KNOWLEDGE OF THE ENVIRONMENT[*]

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Summary

Accumulation of environmental knowledge in the form of science and technology has resulted in huge impacts as humans have transformed their environment into a state favorable for humans. Natural ecosystems have been destroyed on vast tracts of land. On the other hand, development of industry and agriculture accompanied by global population growth has led to increasing rates of anthropogenic environmental pollution. As a result, the stabilizing capacity of the global natural biota has been exceeded and global environmental changes have been initiated.

At present, most efforts are being directed at finding technological solutions to environmental problems that are based on creation of no-waste technologies and improved cleaning facilities. Yet it is not clear whether it is in principle possible to maintain a stable environment on earth by technological means, replacing the natural mechanism of biotic regulation of the environment. On the contrary, studies of information fluxes that can be processed by humankind and are processed by natural biota show that there is a gap of more than ten orders of magnitude between the two fluxes. Thus, information available to humankind will never be sufficient to maintain a stable environment on a global scale.

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Thus, the further long-term development of environmental knowledge—that at present is substantially technology-biased—should be concentrated on fundamental studies of natural biota and its stabilizing properties. The ultimate goal of these studies is to quantify the ecologically permissible amount of anthropogenic transformation of natural biota that is still compatible with environmental stability. Meanwhile the technological dimension of environmental knowledge should be given serious attention when solving problems of local pollution caused by human settlement.

1. Introduction

All living organisms on the earth exist in an environment that surrounds them. The environment provides suitable physical and chemical conditions for life—temperature, air pressure, humidity. The environment provides all living beings with nutrition necessary to support metabolic processes of organisms and assure normal life. Plants consume solar radiation and synthesize organic matter. Animals consume organic matter produced by plants and other animals.

Living organisms on earth not only exist in the environment, they also have a considerable impact on it, changing its chemical and physical properties. Life on earth occupies nearly all the planet's surface. The activity of living organisms is so powerful that it can change the major properties of the environment by several hundred percent over a period of decades. By contrast, geophysical and outer space processes take thousands of years to cause changes of the same magnitude. Thus, the impact of life on the environment is the governing factor of environmental changes and exceeds by orders of magnitude the impact of all possible abiotic factors.

Life can exist in only a very narrow interval of environmental physical properties. Life is able to exist in a temperature interval corresponding to the liquid state of water—under atmospheric pressure this is from 0°C up to 100°C. The temperature interval that is optimal for life is narrower: between 10°C and 20°C. Life on land is only possible given sufficient humidity.

The stable existence of life on earth for many millions of years is a well-documented fact. This leads unambiguously to the conclusion that the environmental impact of certain organisms is completely counteracted by the impact of other organisms. This means that the environmental impact of each organism is not arbitrary. Impacts of different organisms need to be rigidly correlated with one another for the environment to be maintained in a relatively stable state. Thus, all organisms living on the same territory form an internally correlated biological community. It is organized in such a way that biogeochemical processes inside the community can form closed cycles, and the combined environmental impact of all organisms of the community can be close to zero. Such organization makes it possible for a community to maintain its environment in a stable state in the absence of external disturbances.

The huge power of the potential environmental impact of living organisms becomes evident when one considers the intensity of closed biological cycles of different elements. Measured as biological productivity, the intensity of biological cycles exceeds the power of the present-day energy consumption of humankind by approximately an order of magnitude (Table 1). The high intensity of biological cycles makes it easy for communities to compensate for any abiotic environmental disturbances. This can be done by biological induction of directional deviations in closed matter cycles. Biological communities can remove from active cycling excess concentrations of all life-important biogens (e.g. concentration of atmospheric carbon dioxide (CO_2) that is important for plants and also determines the temperature regime on the planet) by transforming them into inert (inactive) organic substances (e.g. soil humus and dissolved organic carbon in the ocean). The deficient concentrations of inorganic substances in the environment can be replenished by decomposition of organic matter accumulated in such inert organic reservoirs.

