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Winter School on

Towards Ecosystem Based Management of Marine Fisheries – Building Mass Balance Trophic and Simulation Models

INFORMATION ONLY

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Technical Notes

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FISHERIES ECOLOGY - CONCEPTS

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Introduction

In nature, organisms can survive only in appropriate environments, interact with each other and are influenced by the whole complex of environmental factors. Ecology is the interaction of organisms with their environment, studied usually by trying to understand the distribution and abundance of organisms. An understanding of the ecological principles is needed for the sustainable use of resources, and to evolve strategies, for the mitigation of environmental problems.

In a natural environment, all organisms depend upon plants, which use light energy in the process of photosynthesis to convert carbon dioxide and water into sugars and other essential compounds, and accomplish the manufacture of organic molecules. Plants are the most familiar of these organisms, but many bacteria can also manufacture organic substances with the aid of light or chemical energy. Plants are consumed by herbivores, and these are, in turn, consumed by carnivores.

Primary productivity is the amount of living material produced in photosynthesis, per unit area per unit time. In contrast, secondary productivity refers to the production of plant consumers, or herbivores, per unit area per unit time. The productivity of carnivores, or consumers of herbivores, is tertiary productivity. In general, primary production is greater than secondary production, which in turn is greater than tertiary production.

Productivity is to be distinguished from **biomass**. Productivity is the amount of living material produced per unit area per unit time (e.g., g/m^2/year), and may be expressed in units of body mass or in terms of the carbon content of the organisms. On the other hand, biomass is the mass of organisms present in a defined area or volume (expressed in units such as g/m^2).

The levels of biological organization of interest in fisheries ecology are: organism-population-community-ecosystem. This involves a series of processes from individuals to ecosystems.

Population

Population is a group of individuals of the same species, inhabiting the same area. For example, all individuals of the oil sardine in a given area constitute its life cycle and experience a similar ecological process at a particular stage of the life cycle. Populations have a number of attributes. Different populations can be compared by measuring these attributes. A population has characteristics like density, birth rate, death rate, dispersal, age distribution, biotic potential and growth.

The size of the population is represented by its density. Density is expressed as the total number of individuals present per unit area or volume at a given time. For instance, 10,000 individuals of oil sardine may occur in one sq. km, which may also be expressed as 1 tonne/km^2. The size of the population is determined by available resources like food at a given time and other characteristics such as birth and death rates and age structure. The increase in the number of individuals in a population is possible due to **birth**. The loss of individuals due to death in a population is termed **mortality**. It is expressed as mortality rate, indicating the number of individuals dying over a time period. Fish populations are affected by two types of mortality, i.e., **natural morality**, which is due to predation, disease and senescence; and **fishing mortality**, which is due to fishing.

Distribution of age groups in a population influences the population growth. Populations with more juveniles grow rapidly while the declining populations have a large proportion of older individuals. Majority of fishes disperse at one time or the other during their life cycle. The individuals move into (**immigration**) and move out (**emigration**) of the population, and these movements influence the size of the population. Migratory fishes like tunas are examples of dispersal.

The inherent maximum capacity of an organism to reproduce or increase in number is termed **biotic potential**. Biotic potential is realized only when the environmental conditions are non-limiting, so that birth rate is maximum and mortality rate is minimum. Under these conditions, population size increases at the maximum rate. If a pair of oil sardine is allowed to reproduce and grow unchecked, the oil sardine population may occupy the oceans in a few years. However, the environment has a check on population size, or its biotic potential. The environmental resistance represents the limiting effect of abiotic (e.g., temperature, salinity, depth, light) and biotic factors (e.g., food, competition) that do not allow the fish to attain their biotic potential and keep the population size at a much lower level.

Generally, the population size stabilizes with time, with some fluctuations around the upper limit. The maximum number of individuals of a population that can be sustained indefinitely in a given habitat represents its **carrying capacity**.

Community

Populations of a different species occurring in a habitat is called community. The community can be recognized and named through features like dominance, stratification and species interactions. Community analysis involves qualitative (species) and quantitative (frequency, density, biomass) analysis of species present in the community.

