawning occurs at all times of the year. Survival of the juveniles is very seasonal, so the secondary spawning peak in February and March actually contributes more recruits to the adult stock than the primary spawning peak in September and October (Figure 16). The result is that average monthly recruitment

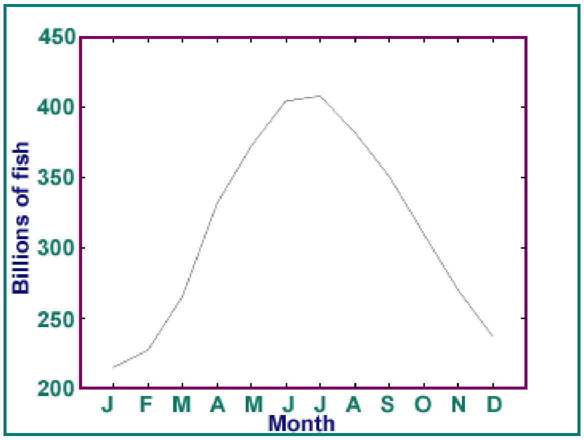

Figure 16. Average monthly recruitment of three-month-old anchovies from 1953 to 1981.

varies by only a factor of two throughout the year. This contrasts rather sharply with the pattern observed in many temperate fish populations, whose spawning is more highly seasonal. The spawning of the anchovy produces continuous recruitment throughout the year and so tends to minimize the impact of circumstances that adversely affect juvenile survival. The result, in the absence of the fishery, was probably a fairly stable level of annual recruitment. Even in the presence of the fishery, recruitment varied by no more than about a factor of three from the mean during the period 1953–1970 (Figure 8).

The impact of the poor recruitment of 1971 was made much worse by the fact that fishing continued through June 1972. Close to 10 Mt of anchovies were fished between September 1971 and June 1972. The adult stock was decimated (Figure 9). In the absence of the fishery the adult stock would probably have recovered rapidly, because recruitment in 1972 was substantially better than in 1971, particularly considering the small size of the adult stock. The fishery kept the adult stock at a relatively low level in subsequent years, contributed to some very poor recruitment years, and caused recovery during favorable conditions to be sluggish. The fishery did not fully recover until roughly 1990 (Figure 5).

The Presence of Competitors. The presence of competitors challenges one of the underlying assumptions of the maximum sustainable yield concept, that more resources become available as the population is reduced. If there is competition for resources, a selective fishery could easily shift the balance in favor of the unfished species. Sardines and anchovies share the same ecological niche, and they are frequently perceived as being in competition. The record of fish scales deposited and preserved in sediments off the coast of California indicates that the population of northern anchovies has been stable in the waters of the Californias over the past two centuries, whereas the California sardine has been abundant only during periods of climate warming. This suggests that the balance of competition favors the sardine during times when the offshore waters are unusually warm, though the record of fish scales does not prove that the two species are in competition. Where competition exists between two species, it may be advisable to fish both species in order to avoid shifting the balance of competition in favor of one or the other. Such a policy was followed by the South African government during the 1960s in an attempt to save the South African sardine fishery. Scientific surveys had shown that the ratio of sardines to anchovies off South Africa had shifted from about 16:1 during the 1955 fishing season to about 1:10 from 1962 to 1965. The South African efforts may have been partially successful, because the sardine fishery remained at a respectable level until 1976. However, despite the best intentions of government officials, the fishery completely collapsed in 1979. The present harvest is less than 20% of the catch during the 1960s.

Significant Harvest before First Spawning. If fish are harvested before they have a chance to reproduce, then the recruitment curve depicted in Figure 12 might be overly optimistic. Unfortunately, some species of fish do not become sexually mature until well after the time when they are large enough to be of interest to commercial fishing. The Peruvian anchovy is one. The fish begins spawning at approximately one year of age, and by age two it may be producing several hundred thousand eggs per year. Figure 10 gives the length and weight of the fish as a function of age. From these data it would appear that the fishing industry might be well advised to wait until after the first spawning by catching only fish larger than about 12–14 centimeters in length, but this policy would be difficult to implement. The anchovies are captured by encircling dense schools of millions of fish with a net called a purse seine. The net hangs like a curtain in the water and is drawn around the school by the fishing boat (Figure 17). When the school has been completely encircled, a line at the bottom of the net is drawn tight to prevent the fish from escaping through the bottom. A vacuum pump sucks the fish from the net into the hold of the fishing boat. To a certain extent one can control the size of fish caught by adjusting the size of the mesh on the purse seine, but only small fish near the edge of the school would be in a good position to escape through the net. The fish in the interior of the school are almost sure to be caught regardless of the coarseness of the mesh.

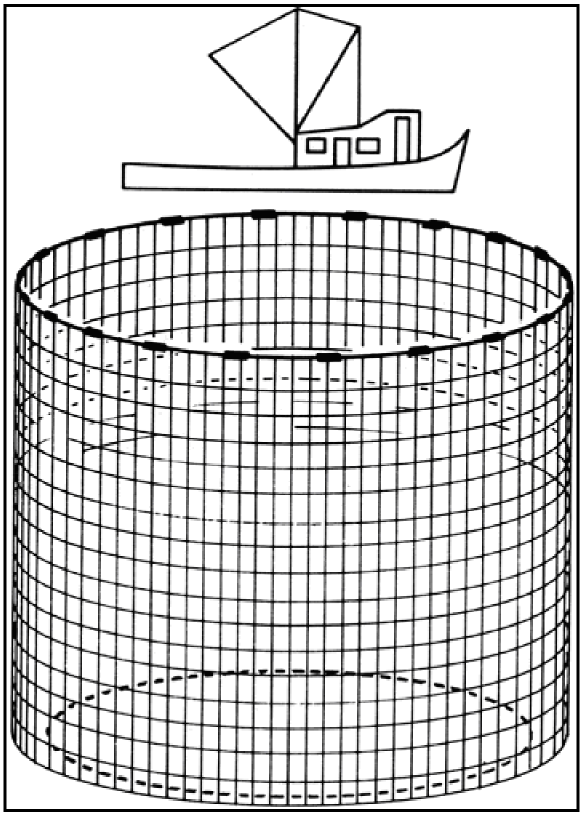

Figure 17. A purse seine net.

It is possible to lessen the impact on reproduction by carefully selecting the size and sometimes the sex of the species caught. During the 1970s the International Whaling Commission imposed restrictions on the size and sex of whales taken by the whaling industry. Implementing such restrictions was relatively straightforward, because it is possible to estimate the size of a whale with reasonable accuracy from a boat, and females with calves are easily identified. In fisheries involving baited hooks it is possible to exclude most small fish from the catch by choosing large hooks. In drift net fisheries, a long net is set like a curtain in the water, and fish are caught when they swim into the net (usually at night) and become entangled. Fish smaller than the mesh of the net can easily pass through and so can be excluded from the catch by appropriate choice of mesh size. In other words, it may be possible with some species of fish and some fishing techniques to reduce the impact of fishing to an acceptable level by focusing only on mature fish that have had some time to reproduce. Where it is clear that an intense fishery is taking sexually immature fish and/or fish that have had a very limited opportunity to reproduce, careful monitoring of recruitment (e.g., by means of egg or larval fish surveys) can help avert a human-induced population collapse. Garth Murphy has succinctly summarized the impact of an intense, selective fishery by noting, “Intense fishing removes the resilience the populations had evolved to resist adverse natural events, and . . . they then fall victims of such events when they eventually occur in the normal course of environmental variation.”

The Costs and Benefits of a Variable Catch

The implication of the foregoing discussion is not that we should stop fishing, but rather that we should not apply the maximum sustainable yield theory naively. For example, it is probably safe to say that an annual catch of 100,000 tonnes of anchovies could be taken from the waters off Peru for hundreds and probably thousands of years, barring some major environmental disaster. However, could an annual catch of 1 million tonnes or 2 million tonnes or 5 million tonnes be sustained over the same time period? The bigger the catch, the less likely that it can be sustained over a long period of time. If one wants to maximize the long-term catch of anchovies, one will have to accept a certain amount of variability in the catch. During good years one can catch a great many fish, but during bad years the catch must be reduced. While trying to maximize the long-term catch of anchovies might seem a rational policy for the fishing industry, there are some important costs associated with implementing it. In a bad year, when the catch must be reduced, people are put out of work, fishing boats and fishmeal plants are idle, and the manufacturers of livestock feed must turn to some other source of protein. While the fishing boats and fishmeal plants are idle, the workers must still support their families, and the payments must still be made on the loans used to buy the fishing boats and build the fishmeal plants. In short, maximizing the long-term fish catch does not necessarily maximize the social benefits or economic rewards of the fishery.

VI. History of the Fishery

The history of the Peruvian anchovy fishery is not a textbook example of how to maximize the sustainable yield, the long-term yield, social benefits, economic rewards, or anything else. It is, however, an interesting and thought-provoking example of how renewable marine resources are sometimes exploited. At a time when societies may need to adjust their behavior in the face of climate warming and other global changes, it poses one recent example of how a society has analyzed and responded to change in the environment.

Setting the Stage

Three events set the stage for the development of the fishery. The first was General Manual A. Odría Amoretti's assumption of the presidency of Peru in 1948. Unlike his predecessor, José Bustamante y Rivero, who discouraged exports of natural resources, President Odría sought to stimulate economic development by encouraging the export of Peruvian resources as a means of acquiring foreign exchange to buy manufactured products needed for the development of national industries. The Peruvian government followed this economic policy until 1968, despite six intervening changes in the presidency. The second important development was the collapse of the California sardine industry in 1950. The result of this collapse was that both fishing boats and equipment for converting fish to fishmeal could be acquired by entrepreneurs in Peru at bargain prices. Finally, the rapid expansion of the poultry and swine industry in the United States after World War II generated a pressing demand for a source of low-cost protein as a component of livestock feed.

With one exception, economic and political conditions were therefore almost ideal for the development of the Peruvian anchovy fishery. The exception was the existence of the Peruvian guano industry. The guano industry was dominated by the traditional elite in Peru, and the Guano Administration correctly realized that the development of a large anchovy fishery would reduce the guano birds' food supply and population and the production of guano. Prior to 1950 the Guano Administration had kept the guano bird population artificially high in order to increase guano production. Because of opposition from the guano industry, the first anchovy fishmeal plant in Peru was constructed secretly in 1950, following the collapse of the California sardine fishery. However, in 1954 the fishery entrepreneurs won an important victory when the government approved initial development of the industry despite opposition from the Guano Administration. In 1956 pressure from the guano industry caused the government to order a halt on further construction of fishmeal plants until an assessment could be made of the impact of the fishery on the bird population. This moratorium was lifted in 1959, and from that date until 1973 the fishmeal industry expanded essentially without government interference. Undoubtedly an important consideration in determining government policy was the realization that an anchovy was worth about five times as much when converted to fishmeal as it was when eaten by birds and ultimately converted to guano.

Technological Developments

The earliest anchovy fishing vessels were wooden ships with hold capacities of 40–100 tonnes. By the 1960s these ships had been replaced almost entirely by much larger vessels made of steel, with hold capacities in excess of 300 tonnes. These larger ships featured a number of technological innovations that significantly reduced operating costs and crewing requirements. Among the most important improvements were power blocks to haul in the purse seines, echo sounders to locate schools of fish, vacuum pumps to transfer anchovies from the purse seine to the hold, and nylon rather than cotton nets. A 350–tonne fishing vessel typically had a crew of 12–14 compared to a crew of 10 for a 100-tonne ship. The improved ratio of crew to tonnes of hold capacity greatly improved the profitability of companies operating with the larger ships.

