protected throughout their range, the lack of enforcement of hunting laws and the need for supplemental protein in many areas contributes to hunting pressure. Damming of rivers poses an emerging threat, both directly and indirectly. Crushing in dam structures has been reported from Senegal, Ghana and Nigeria (and also in Florida). Dams on many rivers in the manatee's range may cut off needed seasonal migrations. Killing of manatees as they aggregate at freshwater overflows of dams has also been reported. In recent years, there has been increasing trade in West African manatees for commercial display facilities. Accelerating habitat destruction and cutting of mangroves for construction and firewood will have negative effects. There is considerable cause for concern for the manatee's future in several regions of Africa unless hunting is reduced. However, there has been increasing interest in West African manatee conservation, and several countries are moving towards increased protection involving coastal sanctuaries and law enforcement. To prevent future loss of manatees from all but a few remote and protected areas of West Africa, law enforcement and protection must become regional in scale, improvements must be made in economic conditions that contribute to hunting, and modifications will be needed on dams and other structures that kill manatees.

See also

Marine Mammal Evolution and Taxonomy. Marine Mammal Overview. Marine Mammals, History of Exploitation.

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SLOPE FRONTS

See **SHELF-SEA AND SLOPE FRONTS**

SMALL PELAGIC SPECIES FISHERIES

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Introduction

The so-called 'pelagic' fish are those that typically occupy the midwater and upper layers of the oceans, relatively independent of the seabed (*see* **Pelagic Fishes**). Small pelagic species include herrings and sprats, pilchards and anchovies, sardines, capelin, sauries, horse mackerel, mackerels, and whiting. Most of these fish have a high oil content and are characterized by a strong tendency to school and to form large shoals. These features have contributed to the development of large fisheries, using specialized techniques, and to a variety of markets for small pelagic species.

Two of the major pelagic species (herring and capelin) are found in polar or boreal waters, but most are found in temperate or subtropical waters. The sardine, anchovy, mackerel, and horse mackerel are each represented by several species around the world, with the largest concentrations being found in the highly productive coastal upwelling areas typically along western continental coasts. Intense fisheries have developed on a few small pelagic species, which occur in very dense aggregations in easily accessible areas near the coast. In recent years the largest fisheries have been on Atlantic herring, Japanese anchovy and Chilean Jack mackerel, although the dominance of individual fisheries has changed as the abundance of these species has fluctuated due to both natural factors and intense fishing. Small pelagic fish species with recent annual landings exceeding 100 000 t are listed in **Table 1**. Over the past three decades, fisheries for small pelagic species have made up almost half the total annual landings of all marine fin-fish species (**Figure 1**).

Catch Techniques in Pelagic Fisheries

Pelagic fish, by definition, are found near the ocean surface or in middle depths. As a result, pelagic fisheries must search larger volumes than demersal fisheries. However, most pelagic fish species exhibit behaviors that increase their catchability. The most import characteristic is shoaling, in which individuals of the same species form and travel in aggregations. Several pelagic species also exhibit clear patterns of vertical migration, often staying deep in the water column, or near bottom, by day but migrating to surface waters at dusk. In some cases fishers have used techniques such as artificial light sources to enhance shoaling behavior and improve fishing.

Pelagic fish shoals can be very large, which greatly increases their detectability. Surface shoals can be located visually, using spotters from shore or aboard vessels, and aerial searches are used in the fishery for some species. The location and depth of shoals can be determined using hydroacoustics, which has developed greatly in association with pelagic fisheries in recent decades. Echo sounders and sonars transmit an acoustic signal from a transducer associated with the vessel and receive echoes from objects within the path of the beam such as fish and

Table 1 Main species of pelagic fish with world catches greater than 100 000 tonnes in 1998. Catch information from FAO 1999