The members of the community are interdependent for food and protection. Organisms living together may benefit each other (mutualism), or one way benefit without affecting the other (commensalism). Sometimes, one organism (predator) may adversely affect the other (prey). Parasitism is the relation in which the smaller organism (parasite) adversely affects the larger host.

The community is dynamic and undergoes changes with the passage of time. These changes are sequentially ordered and constitute **succession**. Succession involves replacement of one community by the other. Ultimately, succession leads to a dominant community, which remains stable as long as the environment remains unchanged.

Ecosystem

An ecosystem is a group of interdependent biological communities in a geographic area, capable of living nearly independently of other ecosystems. Ecosystems are parts of nature where living organisms interact among themselves and with their physical environment. An ecosystem includes biological community integrated with its physical environment. Ecosystems can be recognised as self-regulating and self-sustaining units. Human activities such as fishing and dredging may modify and affect the marine ecosystems.

An ecosystem has two basic **components**: abiotic and biotic. Abiotic components comprise of inorganic materials such as carbon, nitrogen, oxygen, CO_2 etc, and dead organic matter contain protein, carbohydrates, lipids, etc. The climatic parameters like solar radiation and temperature determine the abiotic conditions within which the organisms carryout life functions. Biotic components include producers, consumers and decomposers.

Biotic and abiotic components are physically organized to provide a characteristic **structure** of the ecosystem. Important structural features are species composition and stratification. Some ecosystems (e.g., the coral reef ecosystems) show very high species richness whereas, deepsea ecosystem shows fewer species and extensive bare patches of water.

Within the ecosystem, nutrients recycle between organisms and the environment. Some of the species (e.g. plants) manufacture organic molecules using only solar energy and inorganic chemical sources and the system can continue independently of other systems. Under this definition, a large lake and its immediate drainage comprise an ecosystem, because the organism in the lake can survive indefinitely. A coral reef and its immediate surrounding water also qualify as an ecosystem, because no import is necessary to sustain the system. In reality, all ecosystems exchange nutrients with other ecosystems. It is crucial, therefore to determine the boundaries of an ecosystem and the places where losses and gains may occur.

Another way to depict the ecosystem structure is through food relationships. Ecosystems possess a natural tendency to persist. This is made possible by a variety of **functions** (activities undertaken to ensure persistence) performed by the structural components. For instance, phytoplankton function as sites of food production; herbivores like the oil sardine perform the function of utilizing part of phytoplankton, and in turn, serve as food for carnivores. Decomposers carryout the function of complex organic materials into simpler inorganic products, which can be used by the producers.

In many marine ecosystems, most of the plant material produced is never consumed by herbivores; rather, much of it falls to the seafloor and is decomposed by bacteria and fungi producing dissolved nutrients. The dissolved nutrients are then available for primary producers. This pathway is known as the saprophyte cycle. Knowledge at the rates per which these processes occur in the ecosystem is necessary to understand the interrelationship of ecosystem structure and function.

Energy flow is the key function in the ecosystem. The storage and expenditure of energy in the ecosystem is based on the two **laws of thermodynamics**. The first law states that energy is neither created nor destroyed, but can be transferred from one component to another, or transformed from one state to another. Accordingly, energy of sunlight can be transformed into energy of food and heat. The second law of thermodynamics states that no energy transformation occurs spontaneously unless energy is degraded or dissipated from a concentrated to a dispersed form. Thus, in ecosystem, transfer of food energy from one organism to another leads to degradation and loss of major fraction of food energy as heat due to metabolic activities, with only a small fraction being stored in living tissues or biomass. While energy in food is in concentrated form, heat energy is highly dispersed. It must be understood that, in any system all changes in energy forms can be accounted.

A food chain is a set of connected feeding levels of primary, secondary and tertiary sources of productivity. An example of a simple food chain is:

Seaweed → gastropod → fish → shore bird

In more complicated systems, a simple chain cannot be constructed, and a more complex food web is a better description. A food chain is a linear sequence that reveals which organisms consume which other organisms in an environment. A food web is a more complicated diagram of feeding interactions that shows the overall pattern of feeding among organisms.

Each organism in the above food chain (seaweed, gastropod, fish and bird) represents a **trophic** (food) **level**.