Developments prior to the 1972 El Niño

There was a strong El Niño in 1957–58, but at that time the fishery was taking less than one million tonnes of anchovies per year, and the impact of the fishery on both the anchovies and guano birds was apparently minor. Both the anchovy and the bird populations increased steadily in the next few years. The catch statistics were virtually unaffected by a moderate El Niño in 1965 (Figure 5). The guano bird population dropped dramatically and never recovered (Figure 6). In retrospect, the failure of the guano bird population to recover following the moderate El Niño of 1965 was probably one of the best early indicators that the anchovy stock was in trouble. In order to encourage scientific input to the management of the fishery, Peru and the United Nations Food and Agriculture Organization (FAO) established the Instituto de los Recursos Marinos in 1960, and in 1964 the precursor of the Instituto del Mar del Peru (IMARPE) was established by the Peruvian government with the help of a grant from the U.N. Development Program. Over the years IMARPE has typically been staffed by about 50 Peruvian scientists and several FAO residents and has provided a great deal of scientific information and advice concerning the fishery. Scientists began to apply the maximum sustainable yield concept to the fishery in 1965, and in that year the first closed season (in which no fishing could take place) was established in order to reduce fishing pressures. During subsequent years IMARPE routinely issued catch limitation recommendations, the initial maximum sustainable yield having been estimated at about 7.5 Mt. In practice, however, the catches always exceeded this figure until the 1972 El Niño (Figure 5). It was obvious that the industry was either ignoring or simply could not abide by the advice of the scientists.

In general the closed season included one or more months between June and August, but this period is normally a time when fishing is poor, and closing the fishery therefore did not represent a major concession on the part of the industry. In hindsight, it was unrealistic to expect the industry to adhere to any measures that had a real impact on their annual catch. So many eager entrepreneurs seeking quick returns on their investments had bought fishing boats and entered the industry that, by 1970, the capacity of the fishing fleet greatly exceeded any reasonable estimate of the maximum sustainable yield. There were about 1,450 purse seiners in the fleet, enough to harvest 13 Mt of anchovies in 175 days. Adherence to a quote of 7.5 Mt (the recommendation of IMARPE’s international panel of experts) would have required a fishing season of only 101 days. Few boat owners, however, could afford to tie up their boats for 264 days of the year. The fixed costs of vessel operation (depreciation, maintenance, insurance, interest payments, etc.) are independent of the length of the fishing season. A vessel tied up at the dock costs money.

Excess capacity in the fishmeal plants was even more extreme. By 1970 there were enough fishmeal plants to process 8,000 tonnes of anchovies per hour. An annual catch of 7.5 Mt could have been converted to fishmeal in less than 40 days if the fishmeal plants were operated 24 hours a day. Although some shutdowns could undoubtedly be anticipated for routine maintenance and repairs, it makes economic sense to operate a fishmeal plant as many hours a day as possible. Fishmeal plants, like fishing boats, incur costs but generate no revenue when they are idle. These processing factories indirectly generated pressure to bring in fish catches for processing – legally or illegally.

The Industry after the 1972-73 El Niño

The situation was ripe for government intervention, and two events triggered just that. In 1968 the Peruvian government was seized by the military, and a junta headed by General Juan Velasco Alvarado came to power. The socialist military government sought to convert the country from a free market to a planned economy, and in 1970 it established a Ministry of Fisheries separate from the Ministry of Agriculture. The second important event was the catastrophic failure of the fishery in 1972. When it became clear that the anchovy fishery was in serious trouble, the military government stepped in and nationalized it, giving bonds to factory and boat owners in exchange for their property. This move was resisted by some members of the industry as undesirable intervention in the private sector but was welcomed by owners of the less-efficient fishing boats and fishmeal plants. The exchange of their assets for government bonds, in many cases at above the book value of the assets, saved them from almost certain economic disaster.

The government's first action after taking over the anchovy industry was to cut it in half. The number of fishing boats was reduced from about 1,500 to 800; the number of fishmeal plants was cut from 100 to 50; the number of persons employed in the industry was reduced from 25,000 to 12,000. In order to give the anchovy stock a chance to recover, the fishing grounds off north and central Peru were closed in 1973; only the southern fishing ground remained open. Despite the bet intentions of the Peruvian government, the catch of anchovies in 1974–76 averaged only about 4 Mt, well below the suggested 7.5 Mt limit and much too low to justify the existence of 800 fishing boats, 50 fishmeal plants, and 12,000 employees. Subsidizing the anchovy industry had become an annoying drain on the government's financial assets. A moderate El Niño in 1976 further dampened government enthusiasm for managing the fishery, and in mid-1976 the fishery was denationalized. This move was almost as controversial as the nationalization three years earlier, because it was obvious to the private sector that the anchovy stocks were in no condition to support a fishery of the size implied by the amount of capital invested in the industry.

The policy of striving for a planned economy lasted until 1980, when free elections were held once again. Fernando Belaunde Terry, who had been president at the time of the military takeover in 1968, was returned to the presidency and reinstated free-market policies. However, the change in political leadership and economic policy did nothing to improve the fishing. The actual catches from 1977 to 1982 averaged only 1.4 Mt, and a very strong El Niño in 1982–83 necessitated an almost complete closure of the fishery in 1983 and 1984. The stock appeared to be recovering rather well in 1986, when the catch was almost 5 Mt; but following a very strong El Niño in 1987 the catch was again reduced.

The decade of the 1990s and first few years of the 21st century brought a remarkable series of El Niños in 1991–92, 1993, 1994, 1997–98, and 2002–03. Both the 1991–92 and 1997–98 El Niños were very strong. The latter produced societal impacts as devastating as the 1982–83 El Niño and was almost certainly the strongest El Niño of the 20th century. The increasing frequency and intensity of El Niños during the last two decades of the 20th century has been attributed by some scientists to global warming caused by anthropogenic emissions of greenhouse gases, particularly carbon dioxide. Remarkably, with the exception of 1998 when fishing was restricted, the catch of Peruvian anchovies during the 1990s averaged 7.6 Mt, virtually identical to the maximum sustainable yield estimated by IMARPE scientists. It would thus appear that with proper management the biological resource can sustain a remarkable fishery despite the occurrence of frequent El Niños. This logically brings us to the practical challenge of managing the Peruvian anchovy fishery.

VII. ANCHOVY: The Management Simulation

If you think you could do a better job of managing the anchovy fishery than the Peruvian government during the 1970s, you may be right. The computer simulation ANCHOVY gives you a chance to test your management skills. The program is designed with the idea that the player will try to maximize the long-term profits from the fishmeal industry, but other goals are possible. For example, one might try to maximize the long-term catch. The economic constraints reflect conditions that prevailed during the 1960s.

Instructions for the simulation and background information appear at the end of this module. You must first invest in some fishing boats and fishmeal plants. ANCHOVY assumes that prior to your entry into the industry there has been no anchovy fishing. Your job is to set the catch quotas for as long as you choose to play the game.

The problems that will confront you in setting your catch limits are environmental variability and uncertainty. You can reduce the uncertainty to a minimum by requesting that recruitment and natural mortality be non-random and that there be no El Niño events. For maximum uncertainty, you can ask for random recruitment and natural mortality and for El Niño events. The former case (minimum uncertainty) results in a small annual variation in the number of adults due to the seasonal nature of recruitment (Figure 16). The latter case will produce the most extreme interannual fluctuations in the size of the adult stock.

The sequence of El Niño events is based on a reconstructed 470-year record dating back to 1520. Note that this record does not include the series of frequent El Niños that occurred during the 1990s. Those are assumed to reflect the impact of the current global warming, but at this point the sample record is too short to allow a quantitative assessment of the impact of the current phase of warming on the El Niño cycle. The program starts you out at a random point in the historical record and continues for as many years as you choose to play the game. When the program reaches the end of the 470-year record, it goes back to the beginning.

When you begin fishing, you must decide how many industry units to buy, whether or not to close the fishery during certain months of the year, and, of course, the annual catch you will try to achieve. You will also be asked to decide at what level of anchovy biomass to temporarily close down the fishery. The computer will display graphs of the simulation results and print out your average annual catch, profit (or loss), and so forth.

There are a variety of questions you may want to address. What, for example, is the maximum sustainable yield in the absence of El Niño and random fluctuations in recruitment and natural mortality? Once you have discovered what the maximum sustainable yield is under these very simple conditions, you can go ahead and run the simulation with El Niños and/or random fluctuations in recruitment and natural mortality. One interesting question you might want to explore is the relative importance of El Niños versus random fluctuations in recruitment and natural mortality in reducing the maximum sustainable yield.

After you have become skilled at the ANCHOVY simulation, you should have a good idea of how large the industry should be in order to maximize its profits. Then you may wish to consider several variations. You might try to manage an industry of the size that actually existed in the late 1960s. Another option is to specify that the fishery be closed during certain months of the year. Given the fact that there is an annual cycle in the recruitment process (Figure 16), does it make any difference when the closed season occurs? For example, if the closed season lasts three months, is the sustainable yield any higher when the closed season lasts from June through August versus November through January?

VIII. Discussion

The Global Nature of the El Niño Cycle

The El Niño cycle's impact extends far beyond the coastline of Peru. For example, 1972 witnessed droughts in Central America, the Sahel zone of West Africa, India, the People's Republic of China, and parts of Australia and Kenya. Global per capita food production and global food reserve declined for the first time in 20 years. During the 1982–83 El Niño, parts of southern Ecuador and northern Peru experienced up to 250 centimeters of rain during a six-month period, while Australia, already in the midst of a drought, suffered wildfires and catastrophic agricultural and livestock losses that cost billions of dollars in lost revenue and damage. Drought in sub-Saharan Africa forced normally food-exporting countries such as South Africa and Zimbabwe to seek help from the international community. During the 1997–98 El Niño Indonesia experienced forest and peat fires that blackened skies in many parts of southeast Asia, while storms and rain lashed California for months and damaged or destroyed 1,400 homes. While El Niños were originally thought of as affecting only the coastal region of Peru and Ecuador, it is now clear that El Niño is global in nature and profoundly affects both marine and terrestrial systems throughout the tropics and in some extra-tropical regions, especially in Pacific Rim countries.

The Impact of Global Warming

Although the El Niño cycle is a natural phenomenon, another global change that is largely the result of human activities and is of special relevance to the Peruvian anchovy fishery is the warming of the Earth's climate known as the greenhouse effect. In brief, the greenhouse effect is the warming of the atmosphere due to increases in carbon dioxide and other gases that result from human activities, notably the burning of fossil fuels. The greenhouse effect is discussed in detail elsewhere in this series.

The anchovy fishery could be impacted in several ways by a global warming. William Quinn and colleagues at Oregon State University and in Peru have reconstructed occurrences of El Niño dating back to 1525. Strong El Niños occur more frequently during periods of global warming. This conclusion is certainly supported by the frequency of El Niños during the 1990s.

The second potential impact of a global warming on the El Niño cycle concerns the temperature differential between the equator and the poles. Computer simulations of the impact of a global warming indicate that polar regions would be warmed more than equatorial zones, reducing this temperature differential. Since it is this differential that determines the gross features of general circulation, one consequence of a global warming would very likely be a reduction in the intensity of large-scale atmospheric circulation. Since ocean surface currents and coastal upwelling are largely wind-driven phenomena, one might anticipate a reduction in upwelling along the coast of Peru and a concomitant decline in the productivity of the fishery.

However, we are led to a different conclusion if we examine in closer detail the air-sea interactions in coastal upwelling systems. In general, in these systems atmospheric pressure over the cool offshore ocean is relatively high compared to atmospheric pressure over the adjacent land mass. This pressure differential combined with the Coriolis force leads to a flow of air parallel to the coastline. This alongshore wind stimulates upwelling by driving surface waters offshore. As the global climate warms, it is quite probable that the land masses will heat up faster than the oceans, increasing the pressure differential that drives the alongshore wind system. The result would be an intensification of the alongshore wind system and of coastal upwelling.

Whether the large-scale or small-scale interactions would have the greater effect on coastal upwelling is unclear. As with many issues associated with the greenhouse effect, one can find knowledgeable scientists with very different opinions about the impact of a global warming on coastal upwelling. However, if the historical record is any guide, a global warming will probably lead to an increase in the frequency of strong El Niños. The Peruvian anchovy fishery has an early history of mismanagement, the extent of which you should be able to appreciate after playing the ANCHOVY game. Proper management during a period of global warming will be even more critical if the potential benefit of this important renewable resource is to be realized.

Appendix. Global Circulation and El Niño

The radiant energy from the Sun is not equally distributed over the surface of the Earth. Equatorial latitudes receive much more energy than polar latitudes, and as a result the atmosphere near the surface of the Earth is much warmer near the equator than near the poles. Heating air causes it to expand, become less dense, and rise (a phenomenon routinely used by hot air balloon enthusiasts). Cooling air causes it to sink. Because equatorial latitudes receive more solar energy than the poles, the differential heating of the Earth-atmosphere system causes air to rise near the equator and to descend near the poles. One might imagine that the atmosphere would therefore move directly north and south, rising at the poles and sinking at the equator, as shown in Figure 18.