Order	*Family*	*Species*		*Catch (10^3 tonnes)*
Beloniformes	Scomberesocidae	Pacific saury	*Coloabis saira*	181
Clupeoidei	Clupeidae	Gulf menhaden	*Brevoortia patronus*	497
		Atlantic menhaden	*Brevoortia tyrannus*	276
		Atlantic herring	*Clupea harengus*	2419
		Pacific herring	*Clupea pallasi*	498
		Bonga shad	*Ethmalosa fimbriata*	157
		Round sardinella	*Sardinella aurita*	664
		Goldstripe sardinella	*Sardinella gibbosa*	161
		Indian oil sardine	*Sardinella longiceps*	282
		California pilchard	*Sardinops caeruleus*	366
		Japanese pilchard	*Sardinops melanostictus*	296
		Southern African pilchard	*Sardinops ocellatus*	197
		South American pilchard	*Sardinops sagax*	937
		Araucanian herring	*Strangomera bentincki*	318
	Engraulidae	Pacific anchoveta	*Cetengraulis mysticetus*	181
		European anchovy	*Engraulis encrasicolus*	492
		Japanese anchovy	*Engraulis japonicus*	2094
		Peruvian anchoveta	*Engraulis rigens*	1792
		European pilchard	*Sardina pilchardus*	941
		European sprat	*Sprattus sprattus*	696
Gadiformes	Gadidae	Southern blue whiting	*Micromesistius australis*	184
		Blue whiting	*Micromesistius poutassou*	1191
Percoidei	Carangidae	Cape horse mackerel	*Trachurus capensis*	184
		Japanese jack mackerel	*Trachurus japonicus*	341
		Chilean jack mackerel	*Trachurus murphyi*	2056
		Atlantic horse mackerel	*Trachurus trachurus*	388
Salmonoidei	Osmeridae	Capelin	*Mallotus villosus*	988
Scombroidei	Scombridae	Indian mackerel	*Rastrelliger kanagurta*	284
		Chub mackerel	*Scomber japonicus*	1910
		Atlantic mackerel	*Scomber scombrus*	657
		Japanese Spanish mackerel	*Scomberomorus niphonius*	552
Scorpaeniformes	Hexagrammidae	Atka mackerel	*Pleurogrammus azonus*	344

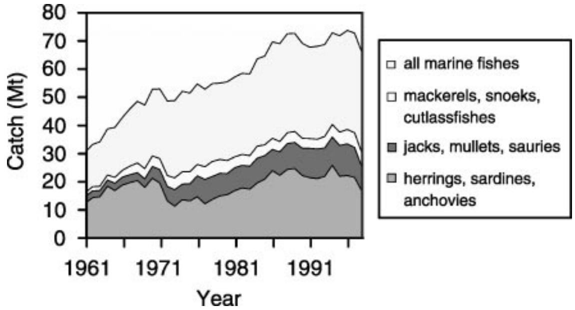

Figure 1 World catch (million tonnes, Mt) of groups of small pelagics in relation to the total world catch of all marine fish species. Catch information from FAO (1999).

the seafloor. When sector scanning and multibeam sonars are mounted on vessels within a moveable housing, they can be used to search the water column ahead and to the sides of the vessel. This permits improved detection of schools and targeting of shoals throughout the water column.

Methods for catching small pelagic fishes range from very simple to highly sophisticated. This section deals only with those catch methods and specialized gear that have been developed specifically for pelagic fisheries, and are widely used around the globe. In general, these methods can be placed in several broad categories:

1. static gear (trap, lift net and gill net)
2. towed gear (trawl net)
3. surrounding gear (purse seine, ring net and lampara net).

Static Gear (Trap, Lift Net and Gill Net)

The earliest fisheries for small pelagic species relied on shoals of fish encountering and becoming entrapped in nets that were fixed to the bottom or floating passively. A variety of forms of trap nets have been used historically where small pelagic species such as herring and mackerel occur near shore. Typically these nets have a lead and wings which intercept and direct a school of fish into a pot or pound where they remain alive until dipped or seined from the net. In the Bay of Fundy and Gulf of Maine, for example, juvenile herring have been caught in heart-shaped traps known locally as weirs (made of fine mesh covering poles driven into the seabed), or even trapped in coves by closing off the entrance with a seine. These catches have formed the basis of the canned sardine industry for over a century.

Unlike trap nets, a lift net functions as a moveable container that traps the target fish. The shoal swims over the net, and the fish are caught by lifting the net and thereby trapping the shoal within. Fish are then usually removed by dipnet. This type of gear is used commonly in South-east Asia. The nets may be operated from shore or from specialized vessels. These vessels often use bright lights to lure the target shoals over their lift nets.