A simplified representation of energy flow through ecosystem has been made in Figure1. The energy flows in one way i.e., from producers to herbivores to carnivores. It cannot be transferred in the reverse direction.

Not all the production from one trophic level is transferred perfectly to the next. To estimate the potential production at the top of a food chain such as fish production, the losses at each trophic level should be determined. Losses result from the following two factors:

(i) Unconsumed: Some proportion of a given trophic level evades consumption through escape, unpalatability or unavailability. Phytoplankton with large spines or toxins are avoided by zooplankton. Phytoplankton cell size may be too small, or too large, to permit ingestion.

(ii) Inefficient conversion: Some portion of the food that is ingested is not converted for growth.

A budget for consumed food can be constructed as follows:

$$C = E + R + G$$

Where C is the amount consumed, E is the amount egested as faeces and nitrogenous waste, R is the amount spent in respiration, and G is the amount used in growth. G can be partitioned between somatic growth and reproduction. This budget is usually constructed in terms of energy units, i.e., calories or joules.

The energy lost in respiration is not available to the next trophic level. The respiration cost increases sharply along successive trophic levels. On an average, respiration of producers consumes about 20% of its gross productivity. Herbivores consume about 30% of assimilated energy in respiration. The proportion of assimilated energy consumed in respiration rises to about 60% in carnivores. Because of this tremendous loss of energy at successive higher trophic levels, the residual energy is decreased to such an extent that no further trophic level can be supported.

Trophic structure in ecosystem can be represented by comparing **standing crop** (either number of individuals or biomass) or energy fixed per unit area at different levels. Graphical representation of the trophic structure is done by drawing ecological pyramids, where the basal, mid and top tiers show the parameter values for producers, herbivores and carnivores in the ecosystem (Fig. 2). It emphasizes that the total biomass or energy flow at successive trophic levels always decreases, compared to the preceding trophic levels.

Animal that have no immediate predators also contribute nutrients to the food web. Marine mammals and turtles, while not specifically targeted for consumption, do produce waste. The waste may be either excretions from digestive processes or dead tissue. It is eventually broken down by decomposers, i.e., primarily bacteria, in a process that releases nutrients that plants can use to start the whole cycle again.

Organisms higher up the food web tend to be larger in size and fewer in number than those at lower levels. This is partly a function of the many trophic steps required to meet advanced energy needs. Because the efficiency rate at each trophic level is only about 10%, each succeeding level supports a smaller total biomass to compensate for the 90% loss of food value.

The incompleteness of transfer up a food chain can be estimated in terms of **ecotrophic efficiency**, EE, defined as the amount of energy extracted from a trophic level divided by the amount of energy supplied to that trophic level. EE is often in the range of 10%. However, high latitude planktonic systems may have higher EE.

EE can be used to estimate the potential fish production at the top of the food chain. If B is the biomass of phytoplankton and n is the number of links between trophic levels, then the production P of fish is: $P = B * EE^n$ (Levinton, 2001). Using this concept, Gulland (1972) estimated the global potential annual yield of fishes as 100 m t. However, even a minor a change in EE, for instance, from 0.1 to 0.2, would magnify the estimate of fish production by 16 times at the fifth tropic level, and hence, may lead to serious potential errors in the estimates. Due to this reason, these estimates are considered as arbitrary.

According to the classifications of Ryther (1969), marine planktonic food chains can be classified into three basic systems (Table 1). The oceanic system has five trophic levels, with a low annual primary production of about 50 g C/m^2/year. The coastal system has three trophic levels, and the primary production is about 100 g C/m^2/year. The upwelling system occurs in areas such as the Kerala coast, and has only two trophic levels. Upwelling provides higher and more continuous material supply, leading to a primary productivity of about 300 g C/m^2/year. The high potential of upwelling systems is enhanced by a greater EE, which is related to the case of consumption and assimilation of large diatoms by planktivorous fishes. Low primary productivity and large number of trophic levels greatly reduce the fishery potential of the oceanic systems.