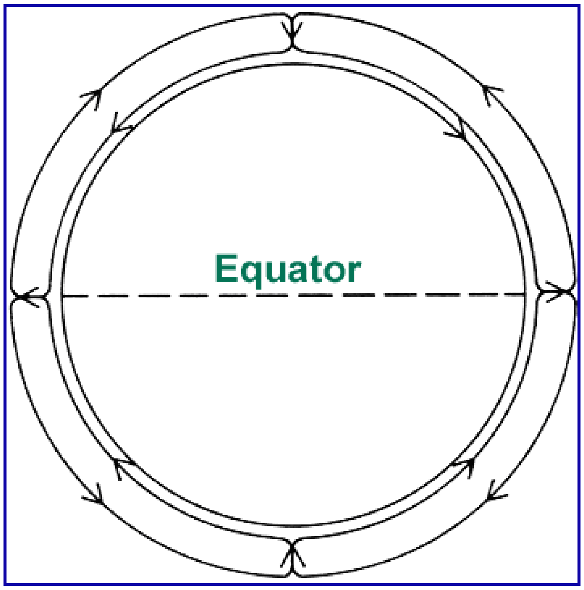

Figure 18. Cross section of the Earth showing the pattern of circulation of the lower atmosphere that might be expected from differential heating of the Earth-atmosphere system by the Sun.

In fact, atmospheric circulation is not so simple. Although air tends to rise near the equator, as it moves poleward it radiates heat into outer space and eventually cools and sinks at about 30 degrees latitude. Similarly, cold air that sinks at the poles tends to be warmed as it flows along the surface of the Earth toward the equator and to rise near 60 degrees latitude. The vertical circulation of the atmosphere, in simplified terms, consists of three circulation cells as shown in Figure 19. The subtropical and temperate-latitude circulation cells are referred to as Hadley cells and Ferrel cells, respectively, after the scientists who discovered them. The high-latitude cells are called polar cells.

The Effect of the Earth's Rotation

In most respects Figure 19 is an accurate characterization of the overall meridional (north-south) circulation of the atmosphere, but it is an oversimplification. The real circulation pattern is neither as uniform nor as continuous as Figure 19 implies. The figure suggests, for example, that surface winds would blow directly toward the equator in tropical and subtropical latitudes and directly toward the poles in temperate latitudes. This is only partly true.

If you were to slice up the Earth along its latitude lines, you would get a series of rings, the largest at the equator and diminishing in size toward the poles. Because the Earth is rotating as a solid body, a point on a large ring moves faster than a point on a small ring. At 30 degrees latitude, for example, the circumference of our latitudinal ring is about 34,600 kilometers. A point on the Earth's surface at that latitude is moving toward the east at a rate of 34,600 kilometers per day, or 1,442 kilometers per hour. At 29 degrees latitude, the surface of the Earth is moving faster, at 1,458 kilometers per hour, because the circumference of a cross section there is 35,000 kilometers.

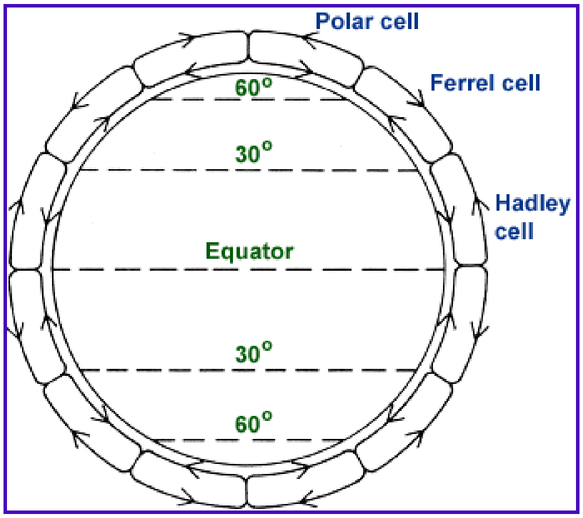

Figure 19. Meridional circulation that results from differential heating of the Earth-atmosphere system by the Sun. Note that the vertical scale of circulation cells is greatly exaggerated. The vertical extent of the cells is approximately 10 km.

If there are no other zonal (east-west) forces acting on it, a mass of air flowing toward the equator across the surface of the Earth will appear to be deflected toward the west, because the underlying Earth is moving faster toward the east the closer to the equator the air travels (see Figure 20). The surface winds that blow from about 30 degrees toward the equator are referred to as the trade winds. Because winds are customarily named on the basis of the direction from which (rather than to which) they are flowing, these winds are known as the northeast trades in the Northern Hemisphere and the southeast trades in the Southern Hemisphere.

Now consider the air that sinks at 30 degrees and flows toward the poles. Since at higher latitudes the surface of the Earth is moving eastward more slowly than at 30 degrees, this air will acquire an apparent eastward motion. The surface winds between 30 and 60 degrees are more complex and unstable than the trade winds, but they consistently have a west-to-east component and hence are known as the westerlies. Because surface winds between the poles and 60degrees are moving toward the equator, they are affected by the Earth's rotation in the same way as the trade winds, blowing out of the northeast in the Northern Hemisphere and the southeast in the Southern Hemisphere (see Figure 21).

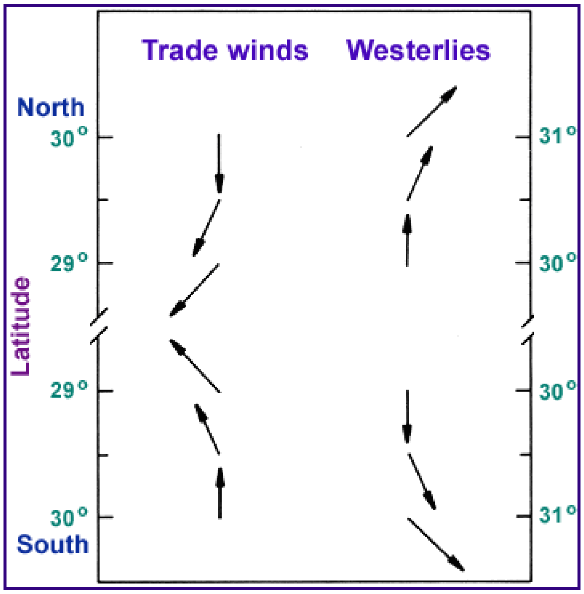

Figure 20. The effect of the rotation of the Earth on a parcel of air initially at a latitude of 30 degrees and moving at a speed of 8 m s^{-1} directly toward the equator (trade winds) or directly away from the equator (westerlies). No east-west forces are assumed to act on the parcel of air. By the time the air has moved 1 degrees, its direction has changed by about 45 degrees. In the trade wind zone the parcel of air acquires a westerly component, while in the region of the westerlies it acquires an easterly component. The effect of the Earth's rotation is always to divert the air to the right of its direction of motion in the northern hemisphere and to the left in the southern hemisphere.

Once again though, the situation is more complicated. The continental land masses influence the flow of the wind, and because the land is unevenly distributed between the Northern and Southern Hemispheres, the winds do not blow in an entirely symmetrical manner with respect to the equator. In fact, the entire wind system shown in Figure 21 is shifted about 5–10° to the north. In addition, in temperate latitudes surface winds tend to circulate about high pressure ridges and low pressure troughs, and shifts in the positions of these ridges and troughs can produce important climatological effects.

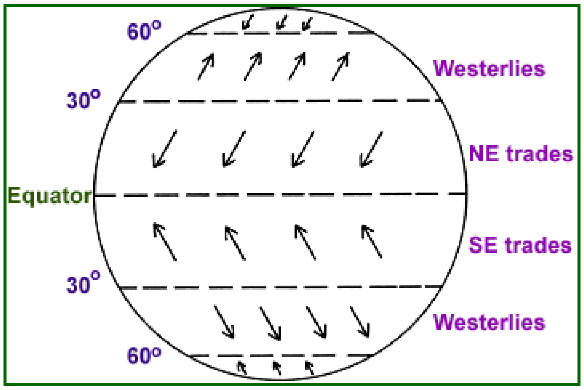

Figure 21. Direction of surface winds resulting from the combined effects of the Coriolis force and meridional cell circulation.

Finally, the difference in the heat capacity of the continents and oceans causes seasonal temperature differentials to develop between them. Because it takes a great deal of heat to warm a mass of water, and because the upper mixed layer of the ocean is large (typically it extends to tens of meters in the summer and perhaps hundreds of meters in the winter), the temperature of the ocean remains relatively constant compared to the temperature of the continents. During the summer the continents are warmer than the ocean, and during the winter they are cooler. The exchange of heat between the Earth and atmosphere therefore causes the air over the continents to be warm and less dense than the air over the surrounding oceans during the summer. During the winter the conditions are reversed. As the continental air warms and rises during the summer, air overlying the surrounding ocean is drawn in to replace it. In the winter, the cool, dense air over the continents tends to sink and flow toward the surrounding ocean. The winds associated with this seasonal circulation pattern are referred to as monsoon winds and are best developed over India, Southeast Asia, and Australia.

The Effect of Surface Winds and the Coriolis Force on Ocean Currents

Because the Earth is a rotating sphere, it appears to an observer on Earth that a force is always pushing the wind to the right of the direction of motion in the Northern Hemisphere and to the left in the Southern Hemisphere (e.g., Figure 20). This force is called the Coriolis force, and it affects the oceans as well as the atmosphere. One would expect that ocean currents would flow in the same direction as the surface winds, but they rarely do. Just as land masses affect the flow of winds, they impose some constraints on the direction in which ocean currents can flow. Virtually all coastal current systems flow parallel to the coast, regardless of the direction in which the wind is blowing. But even in the open ocean, surface currents do not tend to move in the same direction as the wind. Again, this is due to the Coriolis force, which causes those currents to flow at an angle to the right of the wind in the Northern Hemisphere and to the left of the wind in the Southern Hemisphere. The transport of currents at an angle to the wind is referred to as Ekman transport, after the Scandinavian oceanographer who explained the phenomenon theoretically.

The combination of Coriolis force and Ekman transport causes ocean surface currents in the region of the trade winds to flow almost exactly due west across the ocean basins, while in the vicinity of the westerlies the flow is due east. When these transoceanic surface currents encounter continental land masses, they may either turn and flow parallel to the coastline or completely reverse direction and flow back across the ocean basin. In the former case, they are called boundary currents; in the latter case countercurrents. The major current systems driven by the trade winds and Westerlies in the Pacific Ocean are shown in Figure 22. The transoceanic currents to the north of the equator are the North Pacific Current and the North Equatorial Current, and the corresponding boundary currents are the California and Kuroshio currents. The analogous current systems in the South Pacific are the West Wind Drift, the South Equatorial Current, the Peru Current, and the East Australia Current, respectively. The South Equatorial Current actually extends to about 4° N, and much of the flow in the West Wind Drift is actually circumpolar, since there are no continental land masses to impede it between roughly 5 and 65 degrees S . The Equatorial Countercurrent flows from west to east across the Pacific between approximately 4 and 10 degrees N. Another eastward-flowing countercurrent, called the Equatorial Undercurrent, is at the equator at depths of approximately 100–200 meters. Obviously neither the Equatorial Countercurrent nor the Equatorial Undercurrent is driven directly by the wind. The Equatorial Countercurrent, in particular, would seem to be flowing into the teeth of the prevailing trade winds, but it flows through a region of light and variable winds called the doldrums, which offers little resistance. The more-or-less continuous current system consisting of the California, North Equatorial, Kuroshio, and North Pacific currents is called the North Pacific subtropical gyre, and its counterpart in the South Pacific is the South Pacific subtropical gyre.

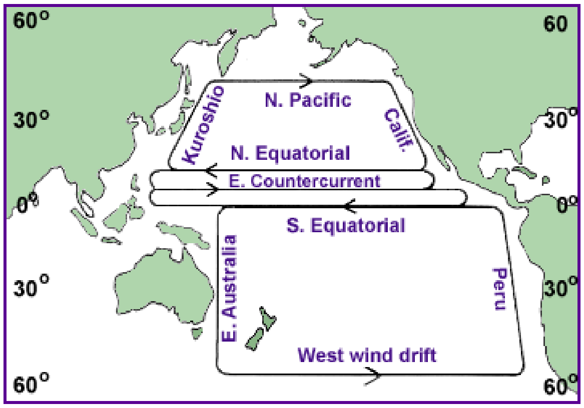

Figure 22. The major surface current gyres driven by the trade winds and westerlies in the Pacific Ocean. Note that the current gyres are not symmetric with respect to the equator. The Equatorial Countercurrent actually flows between about 4 and 10 degrees N latitude.