Table 1. Energy fluxes at the earth’s surface (after Gorshkov et al. 2000)

Power source / sink	**Power**	
	10^{12} W	**Fraction relative to solar power**
Solar power and processes of its dissipation:		
Total solar power coming from the sun to the earth	$1.7\cdot10^{5}$	1.0
Solar power absorbed by the earth’s surface[a]	$8\cdot10^{4}$	0.47
Evaporation from the total surface of earth	$4\cdot10^{4}$	0.24
Evaporation from land (evapotranspiration)	$5\cdot10^{3}$	$3\cdot10^{-2}$
Heat fluxes from the equator to the poles:		
Atmospheric	$3\cdot10^{3}$	$2\cdot10^{-2}$
Oceanic	$2\cdot10^{3}$	10^{-2}
Wind power	$2\cdot10^{3}$	10^{-2}
Oceanic waves	10^{3}	$6\cdot10^{-3}$
Maximum available hydraulic power of rivers	1	$6\cdot10^{-6}$
Biota		
Transpiration of plants	$3\cdot10^{3}$	$2\cdot10^{-2}$
Photosynthesis of plants	10^{2}	$6\cdot10^{-4}$
Non-solar sources of power:		
Total flux of geothermal heat	30	$2\cdot10^{-4}$
Volcanoes and geysers	0.3	$2\cdot10^{-6}$
Chemosynthesizing life	10^{-4}	$6\cdot10^{-10}$
Tidal power	1	$6\cdot10^{-6}$
Moonlight	0.5	$3\cdot10^{-6}$
Humankind at the end of the 20th century:		
Energy consumption (mainly fossil fuel combustion)	10	$6\cdot10^{-5}$
Human-induced increase of greenhouse effect	10^{3}	$6\cdot10^{-3}$

[a] Solar power absorbed by the earth’s surface is equal to the total solar power coming from sun to earth minus solar power reflected by earth back to space minus solar power absorbed by the atmosphere.

The complex and correlated properties of the functioning of different organisms inside a community is genetically programmed in genomes of all natural species. Deviations from the normal genetic program of a species or invasion of an alien species can substantially disintegrate community's functioning and lead to degradation of its environment. Any activity that is performed through transforming the external energy fluxes into certain ordered processes can be termed "work." In this sense, the functioning of all species of the community represents concrete work on stabilizing their natural environment. In a normal community there cannot be any species-lazybones arbitrarily adapted to conditions inside the community and not doing any work on stabilizing the environment. Communities loaded with such lazybones inevitably lose out in competition with communities that do not have such species. Similarly, in a normal community there cannot be any species-gangsters—alien species that disintegrate the normal functioning of aboriginal species.

Paleontological data show that many extant species were absent in the past. Their places in communities were occupied by species that are now extinct. But the stable existence of life over the last three billion years suggests that biological species of the past also formed internally correlated communities that were able to maintain a suitable environment. Evolutionary changes in a community's species composition that were determined by the extinction of old species and the origin of new ones did not affect this most important property of biological communities. This means that during the evolutionary process species-survivors were not those that were just adapted to a certain environment, but those who could also maintain that environment by working on environmental stabilization in the framework of the correlated community.

The totality of all natural biological species that form natural biological communities is called "biota." Biota includes all natural flora and fauna of the earth. The global environment together with biota functioning in it is called the "biosphere." The science that describes the interaction of living organisms with their environment is called "ecology."

Homo sapiens, as well as all other species, originated in the process of biological evolution. Modern paleontological data provide an opportunity to trace the whole succession of evolutionary events that led to the origin of Homo sapiens. Thus, Homo sapiens, as all other species, originally belonged to a certain biological community. Inside the community Homo sapiens, as well as all other species, did a certain amount of work aimed at stabilizing the environment. Unlike all other species, however, Homo sapiens proved to be able to accumulate cultural information that, like the genetic information of a species, can be transmitted from generation to generation. Unlike genetic information, the amount of cultural information increased from generation to generation. At present, the cultural information of the whole of humankind is comparable to the genetic information of Homo sapiens as a species. Most present cultural information of humankind is represented by scientific information about surrounding phenomena (i.e. about the environment of humans). Fundamental studies of physical, chemical, and biological laws of nature gave humans an opportunity to work out technology-based applications of their acquired knowledge. Thus, humans were able to inhabit all continental areas of the earth and even began actively to explore outer space. Note, however, that life in space is not possible without regular contacts with the environment of Earth.