The gill net catches fish by serving as a barrier or screen through which fish larger than the mesh size cannot pass, but become entangled, usually by their gills, and are removed when the net is retrieved. The gill net is constructed of a section of fine netting with a border of stronger netting. The bottom of the net is weighted with a leadline, and the top or headline has floats so that the net hangs vertically in the water. Fishing typically involves a string of nets that can be set to a desired depth. Gillnets may be moored in a specific location (set nets) or may be allowed to float with the prevailing winds and currents (drift nets).

Towed Gear (Trawl Net)

The midwater trawl was developed specifically to capture pelagic species. Like the bottom trawl commonly used in demersal fisheries, it is towed behind the vessel. Trawling may be undertaken from either single or paired vessels, although trawling by one vessel is much more common. The net is set to the depth for a particular, targeted school of fish, and is towed only long enough to pass through (or to encompass) the school.

The trawl net is usually conical in form and may be very large. Typically, the net mouth, which may be circular or square, is held open during a tow by doors which spread the wings of the net, together with the buoyancy of floats placed on the headline, and a weighted footrope attached to the bottom of the net mouth. A transducer is placed on the headline so that the depth of the net can be monitored during a tow, and the school of fish can be seen passing the mouth into the net. Additional sensors on the trawl provide information about the state of the gear and potential catch.

Surrounding Gears (Purse Seine, Ring Net and Lampara Net)

The characteristic of pelagic fishes to occur in large shoals, right at the surface, makes them vulnerable to capture with surrounding gears. The purse seine is used worldwide and accounts for an appreciable fraction of the total annual catch by global fisheries. In general, this fishing method involves setting out a long net hanging vertically in the water to surround a school of fish. The top of the net usually floats at the surface. Following envelopment of the school, the bottom of the net is pulled together to trap the fish in a cup or 'purse' of netting. The net is hauled gradually, such that the purse shrinks in size until the school of fish is alongside the vessel. The fish are then brought aboard using pumps or a lifting net. The seine may be very large, up to 730 m long and 180 m deep. The main area of the net is usually of constant mesh size and material. Only the section of the gear wherein the catch will be concentrated during retrieval is strengthened. Purse seining usually targets fish found at the surface to a depth of about 130 m.

Purse seining may use one or two vessels. The gear is set beginning with one end and the vessel deploys the gear as it slowly steams around the fish school. When two vessels are used, the tasks of setting and retrieving the seine are shared between the vessels, and each vessel carries part of the gear. During deployment, each vessel sets the gear, beginning with the middle of the seine net, and then they proceed to envelope the school. Most often retrieval is with the aid of a power block.

A variation of the purse seine is the ring net. This encircling net is generally smaller than a purse seine and is used in relatively shallow waters. Ring net gear is usually used by pairs of vessels in the 12–19 m range.

A third type of surrounding gear is the lampara net. Although similar in shape and use to a purse seine, the bottom of this net is not pursed during retrieval. The float line on a lampara net is much longer than the weighted bottom line, which causes the middle portion of the net to form a bag. When the net is hauled, both sides (wings) of the gear are retrieved evenly. The leadlines meet, effectively closing off the bag of the net. The bag is brought alongside the vessel and the catch transferred aboard.

Products Derived from Pelagic Fisheries

Some small pelagic species (notably Atlantic herring) have been important as food, and have sustained coastal communities for centuries. Principal products (those used for human consumption) are listed in **Table 2**. The main reason for the underutilization of small pelagics as food is a lack of consumer demand. The development of new products and uses may increase this demand. One such innovation is the use of small pelagics as raw material in processed seafoods such as surimi.

More than half (approximately 65% during the period 1994–1998) of the harvest of small pelagic species in recent years has not been used directly for food, but rather has been processed into a variety of by-products. Some of these by-products, such as fish protein concentrate, may then be used in the production of foodstuffs for human consumption. The main by-products of the pelagic fisheries are:

1. fish meal and oil
2. fertilizer
3. silage and hydrolysate
4. compounds for industrial, chemical and pharmaceutical products.

Fish Meal and Fish Oil

Fish meal and fish oil are the most important by-products produced from pelagic fish. Meal is used mainly as a protein additive in animal feeds in both agriculture and aquaculture. During the 1980s the annual world production of fish meal was in the order of 6–7 million tonnes (Mt), requiring landings of 35–40 Mt of whole fish. Production has declined somewhat during the mid 1990s due to fluctuations in abundance of key target species.