Temporal environmental stability and stable water column may increase the number of trophic levels and promote the survival of complex food webs. In nearshore and upwelling systems, strong temporal changes in environmental parameters would on the other hand, tend to collapse a complex multilevel food web.

Interaction between species

Most of the commercial fish are first or second stage carnivores, and the order of volume of production corresponds quite closely to the order of closeness of the fish to the primary production. On the other hand, predators at the top of food webs are fewer in numbers, but may exert strong effects on entire ecosystems if there are strong interactions between trophic levels. A predator at the top of a food web exerting strong effects is known as **keystone species**. When linkages among trophic levels are strong, changes in abundance of the top predator causes a **trophic cascade** through the trophic levels.

Ecosystem impacts of fisheries

Fish populations do not live by themselves. Rather, they are embedded in ecosystems where they perform their roles as consumers and prey of other organisms, including larger fishes. For describing the ecosystem impacts of fisheries, it is necessary to concentrate on the impacts fisheries have on food webs, i.e., on the net work of flows of matter (= biomass), which in ecosystems, links the plants with herbivores, and the latter with their predators. These networks of flows are affected directly by fishing, which removes predatory fish, or competes with them for their preys, in either case affecting the web within which predators and preys are embedded.

Figure 3 gives an example of a simplified food web, and defines the various elements of such webs (functional groups), the flow between them, the trophic levels, which indicate the position of each functional group within the web.

Here, the plants have a definitional trophic level of 1, as does dead organic matter (detritus), while exclusive plant or detritus feeders (herbivores or detritivores) have a trophic level of 2. Carnivores feeding exclusively on herbivores and/or deritivores have a trophic level of 3, and so on. Carnivores do not necessarily have trophic levels of exactly 3 or 4, but are more likely to have intermediate values, reflective of the mix of preys they consume. For example, a pelagic shark that should have a trophic level of 5.0 because it feeds on small pelagics such as whitebaits with a trophic level of 3.0 will end up having a trophic level of 4.0 if it feeds, equally, on a low level carnivore or herbivore like the sardines with a trophic level of 2.0-2.5.

Because of this effect of mixed diets, top predators in marine ecosystem rarely have trophic levels in excess of 5. Such high values occur only in killer whales, which, by feeding exclusively on marine mammals (which prey on piscivorous fish), can reach trophic levels much higher than those reached by fish. While some fish reach trophic levels in excess of 4.0, the overwhelming bulk of them have trophic levels between 3 and 4.

The trophic level of consumers can be estimated based on the weighted average of the prey's trophic level. A consumer eating 40% plants (with trophic level 1) and 60% herbivores (with trophic level 2) will have a trophic level of $1 + (0.4 * 1 + 0.6 * 2) = 2.6$.

The 1 at the beginning of this equation is the definitional trophic level of producers and detritus. The trophic level is a dimensionless index.

However, the approach to assign numeric trophic level to each species, is an oversimplification due to the following reasons:

? The trophic levels change during ontogeny of fishes. Larvae, which usually feed on herbivorous zooplankton (trophic level = 2.0). Consequently have a trophic level of 3.0. Subsequent growth enables the larvae to consume larger, predatory zooplankton and small fishes or benthic invertebrates. This leads to an increase in trophic level often culminating in values around 4.5 in purely piscivorous, large fishes.

? The role of fishes within ecosystems is largely a function of their body size. Small fish are more likely to have a vast array of predators than very large ones.

? Opportunistic feeders may eat larval forms of their predators. For example, squids feed on juvenile threadfin breams, but small squids are predated by adult threadfin breams.

? Opportunistic feeders may eat their own larval forms. For example, the bombayduck, lizardfish and ribbonfish are cannibalistic and trophic level assigned to cannibalistic fish would be only an arbitrary value.

Fisheries impacts on marine ecosystems

Fishing is one of the oldest human activities, and it developed gradually, when our ancestors moved from the collection of plants and animals they happened to find, to the extraction of organisms, using tools and weapons. The tools were shaped, first of stone, later of wood, bone, ivory etc. The oldest fishing implements so far identified are harpoons, found in the territory of Congo, and dated about 90,000 years (Stergiou, 1999). Well–preserved fishing tools from the Neolithic and Bronze Age (1700-800 BC) indicate further technical improvements. In the Alps region, these included dugout canoes, and curved hook made of bronze and iron and nets made of hemp and flax with mesh size from 5 to 45 mm knot to knot. During 900-800 BC, various fishing methods relying on hooks, nets and harpoon were used. All these early and later developments up to about a century ago indicate that fisheries tended to use highly selective gear. Moreover, their effect on ecosystems, being highly localized, probably resembled the effect of natural predation.