When inhabiting new territories, people transformed nature into a state most favorable to them. People cut down forests and dried out bogs to build houses, turned large territories into fields and pastures to get food. People built mines, roads, and factories. All these activities were accompanied by industrial and agricultural wastes emitted into the transformed environment.

People changed the structure of natural biological communities, reducing population numbers of those species they were not dependent upon, and increasing population numbers of "useful" species that gave necessary products like meat, crops, timber, etc. People also changed genetic programs of species, creating new breeds of cattle and new sorts of agricultural plants. As a result, biological communities began to lose their ability to compensate for environmental disturbances, while the mainly human-induced degradation of the environment became the most important destabilizing factor.

People long ago began to pollute the environment. However, until the beginning of the twentieth century natural biota had been able to counteract anthropogenic pollution. Pollution was noticeable only in local areas, where it was easily coped with. Meanwhile on regional and global scales the environment was maintained by natural biota in a clear and stable state. Ecology as a science was mainly concerned about interactions of species of natural communities with their environment and was considered a branch of biology.

When the rate of anthropogenic pollution began to increase, together with the rate of human-induced degradation of natural biological communities, natural biota began to lose the ability to stabilize the environment on regional and global scales. It became clear that the current state of the environment very much depends on the anthropogenic impact on it. As a result, ecology turned into a much wider branch of knowledge, and began to address not only biological, but also economic, political, and ethical issues.

Ecological problems of civilization manifested themselves clearly when the anthropogenic disturbance of natural biological communities closely approached a certain threshold beyond which biota loses the ability to stabilize the environment. Evidently, the “below-threshold” stable existence of civilization of the past is possible in the future as well. To ensure it, modern anthropogenic activities on the planet must be substantially reduced and, inevitably, constraints must be imposed on the growth of the world’s population. Therefore, possibilities of unlimited economic growth are currently being widely discussed at various levels in various societies, as the concept of unlimited economic growth is in apparent contradiction with the abovementioned principles of the stable existence of civilization. It is evident that unlimited growth will finally lead to overexploitation of natural biota and complete loss of its stabilizing properties. Then people will have to maintain an environment suitable for living in, using available scientific and technological knowledge. If this prospect of the future development of civilization is real or not can only be determined through a scientific approach **(see Section 6.2. The Future of Ecology as a Science)**.

The functioning of natural species that assures biotic regulation of the environment is determined by the genetic information coded in genomes of these species. This information is hereditary and remains unchanged during the whole period of a species’ existence. In this sense, the genetic program of humans does not differ from the genetic programs of other biological species. Under natural conditions, the genetic program of any species determines the correct actions of individuals of this species for maintaining a stable environment. All major aspirations of modern people—to increase living standards, to leave progeny, to care for progeny—and many others are based on the genetic program of Homo sapiens. Environmental conditions of modern civilization differ drastically from the natural environment of humans as a species. In such conditions the genetic program and behavior determined by it no longer ensures environmental stability. The correct behavior of people that would meet the conditions for the maintenance of a stable environment favorable for life on the planet can be worked out only by most comprehensive investigation of Homo sapiens as a species and its ecological problems. So the scientific approach that once gave people sufficient power to destroy their own environment, now has to give people a concrete plan of how to avoid a global ecological catastrophe and how to survive in the future.

2. Environmental Knowledge

All life-important knowledge of the environment in immobile organisms—plants, fungi—is confined to their genetic hereditary information. Such organisms do not have a centralized control of their body (they do not have heads).

Mobile animals need to have concrete information about the place where they live and other components of their environment that are encountered during the life span of a certain organism. Such information changes from one generation to another during the whole time of the species existence and cannot therefore be written as hereditary in genomes of motile animals. Once written, it can become useless for the next generation. Thus, during their life span mobile animals need to process additional non-genetic information about their environment. Such information accumulates in the memory of each motile organism (which in most animals is localized in brain) and vanishes with death of the organism.