Fish meal and oil are usually produced in tandem. The fish is cooked and then pressed to separate the solids (presscake) and liquids (pressliquor). After separation of the oil from the pressliquor, the rest of the soluble components are remixed with the presscake and this mixture is dried to form the finished solid product.

Table 2 World production of the main primary products derived from small pelagics

Product	*Live-weight equivalent of product (10^3 tonnes)* 1995	1996	1997	1998
Fresh or chilled	836	948	950	1084
Frozen	6138	6935	7481	6911
Prepared or preserved	1759	1743	2072	2013
Smoked	61	66	65	63
Dried or salted	464	433	391	360
Fats and oils of fish	3399	3090	2732	1709
Fish meal fit for human consumption	162	118	182	140

Source: FAO

Fish oil is an important by-product of the production process for fish meal. Annual production of fish oil is approximately 1.5 Mt, making up 1–2% of the total production of fats and oils worldwide. The oil is used mainly in margarines and shortenings, but there are also technical and industrial uses, such as in detergents, lubricants, water repellents, and as fuel. Fish oil consists mainly of triglycerides. The oils derived from pelagics comprise two main groups. The first group of oils contains a relatively large amount of monoenic fatty acids and a moderate proportion of polyunsaturated fatty acids. This group of oils is derived from fish caught in the North Atlantic. The second group has a high iodine number and exhibits a relatively high content of polyunsaturated fatty acids. These oils are from fish originating in the Pacific Ocean, and tropical and southern region of the Atlantic Ocean.

Fertilizer

Fish offal and soluble compounds are used as fertilizer on farms in coastal areas. Fertilizers are also produced through industrial processes, but the industry is relatively small compared to the economic value of other fish by-products.

Fish Silage and Hydrolysates

Fish silage is used as an ingredient in animal feed, and is treated separately from fish meal due mainly to differences in the production process. Fish silage is used mainly in fish feeds and moist feed pellets. During production, the fish is usually minced and mixed with materials that inhibit bacterial growth. The product is stored for a period during which the fish is liquefied by digestive enzymes. Some of the water may be removed via evaporation.

The production process for hydrolysates is similar to that of fish silage. Water is added to the minced fish, and suspended solids are liquefied through the action of proteolytic enzymes. Oils and the remaining solids are removed, leaving a hydrolysate. The product may be treated further, depending on how the product is to be used. Fish hydrolysate may be used as an ingredient in compound feeds much like fish silage. It is also used as a flavor additive. A third use for fish hydrolysate is as a component of growth media for industrial fermentation.

Pelagic Fish as a Resource for Biotechnological Products

A number of organic compounds found within small pelagic fish are of interest to the chemical and pharmaceutical industries. These compounds include, among others, fatty acids, lipids, hormones, nucleic acids, and organometallics. Scales have been used as a source of pearl essence.

Management Issues for Small Pelagic Fisheries

The exploitation of many stocks of pelagic fishes has exhibited a pattern of sharply increasing catches followed by an even more rapid decline, leading in several cases to closure of the fishery (**Figure 2**). The rapid increases in catches have been largely due to increasing technical developments, increasing markets and movement into new fishing areas of high abundance. The rapid decline has been considered, in some cases, to have a link with environmental change, but has been attributed generally to heavy fishing pressure, recruitment failure, and ineffective management. Most stocks have recovered after reduction/termination of fishing, and some fisheries have resumed following recovery.

Assessment and management of pelagic fisheries has been complicated by a number of issues. The long history of information of some pelagic stocks prior to mechanized fisheries demonstrates that these stocks are prone to pronounced fluctuations in abundance in the absence of fishing (**Figure 3**). Although such natural fluctuations are undoubtedly linked to the environment, there are likely several mechanisms and these are not well understood. In some cases (e.g., sardines and anchovies, herring, and pilchard) there have been apparent shifts in dominance over time, where periods of high abundance have alternated for the different species groups (**Figure 4**). It has been hypothesized that these switches in dominance relate to shifts in environmental conditions favoring one species over another, possible interactions with other species, and the effects of harvesting. Some species or species groups