The fishing pressure exerted by modern fleets differs radically from natural predation, due to the combination of direct and indirect effects. The direct fishing effort of reducing the abundance of various exploited populations is often enough for them to collapse. There are also strong reductions of mean size in the species landed, reflecting similar reductions of size in the ecosystems. These changes imply changes in the life history of the species concerned, through changes of their age at first maturity and of their sex ratio.

A strong indirect effect of fishing on ecosystem is through habitat alteration. Trawling is a major culprit as far as sea bottom is concerned, while dredging and explosives destroy the coral reefs, which support the fish species, and their prey.

The ecosystem consideration of effect of fishing is gaining importance and has become a thrust area of investigation in the assessment of exploited stocks. It is increasingly realized now that changes in ecosystems could be due to ecological and exploitation parameters either singly or in combination, and hence, assessment of stocks need to be tuned accordingly. Pauly et al (1998) examined the FAO capture fisheries production database for 1950-1994 in terms of trophic levels of the catch and showed that landings from global fisheries have shifted from large piscivorous fishes toward small invertebrates and planktivorous fishes, a process now called "fishing down marine food webs". They estimated that the trophic levels of fisheries landings declined at a rate of about 0.1 per decade. One concern about this trend is that fishing may cause large and vulnerable predatory fish to be replaced by other species lower down the food web. This may not only affect the value of fisheries, but may cause significant problems in the structure and function of marine ecosystems.

Pauly and Christensen (1995) estimated how much primary production was required to sustain the global fisheries in 1988-1991. The results showed that, globally, 8% of aquatic primary production was appropriated by the fisheries, and that there was considerable variation between resource system types: for open ocean fisheries, only 2% was required, while upwelling, shelves and freshwater systems required 25-35% of total primary production. When this is added to arrive at the total requirement of primary production, it may be concluded that the available primary production of the oceans is fully utilized by the humans, since over half of the total primary production can be expected to fall out to the sediment. It appears that humans can be expected to use one third of the total primary production through fisheries. For terrestrial systems (which in general are more fully exploitable and exploited), the global average is that 35-45% of the primary production is appropriated by humans, directly or indirectly.

Natural changes in the ecology of the oceans

Not all ecological changes are anthropogenic. Natural conditions in the oceans fluctuate greatly and sometimes suddenly on time scales that extend for decades to millennia. An important example of the potential magnitude of natural change comes from annually layered sediments of the Santa Barbara Basin (Baumgartner et al., 1992). Abundance of fish scales of anchovies and sardines preserved in these sediments fluctuate more than an order of magnitude and exhibit nine major collapses and recoveries in over 1700 years. Perhaps a parallel may be drawn for the oil sardine abundance along the southwest coast of India.

Another example of nature-driven ecological change is the catastrophic mortality of the western Atlantic coral reefs in the 1980s (Jackson, 2001). The principal cause of coral mortality was overgrowth by macroalgae that exploded in abundance after an unidentified pathogen caused mass mortality of the enormously abundant grazing sea urchin *Diadema antillarum* in 1983-1984. Increasing frequency of coral disease and bleaching were also major factors. Mass mortality of *Diadema* was also caused by overfishing of major fish predators of the sea urchin and of large herbivorous fishes that competed with the urchin for algal food. Thus there were no large grazers remaining to consume the algae, which caused mortality of the coral reefs.

Ecosystem maturity

Odum (1969) proposed the term **ecosystem maturity** to define the stability of the ecosystem. He considered that the stability of the ecosystem is high if the energy flow of the network is high. The complex trophic organization of a community is more stable than a simple one. A more diverse ecosystem has the potential of becoming more complex and possessing more choice than a less diverse one. An ecosystem attains maturity after several ecological successions, and hence development and maturity of an ecosystem stand in opposition to each other. A mature ecosystem has the capacity to withstand perturbations caused by human beings or nature more than an immature ecosystem.