Thus, transmission of non-genetic information from one generation to another is biologically forbidden. Such a situation guarantees there will be no transmission of wrong information about environmental conditions that can change during the life span of the next generation. Mountains become hills, brooks turn into rivers, lakes become bogs, old trees are replaced by young ones, etc. Information that correctly characterizes the environment at any one moment of time may be wrong the next moment. Transmission of such information may lead to wrong behavior of an organism in the next generation and disintegration or even degradation of the biological community. That is why transmission of this information is genetically forbidden in all biological species except Homo sapiens.

Homo sapiens is a unique biological species that can learn and use knowledge of the environment accumulated by former generations. Taken as a whole, this knowledge forms the cultural heritage of humankind. Unlike genetic information of a species, the cultural heritage comprises both true knowledge of environment (e.g. physical laws that have been tested thousands of times) and false knowledge (e.g. superstitions). Initially all this knowledge was stocked in the brains of living people. With the appearance of written languages it became possible to storage information in written form in books and later in electronic form on computer disks. The ability to transmit cultural information to further generations is written in the genome of Homo sapiens. In particular, it is manifested in the ability of people to learn their mother tongue, which is also a part of a cultural heritage.

Phenomena resembling cultural heritage to a certain extent can be found in some other mobile animals. For example, mating-places (i.e. places where males compete with each other for females) of some birds (Gallinaceae) can remain the same during several generations. Non-genetic information about their locality is transmitted from one generation of birds to another. Another example is songs of some species of birds that are different in different regions. The way a bird sings depends on where it was raised. This means that non-genetic information about how to sing is transmitted from parents to progeny. But, unlike in humans, in all such cases hereditary non-genetic information of animals is lost after a few generations and constitutes a small part of the total amount of information that is accumulated and stocked in the memory of an organism during its life span.

In humans, cultural heritage constitutes the major part of individual memory. The rate of accumulation and change of cultural heritage exceeds by many orders of magnitude the rate of evolutionary changes, which can be measured as changes in genomes of species during the process of speciation. That is why humans were able to inhabit rapidly very different regions of the biosphere, forcing out many aboriginal species.

As a biological species, Homo sapiens originally occupied the niche of a primitive forager, something intermediate between niches of herbivorous and carnivorous mammals. A forager is a species with a wide range of objects suitable for food, the productivity of each characterized by their natural distribution in the biological community. Animal production of most terrestrial biological communities is about one-tenth of plant production. Therefore a forager consumes about 10% of animal food and about 90% of vegetable food. A male human can easily cover up to 15 km day^{-1}

(more than 5000 km/yr^{-1}). If, while walking, the forager collects food from a zone that is about 1 m wide (0.001 km) and if food objects completely regenerate in one year, it is evident that one person can occupy about 5 km^2 (5000 $\text{km/yr}^{-1} \cdot 0.001\ \text{km} \cdot 1$ year). This figure is obtained from the condition that all food consumed by the forager on this territory is given sufficient time to regenerate, so that the total amount of food on this territory always remains constant. If the global population of primitive people occupied a territory of about $10^6\ \text{km}^2$ (which is equal to the area of modern arable lands), then at that time the global population of humans did not exceed two million people.