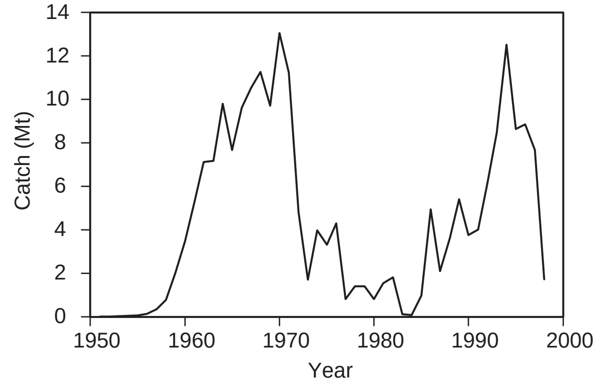

Figure 2 Catch (million tonnes; Mt) of Peruvian anchoveta (*Engraulis ringens*) showing fluctuations in abundance attributed largely to fishing. (Data from FAO, 1999.)

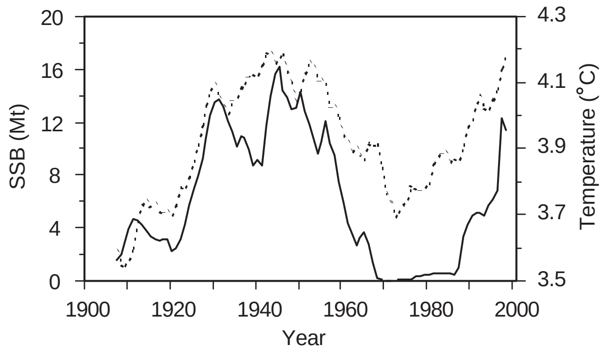

Figure 3 An example of possible environmentally induced biomass changes. Estimated spawning stock biomass (million tonnes; Mt) of Norwegian spring spawning herring (*Clupea harengus*), 1907–1998 and associated long-term temperature fluctuations. —, spawning stock, - - -, temperature. Adapted from Toresen and Østvedt (2000).

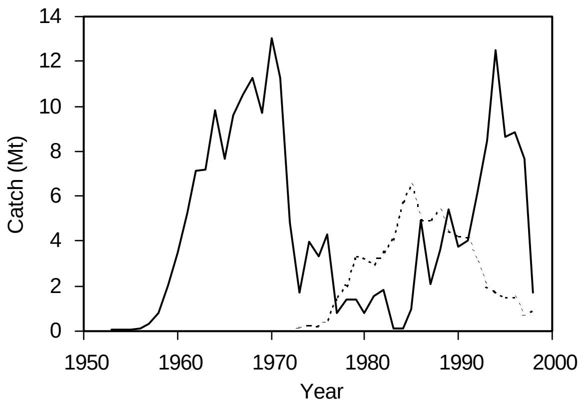

Figure 4 Catch (million tonnes; Mt) of Peruvian anchoveta (*Engraulis ringens*; —), and South American sardine (or pilchard) (*Sardinops sagax*; - - -), showing a shift in species dominance. Data from FAO (1999).

have exhibited coherence in high abundance periods over broad geographical scales (e.g., high abundance of sardines throughout the North Pacific basin during the same time periods).

The shoaling behavior of pelagic species can result in high fishery catch rates when there are relatively few fish remaining in the stock. As a result catch per unit effort, which is commonly used as an indicator of stock decline in demersal fisheries, is less useful in evaluating the state of pelagic fisheries. High catch rates can be maintained, in spite of declining stock size, and this has contributed to sudden stock collapse.

The biological basis for assessment and estimation of stock size for many small pelagic species is complicated by migration, mixing of stocks, lack of fishery-independent abundance indices, and poor analytical performance of common assessment methods. Management attempts have been further complicated by the rapid rate of decline of some small pelagic stocks.

The economic importance of herring to coastal European nations contributed to the prominent consideration of small pelagic fisheries in the evolution of fisheries science and management. Several developments, including the stock concept, recognition of year-to-year differences in year-class strength, development of hydroacoustic survey methods, and early fishery management systems have been based on fisheries for small pelagic species. Most fisheries for small pelagic species are regulated by some form of quota, although in some cases management is complicated by the occurrence of these fisheries outside or across areas of national jurisdiction.