To assess the maturity of an ecosystem, Odum (1971) suggested indices, which were modified to suit fisheries ecosystem by later researchers. Some of the indices for determining the maturity of an ecosystem are as follows:

- (i) **Respiration / assimilation ratio** can be more than 1. For top predators the ratio is close to 1 since the production is low. For organisms with low trophic level, the ratio is lower, but the value is positive.
- (ii) **Production / respiration ratio** is always less than 1.
- (iii) **Respiration / biomass ratio** takes a positive value and depends on the activity of the ecological group; higher the activity, higher the ratio.
- (iv) **Primary production / respiration ratio** is > 1 in the early developmental stages of an ecosystem. In mature system, the value is around 1, but in polluted system, the ratio is < 1.
- (v) **Primary production / biomass ratio** is < 1 in immature system since the biomass accumulates.
- (vi) **System throughput** is the size of the entire ecosystem in terms of flow (consumption + export + respiration + flow to detritus). The value can be compared with the throughput of other ecosystems.
- (vii) **Biomass / throughput ratio** increases to a maximum for the most mature stages of a system.
- (viii) **Net system production** is the difference between total primary production and total respiration. In immature system, the production is large, but in mature systems, it is close to zero.
- (ix) **Efficiency of the fishery** is the relationship between sum of all fisheries catches and total primary production. The global average efficiency of the fishery is 0.0002. The value is high for systems with a fishery harvesting fish low in food web (e.g., upwelling fishery), and the value is low for the systems that are underexploited or where the fishery is concentrated on apex predators.
- (x) **Connectance index** is the ratio of the actual links to the number of possible links in a given food web. Food chain structure changes from linear to weblike as systems mature.
- (xi) **System omnivory index** is a measure of the feeding interactions that are distributed between trophic levels.
- (xii) **Ascendancy** is a measure of knowledge on the location of a unit of energy and where it will flow next. The upper limit of ascendancy is the developmental capacity. Ascendancy = Total system throughput * Information flows.

(xiii) **System overhead** is the difference between the capacity and the ascendancy. It reflects the system's strength in reserve from which it can draw energy to meet unexpected perturbations.

(xiv) **Cycling index** is the fraction of an ecosystem's throughput that is recycled. This index normally takes the value around 0.2%. It is strongly correlated with system maturity, resilience and stability.

(xv) **Primary production required** is an important quantification of the primary productivity required to sustain fisheries harvest by humans. It is estimated mainly from the trophic positions of the various organisms harvested.

(xvi) **Mixed trophic impact** is an assessment of the effect of the changes in the biomass of a group that will have on the biomass of other groups in a system. For example, tunas have a negative impact on their prey, the sardines, but have positive impact on their prey's prey, the phytoplankton. Moreover, the sardines may have a marginal positive impact on phytoplankton since the sardines also feed on zooplankton, which are consumers of phytoplankton.

The question is whether ecology can help in managing fisheries. The two basic answers could be:

(i) Ecology may help in finding out what is the carrying capacity of the ecosystem. This carrying capacity, measured as the sum of all the possible fluxes in the ecosystem, represents the available energy from which maximum can be diverted as fish catch. It is also possible to arrive at a limit of what one can get from an ecosystem.

(ii) Ecology may help by characterizing the space and time where the valuable species should be protected. However protection should not be extended only to a few species. Also, species that have an ecological impact on the valuable species should find protection in space and time, and ecology can elucidate what those species are.

(iii) Recently, ecology and ecosystem analysis are used to interpret the effects of natural and human influence on fisheries, and this analysis is helpful for recommending ecosystem-based fisheries management options.