El Niño

El Niño is characterized by a movement of warm water from the western Pacific to the eastern Pacific. This water is transported largely in the form of Kelvin waves. Kelvin waves and similar waves known as Rossby waves are internal waves (they have their maximum amplitude below the surface of the ocean) whose dynamics are affected by the Coriolis force. Their wavelengths are on the order of thousands of kilometers, and their effects can be felt across an entire ocean basin. Kelvin waves cross the Pacific in two to three months. As their warm water reaches the coast of South America, it flows over the cooler water of the Peru Current system. The result is an elevation of sea level (Figure 23) and an increase in sea-surface temperature. Some of the warm water flows north along the coast. Some flows south and causes El Niño conditions off the coasts of Ecuador and Peru. As sea level rises and warm water accumulates in the eastern equatorial Pacific, air-sea interactions generate Rossby waves that move westward across the Pacific. The time they take to cross the ocean is strongly dependent on latitude; it is about nine months near the equator and four years at a latitude of 12 degrees. When the Rossby waves reach the western Pacific, they travel toward the equator in the form of coastal Kelvin waves. Upon reaching the equator they turn east and begin another crossing of the Pacific. When this second set of Kelvin waves reaches the eastern Pacific, sea level is lowered, the sea-surface temperature declines, and conditions along the coast of Peru return to "normal". Since roughly 1985 these "normal" conditions have come to be known as La Niña (literally "the girl" in Spanish). However, the air-sea interactions associated with the lowered sea-surface temperatures intensify the Trade Winds, and this shift in the winds sends Rossby waves westward across the Pacific. Upon reaching the western Pacific, these waves travel toward the equator as coastal Kelvin waves and then return to the east along the equator. This final set of equatorial Kelvin waves raises the sea level in the eastern Pacific and completes the El Niño cycle. The entire process is illustrated in Figure 24.

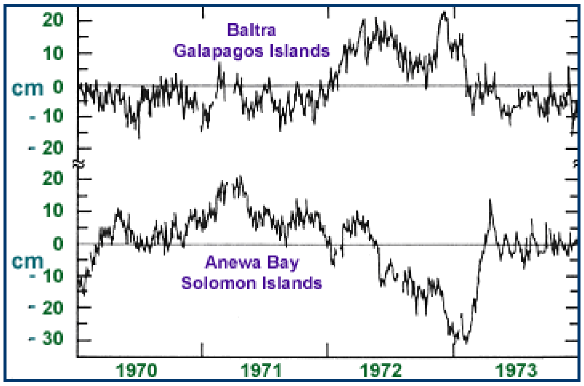

Figure 23. The response of sea level in the equatorial Pacific Ocean to the 1972 El Niño. Note that sea level was high in the western Pacific (Solomon Islands) preceding El Niño, but had dropped dramatically by the end of 1972 as water flowed toward the east along the Equatorial Countercurrent and Undercurrent. Sea level was relatively low in the eastern Pacific (Galapagos Islands) preceding El Niño but rose by almost 30 cm as water arrived from the western Pacific. Redrawn from Wyrtki (1979).

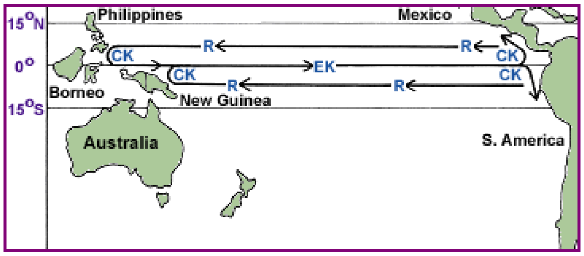

Figure 24. The wave system that constitutes the negative feedback mechanism in the El Niño cycle. Equatorial Kelvin waves travel west to east across the Pacific raising sea levels. When they reach the coastline of South America they propagate poleward and are clearly identifiable as coastal Kelvin waves at latitudes higher than 5 degrees. Air-sea interactions associated with the arrival of warm water in the eastern equatorial Pacific cause the trade winds to slacken. This shift in the winds sends a series of off-equatorial Rossby waves that lower sea levels back across the Pacific. These Rossby waves reach the western Pacific and propagate toward the equator in the form of coastal Kelvin waves that also lower sea levels. The Kelvin waves reach the equator, turn east, and move back across the Pacific as sea-level-lowering equatorial Kelvin waves. The equatorial Kelvin waves require about 2–3 months to cross the Pacific, but the off-equatorial Rossby waves require anywhere from a few months to a few years. A complete El Niño cycle requires

that the Pacific be crossed by two sets of Rossby waves and Kelvin waves, one set raising sea levels in the direction they are moving and the other lowering them. Hence a complete El Niño cycle typically requires 3–5 years.

Air-Sea Interactions

The connection between sea-surface temperature changes and the speed of the trade winds can be appreciated from an examination of Figure 25. As the trade winds blow across the Pacific they pick up warmth and water vapor from the tropical ocean. Because warm, moist air is less dense than cold, dry air, this air tends to rise in the western Pacific near the equator. As the air rises the water vapor condenses and falls as rain.

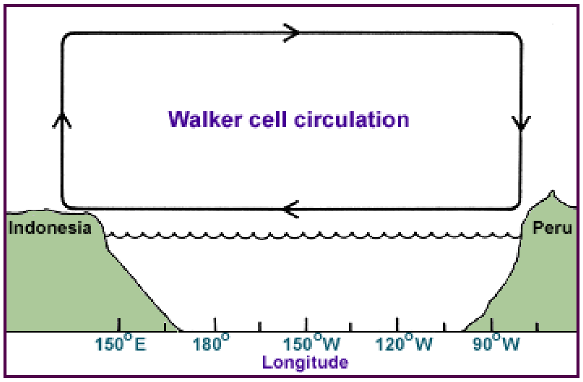

Figure 25. The Walker cell circulation cycle over the Pacific Ocean. The vertical scale is exaggerated, the height of the circulation cell being about 15 km. This atmospheric circulation pattern tends to produce low atmospheric pressure and a warm, moist climate over Indonesia. Atmospheric pressure is relatively high and the climate cool and dry along the coast of northern Peru.

Part of the rising air mass begins to move back toward the east. As it moves, it radiates heat into the surrounding atmosphere and eventually cools and sinks near the eastern edge of the ocean basin. This circulation pattern is called a Walker cell, after British mathematician Sir Gilbert Walker, who made major contributions to our understanding of tropical meteorological in the first half of the 20th century.

Because the air that sinks near the equator in the eastern Pacific has lost heat as well as water vapor, it tends to be denser than the air that rises along the equator in the western Pacific. Consequently there is a small east-west difference in surface atmospheric pressure between the eastern and western Pacific in the trade wind zone, with the eastern Pacific having the higher pressure. The pressure differential is much greater between the equatorial western Pacific (0) and eastern Pacific at a latitude of about 30 degrees (Figure 19), where Hadley cell circulation tends to produce cool, dry air. This latter sea-level pressure differential is usually referred to as the Southern Oscillation Index, and it is frequently reported in terms of the difference in atmospheric pressure between Easter Island and Darwin, Australia.

Because of the exchange of heat between the atmosphere and ocean, changes in sea-surface temperature in the eastern Pacific can have a significant effect on the intensity of the trade wind system. When the eastern Pacific warms during an El Niño year, the Walker cell circulation is slowed because the temperature difference between the eastern and western Pacific is reduced. Thus the speed of the equatorial trade winds and hence the speed of both the South Equatorial and North Equatorial currents decreases. The decline in the strength of the equatorial trades allows more warm water to flow from the western to the eastern Pacific and hence further reduces the temperature differential between the eastern and western Pacific. On the other hand, when the eastern Pacific is cool, the Walker cell circulation is increased, because there is a greater temperature differential between the eastern and western Pacific. The trade winds become stronger, and the North and South Equatorial Currents intensify. The strengthening of the trade winds opposes the transport of warm water via the Equatorial Countercurrent and Undercurrent and hence further increases the temperature difference between the eastern and western Pacific. Those air-sea interactions are an example of what is known as a positive feedback loop. They tend to reinforce El Niño or La Niña conditions, whichever condition prevails.

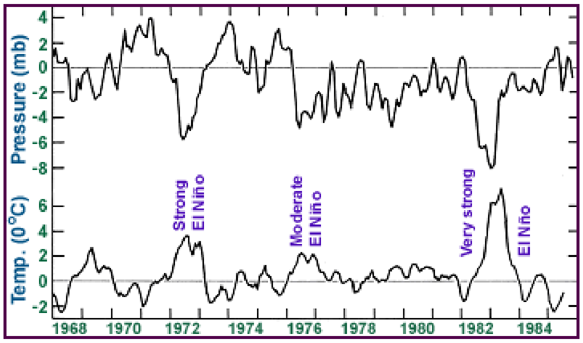

Figure 26. Three-month running mean variations in the Southern Oscillation Index (top) and sea-surface temperature off the coast of Chimbote, Peru (bottom), from 1968 to 1985. Monthly variations are the difference between the value for a given month and the long-term average value for that month. During this period, El Niños occurred in 1972–73 (strong), 1976 (moderate), and 1982–83 (very strong). The El Niños of 1972–73, 1976, and 1982–83 are all apparent as increases in temperature of at least 2 degrees C over a period of several months, and each El Niño is associated with a drop in the Southern Oscillation Index of at least 8 millibars (mb).

The reason there is an oscillation between El Niño and La Niña conditions is the negative feedback loop created by the movement of the Kelvin and Rossby waves across the Pacific. During El Niño conditions, the eastern equatorial Pacific warms and the trade winds slacken. The change in trade wind intensity generates off-equatorial Rossby waves that lower sea levels in the western Pacific. Ultimately these lower sea levels generate Kelvin waves that travel back east and lower sea levels in the eastern Pacific.

One implication of this analysis of air-sea interactions is that the Southern Oscillation Index may provide a useful predictor of forthcoming El Niños. The index is high (the pressure differential is large) when the trade winds are strong (La Niña conditions). The index is low (the pressure differential is small) when the trade winds are weak (El Niño conditions). Figure 26 shows the behavior of the Southern Oscillation Index and sea-surface temperatures off the coast of Peru for the period from 1968 to 1985. The El Niños of 1972–73, 1976, and 1982–83 are all apparent as increases in sea-surface temperature of at least 2 degrees C above long-term monthly averages over a period of several months, and each El Niño is associated with a drop in the Southern Oscillation Index of at least 8 millibars. A drop of greater than 4 millibars is usually a sign that an El Niño is approaching.

Recognition of the connection between the Southern Oscillation Index and El Niño has given rise to the acronym ENSO (El Niño Southern Oscillation). The ENSO cycle is understood to consist of an irregular meteorological oscillation characterized by two extreme conditions, a warm phase (El Niño) and a cool phase (La Niña), that is driven by exchanges of heat and water between the ocean and atmosphere in the tropical Pacific.

Study Questions and Answers

Fisheries and Resource Management

1. Does the record of fish scales preserved off the coast of California necessarily prove that California sardines and northern anchovies are competitors? Can you suggest an alternative explanation for the alternation in abundance of the anchovy and sardine scales?

2. Why would anchovy yields be roughly 5–25 times smaller if anchovies were primary or secondary carnivores rather than herbivores?

3. One variation of fisheries management is to try to maximize the "yield per recruit" to the adult stock. The idea is to try to harvest the fish at a size that maximizes the yield from all the fish recruited at a particular time. As the fish grow older they become larger, but some of them die from natural causes and are removed from the stock. The longer one waits to harvest the fish, the bigger they grow, but the greater the odds they will die of natural causes. So one would be catching larger fish but fewer of them. Wait too long and there are no fish left; harvest too soon and the fish are small. There should be some point in the life span of the fish when the yield (in total weight) is greatest. Let's see if it makes sense to try to maximize the yield per recruit in the case of the Peruvian anchovy.