Continued increase in mechanization of fisheries and expansion of markets increases the fishing pressure on several pelagic stocks. Technical developments such as improved hydroacoustic (sonars and sounders) detection of fish, global positioning systems, improved net design and materials, and improved vessel characteristics (e.g., larger size and refrigeration) have increased the efficiency of the fishery. These developments have contributed to increasing fishing effort, in spite of management attempts in some cases to regulate fishing capacity. The historical exploitation of several pelagic fish stocks can be shown to be directly linked to changes in markets. The increasing demand for fishmeal, for example, resulted in large increases in the landings from some pelagic fish stocks in the 1970s and 1980s.

Current research areas of particular interest for small pelagic species include the link between stock abundance, environmental fluctuation (particularly in areas of fronts and upwelling) and climate change. Most small pelagic species feed on zooplankton, and are in turn important food items for other fish, marine mammals, and seabirds. Assessment and management of fisheries for small pelagic fisheries are increasingly becoming concerned with multispecies interactions, including both the estimation of mortality of the pelagic species caused by predation and maintaining sufficient stock size of small pelagic fish as forage for other species.

See also

Acoustics, Arctic. Acoustics, Deep Ocean. Acoustics, Shallow Water. Demersal Fishes. Demersal Species Fisheries. Dynamics of Exploited Marine Fish Populations. Fish Migration, Vertical. Fisheries and Climate. Fishery Management. Fishing Methods and Fishing Fleets. Pelagic Fishes. Plankton.

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SMALL-SCALE PATCHINESS, MODELS OF

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Introduction

Patchiness is perhaps the most salient characteristic of plankton populations in the ocean. The scale of this heterogeneity spans many orders of magnitude in its spatial extent, ranging from planetary down to microscale (**Figure 1**). It has been argued that patchiness plays a fundamental role in the functioning of marine ecosystems, insofar as the mean conditions may not reflect the environment to which organisms are adapted. For example, the fact that some abundant predators cannot thrive on the mean concentration of their prey in the ocean implies that they are somehow capable of exploiting small-scale patches of prey whose concentrations are much larger than the mean. Understanding the nature of this patchiness is thus one of the major challenges of oceanographic ecology.

The patchiness problem is fundamentally one of physical–biological–chemical interactions. This interconnection arises from three basic sources: (1) ocean currents continually redistribute dissolved and suspended constituents by advection; (2) space–time fluctuations in the flows themselves impact biological and chemical processes; and (3) organisms are capable of directed motion through the water. This tripartite linkage poses a difficult challenge to understanding oceanic ecosystems: differentiation between the three sources of variability requires accurate assessment of property distributions in space and time, in addition to detailed knowledge of organismal repertoires and the processes by which ambient conditions control the rates of biological and chemical reactions.

Various methods of observing the ocean tend to lie parallel to the axes of the space/time domain in which these physical–biological–chemical interactions take place (**Figure 2**). Given that a purely observational approach to the patchiness problem is not tractable with finite resources, the coupling of models with observations offers an alternative which provides a context for synthesis of sparse data with articulations of fundamental principles assumed to govern functionality of the system. In a sense, models can be used to fill the gaps in the space/time domain shown in **Figure 2**, yielding a framework for exploring the controls on spatially and temporally intermittent processes.

The following discussion highlights only a few of the multitude of models which have yielded insight into the dynamics of plankton patchiness. Examples have been chosen to provide a sampling of scales which can be referred to as 'small' – that is, smaller than the planetary scale shown in **Figure 1A**. In addition, this particular collection of examples is intended to furnish some exposure to the diversity of modeling approaches which can be brought to bear on the problem. These approaches range from abstract theoretical models intended to elucidate specific processes, to complex numerical formulations which can be used to actually simulate observed distributions in detail.

Formulation of the Coupled Problem

A general form of the coupled problem can be written as a three-dimensional advection-diffusion-reaction equation for the concentration C_i of any particular organism of interest:

$$\underbrace{\frac{\partial C_i}{\partial t}}_{\text{local rate of change}} + \underbrace{\nabla\cdot(\mathbf{v}C_i)}_{\text{advection}} - \underbrace{\nabla\cdot(K\nabla C_i)}_{\text{diffusion}} = \underbrace{R_i}_{\text{biological sources/sinks}} \qquad [1]$$