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Table 1. Characteristics of three principal types of marine food chains (after Ryther,1969)

Type of system	Primary productivity (g C/m^2/year)	Number of trophic levels	Ecotrophic efficiency (%)	Potential fish production (mg C/m^2/year)
Oceanic	50	5	10	0.5
Shelf	100	3	15	340
Upwelling	300	2	20	36,000

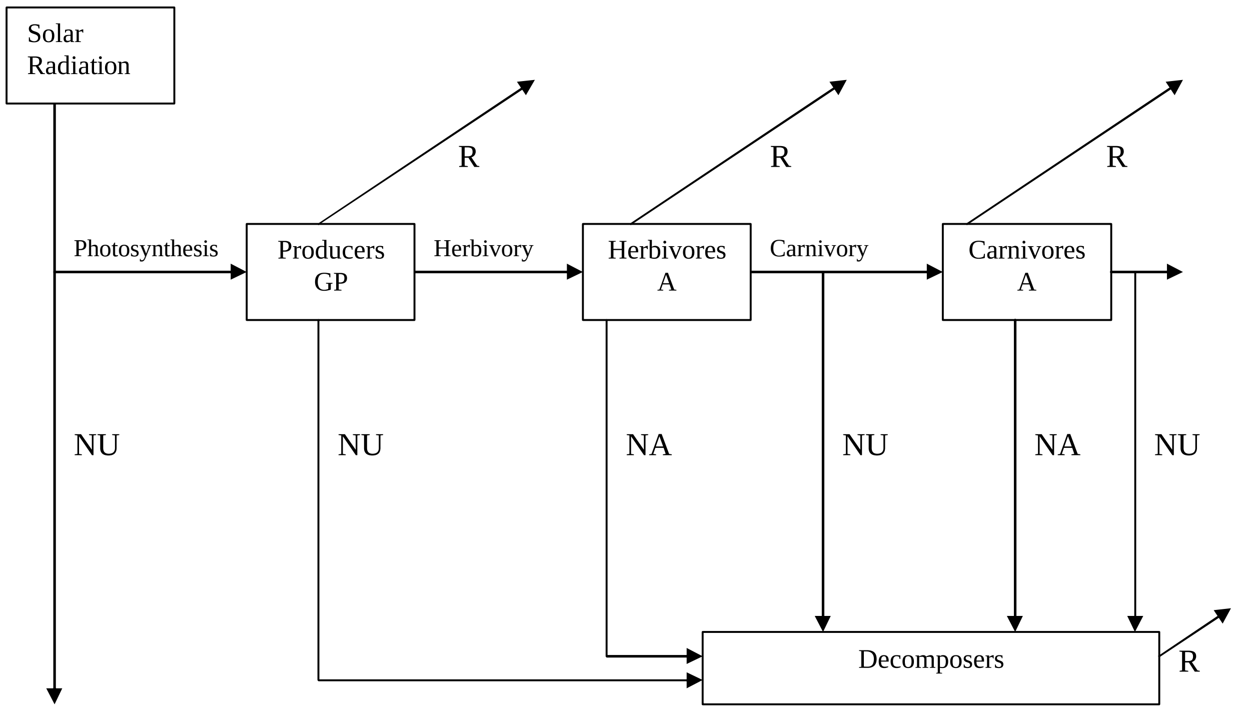

Fig. 1. A generalised energy flow model of ecosystem. Boxes represent biotic components and the arrows show the pathways of energy transfer; Sr, Solar radiation; GP, Gross primary productivity; A, Assimilation; R, Respiration; NU, Not utilised; NA, Not assimilated