   Assume that at age 5 months, when they are recruited, anchovies weigh 2 grams. They gain 1.15 grams per month until age 25 months and 1.0 gram per month from 25 to 48 months. Assume that in the absence of a fishery natural mortality reduces the number of anchovies by 16% per month and that each month 315 billion (315x10 to the ninth) anchovies are recruited into the adult stock. Make a graph of the biomass (in Mt) of all the recruits from a given month versus time. If you could design fishing gear so that you had complete control over the age (i.e., size) of the anchovies you caught, at what age (or size) would the yield per recruit be maximized? If you applied this strategy each month of the year, and if recruitment were unaffected by this harvesting strategy, what would be the annual yield? Would it be reasonable to use this strategy to try to maximize the harvest of Peruvian anchovies?

4. Now let's apply similar logic to a temperate fish species. We will assume that the fish is recruited to the adult stock at age 5 months and that the natural mortality rate is 4%, rather than 16%, per month. We will again assume that the fish weighs 2 grams at age 5 months, gains 1.15 grams per month until age 25 months and 1.0 gram per month thereafter until dying at age 48 months. The fish spawns at one-year intervals beginning at age 12 months. Let's assume that each spawning results in 1.0 billion (1.0 x 10 to the ninth) recruits 5 months later. Make a graph of the biomass (in Mt) of a cohort (the population of fish born in a given month) versus time and determine at what age one should harvest the fish in order to maximize the yield per recruit.

5. Suppose harvesting the fish at the age specified in your answer to Question 4 led to very poor recruitment because the adult stock was too small. At what other age would it make sense to harvest the fish in order to maximize the harvest from each cohort without adversely affecting recruitment?

6. Figures 12 and 13 provide a graphical way to determine the sustainable fishery yield as a function of the size of the adult stock. It is apparent from Figure 13 that, with the exception of the maximum sustainable yield (msy), each sustainable catch is associated with two different stock sizes. For example, a sustainable catch of zero is associated with both the virgin stock and a stock equal to zero.

   Population losses and gains balance when F + M (losses) = R (gains). The system is then said to be in equilibrium, and F represents a sustainable catch. In the real world, however, the balance between F + M and R will undoubtedly be perturbed from time to time (e.g., by natural fluctuations in M and R), and it is important to ask whether the equilibrium points associated with F + M = R are stable despite such perturbations. In other words, does the system tend to return to the equilibrium point if perturbed?

   To answer this question, we assume that the industry decides upon a certain catch F, which is less than the msy. If F is constant, a plot of F + M and R versus population size would appear as in Figure 27. Here we have assumed that R behaves qualitatively like the recruitment curve for Peruvian anchovies (Figure 14). The intercept of the F + M curve on the vertical axis equals F, because M = 0 when the adult stock is zero. There are two equilibrium points, A and B, where F + M = R.

   The equilibrium points are stable to a small change in the size of the adult stock if such a perturbation leads to changes in the population dynamics that cause the size of the adult stock to return to its equilibrium value.

   Consider equilibrium point B. If the size of the adult stock increases, F + M exceeds R (losses exceed gains), and the size of the adult stock decreases back toward the equilibrium point. Hence equilibrium point B is stable to an increase in the size of the adult stock.

   Is equilibrium point B stable to a small decrease in the size of the adult stock? Is equilibrium point A stable to either an increase or a decrease in the size of the adult stock?

   Now suppose that we move the F + M curve upward (i.e., increase F) until the F + M curve intersects the R curve at only one point. The value of F corresponding to this intersection point is the msy. Is this equilibrium point stable to either a small increase or a small decrease in the size of the fish stock?

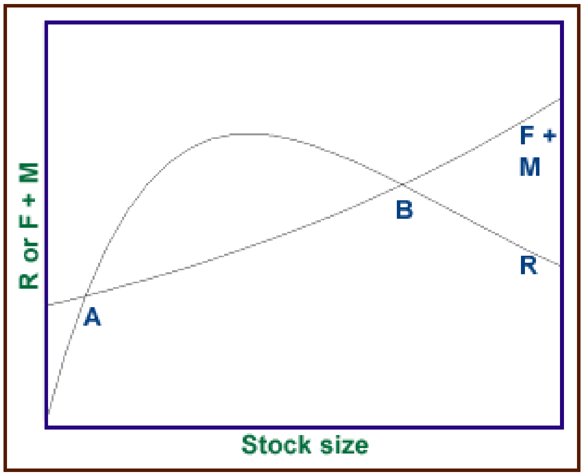

Figure 27. Plot of recruitment (R) and fishing mortality plus natural mortality (F + M) versus size of the adult stock for a constant value of F. Note that F equals the intercept of the F + M curve on the vertical axis, since M = 0 when there are no adult fish.

7. Which of your answers in Question 6 would change if the changes in the size of the adult stock were large rather than small? How large would the change in stock size need to be before the system could no longer return to steady state? Would the amount of change in stock size needed to create an unstable perturbation increase or decrease as the F + M curve moved upward (i.e., as the fish catch increased)?

8. Now let's consider the economics of striving for the msy from a fishery. For purposes of this discussion, we will use the Schaefer approach to fisheries management. We first make a plot of sustainable catch versus fishing effort, as shown in Figure 28. In the case of the Peruvian anchovy fishery, a good measure of effort might be the number of industry units actively involved in the fishery. If we make no effort, we will catch no fish, and the graph will pass through the origin. On the other hand, if we make too much effort year after year, we will eventually wipe out the stock of fish. The sustainable yield under such conditions is also zero. Somewhere in between these two extremes we hope and expect that a modest amount of effort will produce a sustainable catch. Furthermore, if we make just the right effort, the sustainable catch will equal the msy.

   What is the return for each increment of effort above zero? An increment of effort will be a fixed distance in the horizontal direction on our graph in Figure 28. The associated incremental catch is the vertical distance to the curve from the right-hand end of the horizontal line. It is obvious from this analysis that as we approach the msy, the additional catch for each additional unit of effort becomes smaller and smaller. In fact, as we make very small incremental increases in effort approaching the msy, the ratio of incremental catch to incremental effort approaches zero.

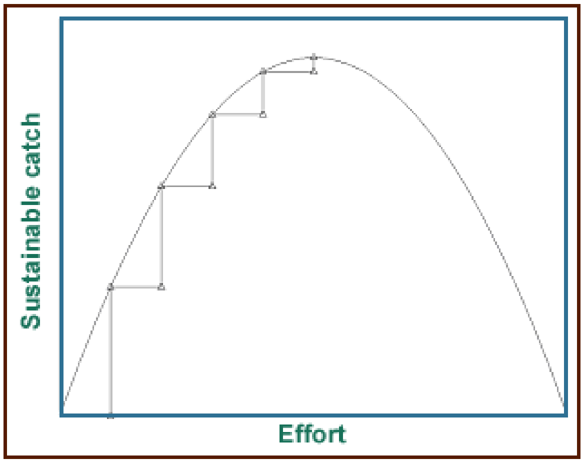

Figure 28. Hypothetical plot of sustainable catch versus fishing effort (Schaefer model) for a species of fish. Horizontal and vertical lines indicate the variable additional catch (vertical distance) associated with a fixed addition of effort (horizontal distance). As the msy is approach, the ratio of additional catch to additional effort approaches zero.

   Obviously it would be silly to make any additional effort if the value of the additional catch did not exceed its cost. Let's assume that the sustainable catch versus effort curve is described by the equation

$$C = (E/2.5)(1 - E/72)$$

where C is the sustainable catch in Mt per year and E is the number of fully employed industry units in the fishery. We will assume, as in the ANCHOVY simulation, that one Mt of anchovies is worth $20,625,000. We will also assume that operating one industry unit at full capacity for one year costs $5,856,000.

a) Make a graph of the equation relating C and E. What is the msy?

b) Make a graph of net profit versus E. At what level of effort is net profit maximized? What is the associated sustainable catch?

9. Based on your answers to Questions 6–8, what do you conclude about the advisability of the msy as a goal of fisheries management?

10. Assume that a codfish lives to be 20 years old and suffers no natural mortality between the ages of 4, when it is recruited to a fishery, and 12. If the fishermen catch 20% of the stock of cod each year without regard to the size or age of the fish, show that a codfish has about one chance in six of surviving to age 12 after being recruited to the fishery.

11. List some important natural resources and classify them as renewable or nonrenewable. Which ones might be renewable if we used them more slowly? Which ones are clearly nonrenewable? Do you think we should exploit some of the nonrenewable ones more slowly?

Meteorology and Physical Oceanography

Note: These questions are based on both the main text and the Appendix.

12. Explain why the Coriolis force tends to focus waves traveling from west to east along the equator. Why is it impossible for equatorial Kelvin waves to travel from east to west?

13. Explain why the atmospheric circulation cells tend to produce cool, dry air at latitudes near 30 degrees. Consider the distribution of the world's great deserts: the Sahara Desert in northern Africa, the Namib and Kalahari deserts in southern Africa, the Great Victoria Desert in Australia, the Gobi Desert in China, the Arabian Desert, and the Great Desert of the southwestern United States and northern Mexico. Does it seem likely that atmospheric circulation has contributed to the existence of these deserts?

14. Explain how air-sea interactions constitute a short-term positive feedback loop but are a component of a long-term negative feedback loop in the control of the El Niño cycle.

15. How would you account for the fact that many of the world's important rain forests are found in tropical latitudes?

16. The coastal region of Peru is normally very dry. In some places no rain may fall for years. However, during El Niños it is not uncommon for torrential rains to fall in these areas. How would you account for this fact based on what you know about air-sea interactions during the El Niño cycle?

17. Show that if the circumference of the Earth is 40×10^3 km, then the speed of the Earth's surface toward the east (V) is given by the equation

$$V = 40\text{x}10^3 \cos(\theta) \text{ km d}^{-1},$$

where θ is the latitude.

18. Suppose that the Earth rotated in the opposite direction. Refer to Figures 21 and 22 and then draw the surface winds and major ocean surface currents that you would expect to find on such an

Earth. How would the climate along the coast of Peru be affected? How would upwelling along the coast of Peru be affected?

19. Open ocean upwelling can occur where the Coriolis force acting on surface currents creates a divergence of surface water flow. On the basis of the current systems shown in Figure 22, where do you think open ocean upwelling might occur?

20. Assume that a satellite in polar orbit passes directly over the South Pole at midnight. Immediately afterward the satellite is headed due north along the 90 degrees W meridian. The orbit of the satellite is circular, and its speed is such that it takes 12 hours to make one complete orbit around the Earth. What are the latitude and longitude of the satellite each hour over a 24-hour period? Plot the position of the satellite on a globe of the Earth. Explain why the orbit does not appear to be circular. The Coriolis force on a moving object depends on both the speed and the latitude of the object. In this case the speed of the satellite is constant, but its latitude is constantly changing. By examining the orbit you have plotted on a globe of the Earth, at which latitudes would you say the Coriolis force is a maximum and a minimum?

Answers to Questions

1. The aim of this question is to point out how easy it is to jump to a reasonable, but incorrect, conclusion in science. The idea that sardines and anchovies compete with one another has appeared in the literature numerous times. The hypothesis has some logical appeal, and it may be true in some cases. However, not all the evidence is consistent with the hypothesis. For example, Garth Murphy has pointed out that the northern anchovy population did not begin to increase until several years after the collapse of the California sardine stock in 1949–50. In other words, there is no evidence that the anchovies somehow gained the upper hand in the competition for resources and drove the sardine population down. On the other hand, the anchovies may certainly have moved in to fill a niche vacated by the sardines.

   While the record of fish scales is consistent with the hypothesis that the anchovies and sardines are in competition with one another, the fish scale record does not prove that the hypothesis is true. An alternative explanation for the fish scale record would be that temperature, or some characteristic of the environment correlated with temperature, is favorable to the sardines when the water is warm and favorable to the anchovies when the water is cool. For example, the physiology of the sardine may be such that it grows or multiplies rapidly when the water is warm but slowly when the water is cool, while the anchovy behaves in the opposite manner. Hence the relative abundance of the two species may be controlled either directly or indirectly by temperature and not by competition for a limiting resource.