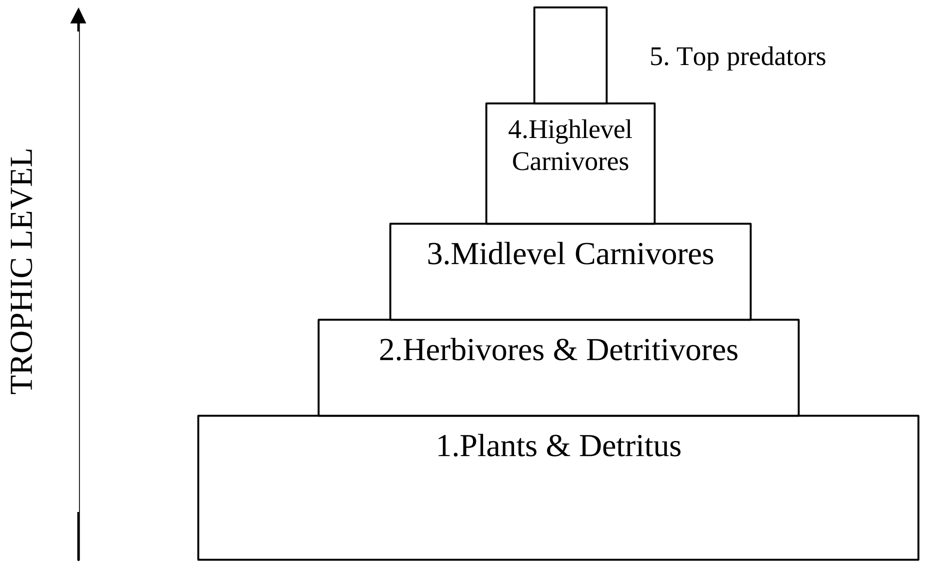

Fig. 2. Typical trophic structure in a marine ecosystem; the boxes represent number of individuals or biomass or energy at each trophic level

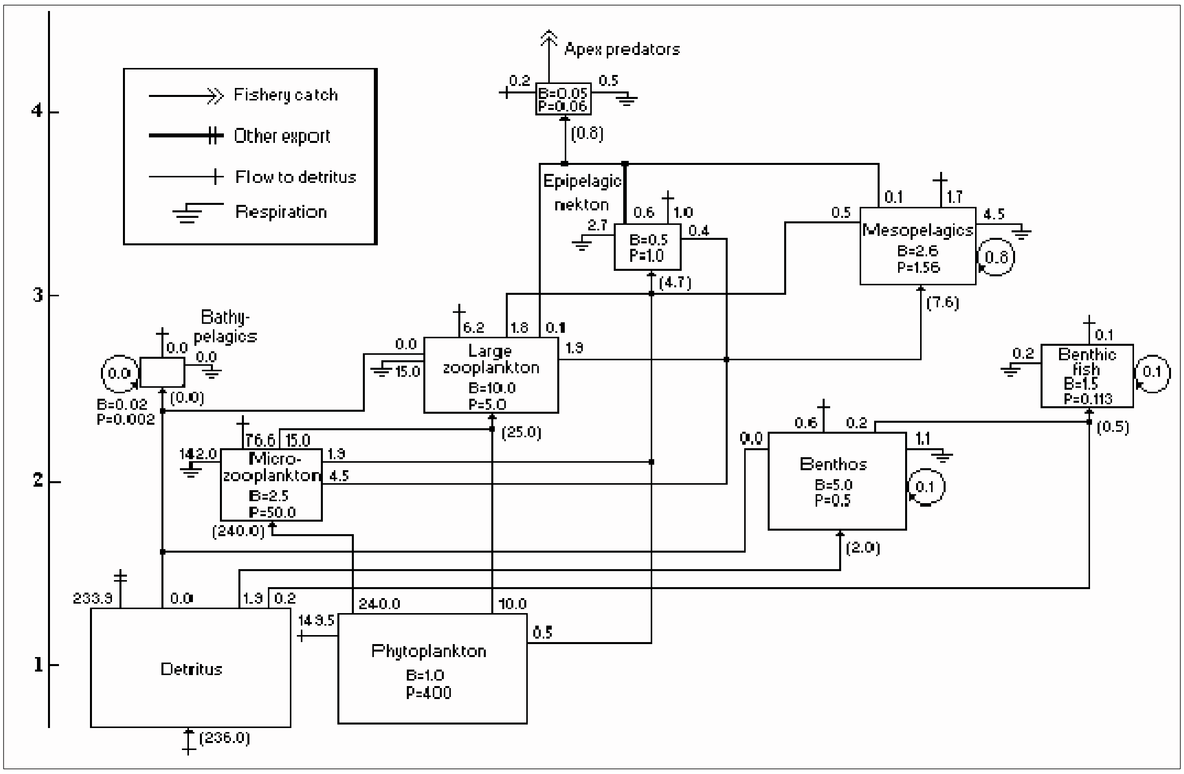

Fig. 3. A simplified food web in the marine ecosystem