2. Given that aquatic organisms convert only about 20% of the food they eat into biomass, anchovy production would be only 20% as much as it is if anchovies were primary carnivores or (20%)(20%) = 4% as much if anchovies were secondary carnivores.

3. This question is best answered with the help of a pocket calculator or a desktop

computer. Given the assumptions in the question, one finds that the biomass of the cohort (the population of fish born in a given month) increases from 0.63 Mt at age 5 months to 1.04 Mt at age 9 months but declines steadily thereafter. If you could precisely control the age or size of the fish you caught, the maximum yield per recruit would be at 9 months. If this harvesting strategy had no impact on recruitment, the annual yield would be (12)(1.04) = 12.5 Mt. Managing the fishery in this way is known as maximizing the yield per recruit. There is, unfortunately, a serious problem with using this approach on Peruvian anchovies. Since the anchovies do not become sexually mature until they are 12 months old, catching all the fish at age 9 months would very quickly wipe out the stock of fish. The total yield is the product of yield per recruit and the number of recruits. Maximizing the yield per recruit maximizes the total yield only if the number of recruits is unaffected by the harvesting strategy. Maximizing the total yield may therefore require harvesting fish older than the age associated with the maximum yield per recruit. On the other hand, when the age associated with the maximum yield per recruit is much greater than the age of sexual maturity, then maximizing the yield per recruit may have little impact on recruitment. The growth of individual fish and the decline in the numbers of surviving fish produce opposite effects in the biomass of the cohort. When the cohort is young the biomass gains due to growth more than offset the losses due to natural mortality. However, as the fish grow older the opposite is true. This is characteristic of any population.

4. In this case the biomass of the cohort increases from 2 Mt at age 5 months to 11.1 Mt at age 25 months and declines thereafter. The age associated with the maximum yield per recruit is therefore 25 months.

5. If we harvest the fish at age 25 months, we are giving the fish two chances to spawn (at ages 12 and 24 months) before removing them from the population. It is possible that only two spawnings per adult would result in erratic and perhaps low recruitment. The solution would be to harvest at a later age, but since we know each cohort is losing biomass after age 25 months, there is no point in waiting any longer than necessary to permit additional spawning. Thus the logical age to harvest would be 37 months.

6. Point B is stable to small increases or decreases in the size of the adult stock. Point A is unstable to any change in the size of the adult stock. If the adult stock increases, R exceeds F +, and the stock increases to the size associated with point B. If the adult stock decreases, F + M exceeds R, and the stock decreases to zero.

   The equilibrium point associated with the msy is stable to an increase in stock size but is unstable to a decrease in stock size. In either case F + M exceeds R if the stock is changed from its equilibrium value. A small decrease in stock size causes the stock to steadily decrease to zero.

7. Only one answer would change. Equilibrium point B is stable to any increase in stock size but is unstable to a decrease below the stock size associated with point A. As the F + M curve moves upward, the decrease in stock size needed to create this unstable situation becomes smaller and smaller, until at the

value of F equal to the msy even a small decrease in stock size will lead to the extinction of the fish stock.

8. A pocket calculator or desktop computer comes in handy here. Of course one can also use calculus to arrive at the answer. The msy is 7.2 Mt with 36 industry units. However, profit is greatest with only 10.45 industry units, catching 3.57 Mt. Operating with an integral number of industry units the answer to part (b) is 11 industry units and a catch of 3.73 Mt per year. Incidentally, one would actually lose over $63 million per year by operating with 36 industry units, according to the equation relating sustainable catch and effort.

9. The obvious answer is that striving for the msy is not very wise. In the Beverton-Holt model, the equilibrium associated with the msy is unstable. Even a small decrease from the equilibrium stock size could lead to a steady decrease in the fish population. Given the well-known year-to-year variability in recruitment of many important stocks of fish, it would seem foolish to insist on taking a catch equal to or very close to the theoretical msy year after year. A single good recruitment year could shift a doomed fish stock back into the viable category, but several poor recruitment years in a row are much more likely to decimate a population if it is being fished at close to the msy. Once a population is in serious trouble, the only rational response from a biological standpoint is to stop or greatly reduce fishing. However, closing the fishery or greatly reducing the catch is sometimes very difficult, even when it is obvious that the stock is in serious trouble.

Question 8 is very thought provoking because we found that the msy is associated with a net loss of money to the fishery. A key assumption was that the sustainable catch per unit effort decreases in a linear manner with effort. In traditional fisheries management theory, catch per unit effort (C/E) is assumed to be proportional to the size of the population of adult fish. If one were fishing blindly or casting one's nets in a random manner, this assumption might be a reasonable one. However, in many purse seine fisheries, including the Peruvian anchovy fishery, C/E may remain virtually constant until the population is reduced to almost zero. One reason is that the population does not remain dispersed over the same geographical area as the number of fish is reduced, but instead contracts into the more favorable regions of the original habitat. This behavior, combined with the tendency of the anchovy to congregate in large schools, means that a plot of sustainable catch versus effort could be rather well described by a straight line drawn from the origin to almost the msy. Economic considerations do not come to the aid of the anchovy.

10. The cod has an 80% chance of surviving each year from age 4 to 12. Since the time interval is eight years, the chance that a fish recruited at age 4 will each its 12th birthday is 0.80 raised to the eighth power, which is 0.168. Hence the cod has about one chance in six (i.e., 1/0.168) of surviving to age 12.

11. There are a great many reasons that could be listed here, and the question is intended primarily to provoke discussion. Whether most resources are renewable or not depends on how slowly

one is willing to exploit them and to what extent one is able and willing to recycle them. In the clearly nonrenewable category one might include radioisotopes such as uranium-235. It seems reasonable to classify solar energy as a renewable resource. The responses to this question could be very interesting.

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12. The Coriolis force pushes to the right of the direction of motion in the Northern Hemisphere and to the left in the Southern Hemisphere. Therefore, water moving from west to east at any off-equatorial latitude will be pushed toward the equator by the Coriolis force. Hence the Coriolis force will focus toward the equator any wave traveling from west to east near the equator. It is impossible for a Kelvin wave to travel from east to west along the equator because the Coriolis force would defocus any such wave.

13. Air sinks near 30 degrees latitude because it has radiated energy into space during its trip from higher and lower latitudes. This air began its journey toward 30 degrees when it rose near the equator or 60 degrees. As it rose and cooled, much of the water vapor in the air condensed and rained out. Since the air had no opportunity to pick up additional water vapor during its trip toward the pole at an elevation of several kilometers, it is naturally cool and dry by the time it sinks.

    The deserts mentioned in this question are undoubtedly all affected by atmospheric circulation cells. The Sahara, Namib, Kalahari, Arabian, and Great Victoria deserts, and the Great Desert of the southwestern United States and northern Mexico, are all located near 30 degrees. In the absence of mitigating factors, they would be expected to experience little precipitation based on Hadley and Ferrel cell circulation. The Gobi Desert, at approximately 40–45 degrees N latitude, cannot be attributed to the sinking of cool, dry air in the subtropical high-pressure zone. However, it does lie in the region of the westerlies, one manifestation of Ferrel cell circulation, which places it in the rain shadow of some very high mountain ranges.

14. The short-term positive feedback loop involves the Walker cell circulation. When the eastern Pacific warms during El Niño, heat exchange between the atmosphere and the ocean causes the atmosphere to become warmer. Consequently the temperature differential between the atmosphere in the eastern and western Pacific is reduced. Since it is primarily the ocean's differential heating of the atmosphere above the eastern and western Pacific that causes Walker cell circulation, the result is a reduction in the Walker cell circulation. In particular, the intensity of the trade winds blowing from east to west across the Pacific near the equator is reduced. This reduction in the strength of the south trade winds reduces the intensity of the South Equatorial Current, with a resultant net movement of water across the Pacific via the Equatorial Countercurrent and Undercurrent. This transfer of water and change in trade wind intensity further decreases the sea-surface temperature differential between the eastern and western equatorial Pacific. During La Niña conditions the process is reversed.

    The negative feedback loop involves the Kelvin and Rossby waves that propagate across the Pacific. During El

Niño conditions, the eastern equatorial Pacific warms and the trade winds slacken. The change in trade wind intensity generates off-equatorial Rossby waves that lower sea level in the western Pacific. Ultimately the lower sea levels in the western Pacific generate Kelvin waves that travel back east and lower sea levels in the eastern Pacific. During La Niña conditions, this process is reversed.

15. The differential heating of the Earth-atmosphere system by the Sun causes air to rise in equatorial latitudes. As the air rises it expands and cools, and water vapor condenses to rain. The precipitation pattern is significantly modified by Walker cell circulation and the presence of mountain ranges, but on average precipitation greatly exceeds evaporation in the tropics, so that is where many of the world's important rain forests are found.

16. Three factors make the coastal region of Peru unusually dry during La Niña conditions. First, Peru lies in the rain shadow of the Andes Mountains. Second, Walker ahd Hadley cell circulations tend to create a precipitation differential between the eastern and western equatorial Pacific, with the western Pacific having far more precipitation. Third, evaporation of water vapor from the offshore ocean is minimized by the cold Peru Current. The temperature of the water in the Peru Current during La Niña conditions ranges from 10 degrees C in the south to no more than 22 degrees C in the north. Although the northernmost part of Peru lies only 3 degrees from the equator, the average air temperature is only 18 degrees to 22 degrees C. Fogs are quite common along the Peruvian coastline, but the water vapor needed to produce rain clouds is lacking. During El Niño conditions, however, the Walker cell circulation is reduced and the offshore ocean becomes much warmer, sometimes by as much as 10^{o}C. Under these conditions, the climate along the Peruvian coast may resemble the climate in the western equatorial Pacific. There is much evaporation of water from the warm ocean, and as the warm air rises and expands, the water vapor condenses to form rain clouds. Heavy rains do not always occur during El Niños; the extent of climate change depends on the degree of sea-surface temperature warming and the alternation of wind patterns. The Andes will certainly continue to create a rain shadow, to the extent that the prevailing winds are still out of the southeast, but during a strong El Niño the change in sea-surface temperature and Walker cell circulation will significantly alter both the evaporation rate from the ocean and the local wind field.

17. Draw a cross section of the Earth through the poles and note that the radius of any east-west cross section equals the radius of the Earth times the cosine of the latitude. Since the circumference is proportional to the radius, and since the Earth rotates once per day, the answer follows immediately.

18. If the Earth rotated in the opposite direction, the direction of the Coriolis force would be reversed. However, differential heating by the Sun would still cause air to rise at the equator and 60 degrees latitude and to sink at the poles and 30 degrees latitude. The net result is that the trade winds would blow out of the southwest and northwest in the Southern and Northern Hemispheres,

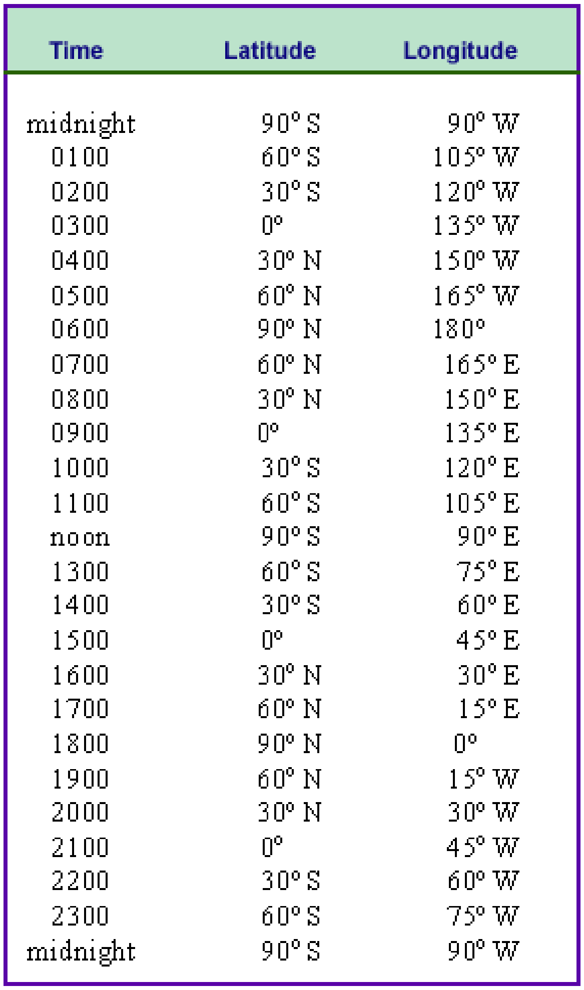
respectively. The westerlies would become the easterlies. Consequently the subtropical gyres would rotate in the opposite direction, and Walker cell circulation would create warm and wet conditions in the eastern tropical Pacific. The climate along the coast of Peru would be warm and extremely wet. The high amount of precipitation would result from the change in Walker cell circulation, from the fact that the offshore ocean would be warm, and from the fact that the Andes Mountains would form a barrier to the flow of the southwest trade winds. Much of the water vapor transported by the trade winds would rain out on Peru.

If the Earth rotated in the opposite direction, the southwest trades would blow directly onshore along the Peruvian coastline. Hence there would be no offshore transport of water to cause upwelling. In fact, the prevailing onshore winds would cause downwelling, and the offshore ocean would be very unproductive. The transport of warm and relatively fresh water from west to east across the Pacific would also tend to depress the nutricline in the eastern Pacific, as is the case during El Niño conditions now. Thus even if upwelling were to occur along the coast of Peru, the upwelled water would very likely not contain a high concentration of nutrients and so would have little impact on productivity.

19. On the basis of Figure 22, there are two places where one might anticipate upwelling in the open ocean to occur. The South Equatorial Current flows from east to west on both sides of the equator. Recalling that the Coriolis force diverts flow to the right of the direction of motion in the Northern Hemisphere and to the left in the Southern Hemisphere, it is obvious that the Coriolis force will tend to create a divergence of surface water flow at the equator. In fact such a divergence does exist, and the equatorial upwelling system is probably the best-known open ocean upwelling system. Given that the Coriolis force is zero at the equator, it may seem surprising that there is much upwelling in this area. The off-equatorial Coriolis force is certainly small at low latitudes, and the fact that upwelling caused by this small force has a significant impact on productivity in the sea attests to the ineffectiveness of other mechanisms in bringing nutrients into the euphotic zone.

    Based on the current systems shown in Figure 22, the other area where open-ocean upwelling should occur is at about 10 degrees N latitude. Here the effect of the Coriolis force on the eastward-flowing Equatorial Countercurrent and the westward-flowing North Equatorial Current creates a divergence of surface flow. This upwelling area is given little or no attention in textbooks on oceanography, but its effect on fish production is well known to the fishing industry.

20. The Earth rotates to the east at a rate of 15 degrees longitude per hour, and the satellite is moving from pole to pole at a rate of 30 degrees latitude per hour. Thus the position of the satellite as a function of time is as follows:



Time	Latitude	Longitude
midnight	90° S	90° W
0100	60° S	105° W
0200	30° S	120° W
0300	0°	135° W
0400	30° N	150° W
0500	60° N	165° W
0600	90° N	180°
0700	60° N	165° E
0800	30° N	150° E
0900	0°	135° E
1000	30° S	120° E
1100	60° S	105° E
noon	90° S	90° E
1300	60° S	75° E
1400	30° S	60° E
1500	0°	45° E
1600	30° N	30° E
1700	60° N	15° E
1800	90° N	0°
1900	60° N	15° W
2000	30° N	30° W
2100	0°	45° W
2200	30° S	60° W
2300	60° S	75° W
midnight	90° S	90° W

If these points are plotted sequentially on a globe, the effect of the Coriolis force will be obvious. The orbit is by no means circular to an observer on the Earth. However, to someone in outer space, the satellite would appear to be traveling in a perfectly circular orbit. The curvature of the orbit apparent to someone on the Earth is maximal at the poles and zero at the equator. Hence it is reasonable to infer that the Coriolis force is maximal at the poles and zero at the equator. Note that if the orbital positions of the satellite are plotted on a Mercator projection of the Earth, the orbit will plot as a series of parallel lines. The only way to get an accurate picture of the shape of the orbit as perceived by a person on Earth is to use a globe.

Glossary

aphotic zone—In the oceans, the stratum of water where there is inadequate light to support photosynthesis (see also euphotic zone).

Beverton-Holt model—The model or method of fisheries management developed by Ray Beverton of the Fisheries Laboratory in Lowestoft, England, and Sidney Holt of the United Nations Food and Agriculture Organization in Rome, Italy. The model uses the population dynamics of the stock of fish to predict the sustainable yield as a function of the size of the adult stock.

boundary current—A current that flows parallel to and close to a continental coastline. Most boundary currents result from the deflection of transoceanic zonal currents by continental land masses.

Clupeids—A family of fish including anchovies, sardines, and herring. A primitive form of marine fish, the clupeids account for the largest percentage of world catch of all fish, shellfish, and other aquatic organisms.

Coriolis force—An apparent force that acts on particles and fluids moving over the surface of the Earth, because the Earth is a rotating sphere. The force deflects moving objects to the right of their direction of motion in the Northern Hemisphere and to the left in the Southern Hemisphere. It is zero at the equator and reaches its maximum value at the poles. The Coriolis force is a weak force, and its effect becomes apparent only if objects are moving very rapidly or (in the case of ocean currents) over great distances.

Countercurrent—An ocean current that flows in the opposite direction to the dominant, wind-driven surface current. Countercurrents may exist at the surface, as in the case of the Equatorial Countercurrent but more commonly are subsurface currents, like the Equatorial Undercurrent or the Peru Undercurrent.

Detritus—Nonliving organic particles, including fecal material, molts, dead organisms, or parts of dead organisms.

Ekman transport—movement of surface ocean currents at an angle to the direction of the wind, due to the effect of the Coriolis force. The currents flow at an angle to the right of the direction of the wind in the Northern Hemisphere and to the left in the Southern Hemisphere. Also referred to as Ekman drift.

El Niño—An oceanic event that occurs roughly every three to seven years, when warm surface seawater of relatively low salinity moves southward from the region of the equator along the coast of Peru to as far as 12 degrees S latitude. It is frequently associated with a significant reduction in productivity of the coastal current system, either because upwelling physically ceases or because the upwelled water is no longer rich in nutrients. The intruding water may overflow the Peru Coastal Current to a depth of as much as 30 meters.

ENSO—(El Niño Southern Oscillation) An irregular meteorological oscillation characterized by two extreme conditions, a warm phase (El Niño) and a cool phase (La Niña), that is driven by exchanges of heat and water between the ocean and atmosphere in the tropical Pacific.

essential nutrients—Those elements required by virtually all living organisms. The major essential nutrients are oxygen, carbon, nitrogen, hydrogen, phosphorus, sulfur, potassium, magnesium, and calcium.

Essential nutrients required in lesser amounts include iron, manganese, copper, zinc, boron, silicon, molybdenum, chlorine, vanadium, cobalt, and sodium.

euphotic zone—In the oceans, the stratum of water where there is adequate light to support photosynthesis. The euphotic zone usually extends from the surface to the depth where the light intensity is approximately 0.1–1.0% of surface irradiance, depending on the season of the year and latitude.

Ferrel cell—An atmospheric circulation cell in the region of the westerlies (between roughly 30 and 60 degrees latitude) caused by the differential heating of the Earth-atmosphere system.

Finfish—Fish with fins, as opposed to shellfish.

Fishery—The industry or occupation of catching, processing, and selling fish. The term is also sometimes used to refer to fishing grounds.

Gadoids—A family of fish including cod, pollock, haddock, and hake. Gadoids live mostly in the shallow to moderate depths of northern seas, where they form the basis for extensive commercial fisheries.

guano birds—Fish-eating birds whose droppings, called guano, are utilized in the production of fertilizer. This designation is regional. The guano birds consist primarily of cormorants and to a lesser extent of gannets and pelicans. They inhabit offshore islands along the coast of Peru. The guano bird population, which in the past has approached 30 million, has in recent years been as low as half a million due to the impact of the anchovy fishery and El Niño. Guano birds feed primarily on anchovies.

gyre—In oceanography, a basin-wide continuous current system formed by alternating boundary currents and wind-driven, transoceanic zonal currents.

Hadley cell—An atmospheric circulation cell in the region of the trade winds (between roughly 30 degrees latitude and the equator) caused by the differential heating of the Earth-atmosphere system.

Kelvin wave—An internal wave whose dynamics are affected by the Coriolis force and whose maximum amplitude occurs at the equator. The wavelength of Kelvin waves is on the order of thousands of kilometers, and their existence requires the presence of a barrier to the right of their direction of motion in the Northern Hemisphere and to the left in the Southern Hemisphere. For coastal Kelvin waves, the barrier is the coastline. For equatorial Kelvin waves, the barrier is the equator.

La Niña—the phase of the ENSO cycle characterized by cool sea surface temperatures in the eastern tropical Pacific, stronger-than-usual trade winds, vigorous upwelling and high biological productivity in the equatorial upwelling system and coastal upwelling system along the west coast of both North and South America, humid and wet conditions in the western tropical Pacific, and cool and very dry conditions along the coastlines of both North and South America.

lantern fish—Small marine fish belonging to the family Myctophidae that live in the deep sea during the day and migrate to the surface or near-surface at night.

match/mismatch hypothesis—A hypothesis developed by David Cushing of the Fisheries Laboratory in Lowestoft, England, to explain the highly variable recruitment observed in many important commercial fish stocks. The hypothesis holds that there is often a temporal or spatial mismatch between the availability of food for larval fish and the larval fish's greatest need for food. A good match between supply and demand is followed by spectacular recruitment, but during most years recruitment is much reduced due to the mismatch between supply and demand at a critical stage in larval development.

maximum sustainable yield—The maximum fish catch that can be sustained year after year, more or less indefinitely, without destroying the stock of fish.

meridional circulation cell—A semiclosed atmospheric circulation cell that results from the differential heating of the Earth's atmosphere by the Sun. Air tends to rise at the equator and at 60 degrees latitude and to sink at the poles and at 30 degrees latitude. The rising or sinking air then moves either toward the poles or toward the equator to complete the circulation cell. Both the trade winds and the westerlies are surface manifestations of meridional circulation cells. These circulation cells have a major influence on the distribution of precipitation over the surface of the Earth.

mixed layer—The surface layer of the ocean where the chemical and physical characteristics of the weather are rather uniform due to turbulent mixing caused by winds blowing over the surface of the ocean. The mixed layer usually extends from the surface to a depth of tens of meters to perhaps several hundred meters, depending on the latitude and season of the year.

phytoplankton—Minute, floating aquatic plants. Phytoplankton are the base of the food chain in the ocean. They synthesize virtually all of the organic matter produced in the ocean.

polar cell—An atmospheric circulation cell in polar latitudes caused by the differential heating of the Earth-atmosphere system.

protein utilization efficiency—The percentage of the protein in a particular food that is retained by human beings, assuming they are provided with an adequate diet in all other respects. Differences in protein utilization efficiency between different foods largely reflect differences in the amino acid composition of protein.

purse seine—A usually very large net hung like a curtain in the water and drawn around a school of fish by the fishing boat. A line at the bottom of the net is drawn tight (pursed) to prevent the fish from escaping through the bottom. The net is then pulled in until the fish are sufficiently concentrated, and the fish are removed either with suction pumps or a brail (dip net).

recruitment—The attainment by fish of a size sufficient to be caught by fishing gear. Being recruited to the stock of catchable fish does not mean that a fish is caught but only that it is big enough to be caught.

renewable resource—A resource that can be replaced as fast as it is exploited, as opposed to a nonrenewable resource. Fish, along with most foods, are considered renewable resources. Petroleum and metal ores are not.

Rossby wave—An internal wave whose dynamics are affected by the Coriolis force and whose wavelength is on the order of thousands of kilometers. Rossby waves propagate off the equator, and their speed is strongly dependent on latitude. Near the equator a Rossby wave moves at about 50–

60 kilometers per day, but at 12 degrees latitude the speed is only about 10 kilometers per day. The Rossby waves associated with El Niño invariably propagate in a westerly direction.

Schaefer model—A model or method of fisheries management developed by Milner Schaefer of the Scripps Institution of Oceanography in La Jolla, California. The model uses information on fish catch and population size to estimate the sustainable yield as a function of the size of the adult stock.

Southern Oscillation Index—The difference in sea level pressure between the subtropical high-pressure region at about 30 degrees S latitude in the southeastern Pacific and the Indonesian equatorial low-pressure region in the western Pacific. Frequently the Southern Oscillation Index is reported as the difference in pressure between Easter Island and Darwin, Australia.

subtropical gyre—A very large surface circulation system driven by the trade winds and westerlies and extending from roughly the equator to a latitude of about 45°. The subtropical gyres cover approximately 40% of the ocean’s surface area. Their rotation is clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere.

sustainable yield—A yield that can be sustained year after year, more or less indefinitely. See also maximum sustainable yield.

trade winds – The surface winds that blow out of the east and toward the equator between the subtropical high-pressure region near 30 degrees latitude and the low-pressure region near the equator.

upwelling—The upward movement of water from depths of typically 40–80 meters at speeds of approximately 1–3 meters per day, resulting from the lateral movement of surface water. Upwelling is especially well developed along the coast of Peru, where it may supply virtually all of the nutrients to the euphotic zone.

virgin stock—The stock of fish prior to any commercial fishing activity.

Walker cell—An atmospheric circulation cell near the equator with an east-west motion that results from air-sea interactions and the westward movement of the trade winds. The circulation is associated with the rising of warm, moist air at the western edge of the ocean basin and the sinking of relatively cool, dry air at the eastern edge. The vertical extent of the circulation is approximately 15 kilometers.

water column—A hypothetical column extending from the surface to the bottom of a body of water.

westerlies—The surface winds that blow out of the west and away from the equator between the subtropical high-pressure region near 30 degrees latitude and the subpolar low-pressure region near 60 degrees latitude. The westerlies are much more variable temporally and spatially than the trade winds.

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The ANCHOVY Simulation

Introduction: So You Think You Can Do Better?

The ANCHOVY simulation gives you a chance to try your skills at fisheries management. You can invest in fishing boats and fishmeal plants, decide how many fish to catch and how many months of the year to keep the fishery open, and turn on random variations in recruitment and natural mortality to see how these environmental uncertainties affect the potential yields from the fishery. Finally, you can allow El Niños to occur and determine their impact on the fishery yields.

The economic constraints reflect conditions that prevailed during the 1960s. The simulation is designed to illustrate the folly of overcapitalization and the importance of not fishing down the stock to the point where recruitment is seriously compromised.

By running the simulation you can determine the maximum sustainable yield from the fishery under steady-state conditions, and you can determine the relationship between sustainable yield and the size of the adult stock. The simulation program was written using Matlab and can be run on either Macintosh or PC desktop computers.

Getting Set Up

You begin the simulation by typing in the word ANCHOVY and hitting the return key.

COMPUTER: WELCOME TO THE ANCHOVY GAME

COMPUTER: HOW MANY YEARS WOULD YOU LIKE THE SIMULATION TO RUN?

The simulation assumes that you begin with the virgin stock of anchovies, and it will of course take a few years to fish down that stock and settle down. A good running time is 100 years, but you can use shorter or longer times if you like.

ACTION: Type in the number of years and press the enter key.

COMPUTER: HOW MANY INDUSTRY UNITS DO YOU WANT TO BUY?

In ANCHOVY one fishing boat can catch about 50 tonnes of anchovies per day, and it takes 32 boats to supply enough anchovies for each fishmeal plant, which can process about 1,600 tonnes of anchovies per 20-hour day (down time at the plant is assumed to average 4 hours per day). One fishmeal plant and 32 fishing boats constitute one unit of the industry.

Each fishing boat has a crew of 13, and each fishmeal plant employs 50. So each industry unit employs 50 + 32 x 13 = 466 people. The variable costs (salaries, fuel, etc.) for a unit of the industry average $14,000 per operating day, or about $14,000/466 = $30 per person-day. Fixed costs for one unit of the industry are assumed to be $180,000 per month.

About 5.3 tonnes of anchovies are required to produce 1.0 tonne of fishmeal. The wholesale value of the fishmeal is about $110 per tonne. So 1,600 tonnes of anchovies yield 302 tonnes of fishmeal worth $33,200. You can catch about 0.42 Mt of anchovies per year with one industry unit operated at full capacity, and you will make a profit of about $2.9 million.

In summary, for each industry unit:

Fishing boats = 32
Fishmeal plant = 1
Personnel = 466
Fixed costs = $180,000 per month
Variable costs = $14,000 per operating day
Revenue = $33,220 per operating day

A workweek is assumed to consist of seven days (sorry, no time off in the fishing industry), and all months are assumed to contain 365/12 days. If you invest in 20 industry units, you have the capability of catching 20 x 365 x 1,600 = 11.68 Mt per year or almost 1 Mt per month. The game does not allow you to catch more anchovies in a month than your investment in fishing boats and fishmeal plants will permit.

ACTION: Type the number of industry units you want to buy and press enter. (You cannot buy fractional parts of industry units because you cannot build part of a fishmeal plant. If you try to invest in 8.7 industry units, for example, the computer will ignore the 0.7 and give you 8.0 units.)

Controlling the Catch

ANCHOVY assumes that prior to your entry into the industry there has been no anchovy fishing. The virgin stock of adults (age five or more months) averages 14 Mt over the course of a year but varies a bit from month to month because recruitment is not constant. Your job is to set the catch quotas for as long as you choose to play the game.

There are several ways to control the catch. First, you can set an upper bound on the catch. Obviously that upper bound must be no greater than the maximum possible catch implied by the number of industry units you have purchased. Second, you can shut down the fishery for a month at a time if the biomass of anchovies has dropped below a level that you specify. The fishery will remain closed until the biomass has increased above your threshold value. A third built-in control is the fact that the game shuts down the fishery for a month at a time if your requested catch for the month exceeds the biomass of all the anchovies. In other words, not only are you forbidden to wipe out the stock of anchovies, but your catch will be set to zero for any month in which your requested catch would produce that result. Finally, you are given the option of arbitrarily closing the fishery during certain months of each year.

COMPUTER: DO YOU WANT TO HAVE ANY CLOSED SEASONS (NO = 0, YES =1)

ACTION: Type **1** for **yes** or **0** for **no** and press enter.

If you responded yes, you will then be asked: LIST THE MONTHS THE FISHERY IS TO BE CLOSED; JAN = 1, FEB = 2, ETC., IN MATRIX FORMAT, E.G., [1 2 7 10]

For example, if you want the fishery to be closed during May, June, and July, you would type [5 6 7] and press enter. The months do not have to be consecutive, and you can enter them in any order. For example, typing [6 3 8] would cause the fishery to be closed during the months of March, June, and August.

COMPUTER: AT WHAT LEVEL OF ANCHOVY BIOMASS WOULD YOU LIKE TO TEMPORARILY CLOSE THE FISHERY (ANSWER IN MILLION TONNES)?

ACTION: Type in the anchovy biomass below which you want the fishing to stop and press enter. You can type in zero if you like. As noted, the biomass will never drop to zero, because the simulation will always shut down the fishery if the requested catch for the month exceeds the biomass at that time.

At this point the computer will tell you your maximum allowable catch in Mt. For example, if you invested in 20 industry units and specified no closed seasons, your maximum allowable annual catch is 11.68 Mt. If you specified a closure during two months, then your maximum allowable catch would be (10/12) x 11.68 = 9.73 Mt.

COMPUTER: WHAT WOULD YOU LIKE THE ANNUAL CATCH TO BE IN MILLION TONNES?

You can specify any catch less than or equal to the maximum allowable. (If you specify a larger number, the computer will set the catch equal to the maximum.) Why would you want to specify a catch less than the maximum? By adding industry units one at a time you increase the allowable catch by 0.584 Mt (if the fishery is open year round). Economically it is unwise to specify a catch that is not an integral multiple of 0.584 Mt. For example, if you want to try to catch 5.0 Mt of fish per year, then you would need to invest in at least nine industry units, which would allow you to catch 5.256 Mt at full capacity. However, keep in mind that the more your capacity to catch fish exceeds your actual catch, the less money you will make. Idle boats and fishmeal plants cost you money.

ACTION: Type in a number and press enter.

The computer will tell you what your maximum annual catch will be, your estimated operating costs, your maximum annual revenue, and your maximum annual profit. The actual numbers at the end of the simulation may be less than these if the fishery is forced to shut down from time to time because the anchovy biomass has dropped below the threshold you specified or because your requested catch has threatened to wipe out the stock during some months.

Random Variability

The problems that will confront you in achieving your catch goals are environmental variability and uncertainty. You can reduce the uncertainty to a minimum by requesting that recruitment and natural mortality be nonrandom and that there be no El Niños. The natural mortality rate will be 16% per month, and the relationship between recruitment and adult population size will follow the curve shown in Figure 14.

COMPUTER: DO YOU WANT RANDOM RECRUITMENT AND NATURAL MORTALITY? (NO = 0, YES = 1)

If you request random recruitment and natural mortality, then recruitment will on the average follow Figure 14 but will vary in a random manner between a minimum equal to 2/3 and a maximum equal to 4/3 of the value predicted by the curve. Similarly, natural mortality will average 16% per month but will vary in a random manner from a minimum of 6.4% to a maximum of 25.6% per month (a factor of four). This range of variability is consistent with field observations (see Figure 7).

ACTION: If you want random recruitment and natural mortality, respond **yes** by typing **1**. If not, type **0**.

COMPUTER: DO YOU WANT EL NINOS TO OCCUR? (NO = 0, YES= 1)

The sequence of El Niños is taken from a 470-year record dating back to 1520. During this time there were a total of 110 El Niños, 62 classified as moderate, 33 as strong, 10 as strong/very strong, and 9 as very strong. If you elect to subject your fishery to El Niños, the program starts you out at a random point in the historical record and continues for as many years as you choose to play the game. The cycle repeats itself every 470 years. All El Niños begin in January and last for one year.

During El Niños the growth rates of anchovies are reduced by an amount directly proportional to the strength of the El Niño. El Niños are assumed to affect the productivity of the anchovy stock, but there is no consistent correlation between El Niños and either natural mortality or recruitment. El Niños do depress photosynthetic rates off the coast of Peru. During the months of peak intensity the depression may amount to a factor of 10 or more, but annual average photosynthetic rates do not fluctuate as much. The lowest annual photosynthetic rates are about 60% of the maximum rates. ANCHOVY assumes that the lowest rates are associated with very severe El Niños and that the extent of the depression is linearly related to the intensity of the El Niño. So El Niños are assigned to one of four categories: moderate, strong, strong/very strong, and very strong. The growth rates of the anchovies are assumed to be directly proportional to the photosynthetic rates and hence are assumed to be depressed by 10%, 20%, 30%, and 40%, respectively.

ACTION: As before, **0** means **no**, and **1** means **yes**.

Once you push the enter key, the simulation will run for the number of years you have specified. The computer will print out the average annual catch in Mt, and the average annual profit, cost, and revenue, all in millions of dollars. The computer will also generate four graphs: annual catch of anchovies in Mt, annual profit in millions of dollars, average annual anchovy biomass in Mt, and annual recruitment (R) and fishing mortality (F) in trillions of fish.

Some Tips

When you are first becoming familiar with the game, set the catch to zero so that you can study the behavior of the anchovy population in the absence of fishing. With random recruitment and natural mortality, you will find that the anchovy stock goes through some perhaps surprising fluctuations. Over the course of 100 years, the biomass may be as high as 3040 Mt and as low as 5 Mt. This natural variability is what makes management of the fishery difficult. If you invest in enough industry units to take full advantage of the good years, you will lose money during bad years, because your boats and fishmeal plants will be idle much of the time during bad years. On the other hand, if you invest in only a few industry units to avoid losing money during the bad years, you will be unable to take full advantage of the years when the anchovies are abundant.

You will find that one of the critical determinants of success in managing the fishery is the size of the stock when the fishery is shut down. If you make that cutoff too low, recruitment to the adult stock will be poor, and the fishery will remain unproductive for the rest of the game. This is known as recruitment overfishing. On the other hand, if you make the cutoff too high, the fishery will be shut down so much of the time that your average catch will again be small. This is underfishing.

There are several interesting questions you can explore with the game. First, try managing an industry of the size that actually existed in the late 1960s: 1,450 boats (45 industry units). Can you make a long-term profit with 45 industry units? Second, is the strategy that maximizes the long-term profit the same strategy that maximizes the long-term catch? Third, is there any advantage to having closed seasons, and if so, does it make any difference at what time of year you close the fishery?