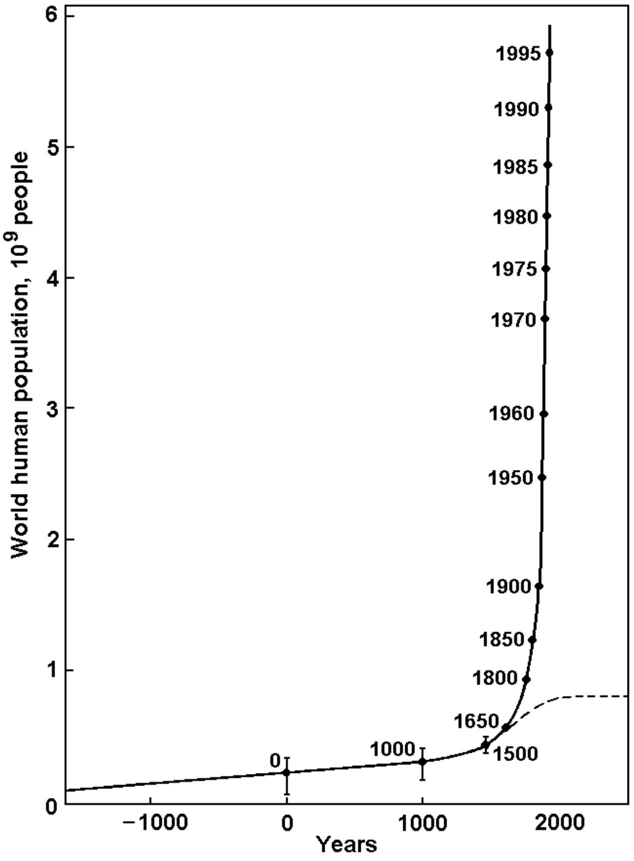
Knowledge of how to use human-made tools in hunting was, presumably, the first cultural information of humankind. It gave people an opportunity to eat more animal food, and even made it possible for some populations to form food habits based predominantly on meat. Use of animal skins as clothes resulted in substantial widening of territories occupied by humans, because hunters could live in temperate zones where natural production of plant food was insufficient. Yet the global population of humans did not increase drastically at that time, because the stable population density of hunters is nearly 10 times lower than that of foragers.

The next essential step in the accumulation of cultural knowledge was knowledge of how to use fire for heating and preparing food. People could then use for food many animal and plant products that were inedible raw. As a result, the area inhabited by humans increased further into temperate and cold zones. The use of fire presumably allowed the world's population of humans to increase to ten million.

One of the most important inputs into cumulative cultural knowledge of the environment was the invention of agriculture—the total destruction of natural biological communities on a certain territory and cultivation of monocultures consumed by a single species, Homo sapiens. Degradation of natural biological communities on arable territories led to shortage of animal food indispensable for humans, especially for the normal growth of children. This shortage was compensated for by cattle breeding on pasture—additional territory where natural biological communities were destroyed—as well as on arable lands. The territory occupied by one farmer was about 50 times less than the territory occupied by a primitive forager (i.e. about 10 ha person^{-1}). Thus, the transition from foraging and hunting to agriculture resulted in a 50-fold increase of the global population of humans to about 100 million.

Later, the accumulated knowledge of the environment mostly pertained to military technology, shipbuilding, and navigation. This was a period of great geographical discoveries, a period of active exchange of environmental knowledge accumulated by geographically separated populations of people. For many centuries people mostly used wind energy when traveling by sea and horses when traveling on land. Knowledge of the environment approached a certain saturation level. Its further gradual accumulation had no appreciable impact on civilization. The global population of people continued to grow slowly, for the most part at the expense of new territory that was gradually inhabited. There are all grounds to think that at that time the global population was tending to stabilize at the point of about one billion people (Figure 1), which is near the critical population number corresponding to the threshold level of degradation of natural biota and loss of regional and global biotic regulation of the environment.

Figure 1. World population growth (after Gorshkov 1995)



The solid curve with points on it describes the observed growth of the world's human population. The dashed curve represents the possible stabilization of the world's population in the absence of the scientific and technological revolution, a preconditioned of which was the discovery of fossil fuels. The asymptotic horizontal part of the dashed curve represents the ecologically permissible limit for world human population compatible with the functioning of biotic regulation of the environment on a global scale.

The situation changed drastically with discovery of fossil fuel. This discovery was a prerequisite of the scientific and technological revolution that began in the nineteenth century and is still going on. Its most important achievement was the discovery of mechanical traction based on fossil fuel combustion. The invention of the internal combustion engine made it possible to achieve colossal power in a limited volume and cover huge distances with a small expenditure of fuel. This led to an explosive development of motorized transport both on land and sea. Continents were covered with dense networks of railways and roads. The discovery of electricity allowed people to transmit huge power for almost unlimited distances. New means of transport and wire transmission of electricity stimulated rapid development of industry and intensification of agriculture.

The invention of radio and television sped up the exchange of knowledge throughout the world. Progress in medicine significantly lowered rates of child mortality. This led to a considerable increase in the mean life expectancy of humans.

All of these achievements and discoveries of modern civilization opened the way for an overall increase in population density caused by increased per capita energy consumption. The present-day high rate of population growth is unprecedented. Since about 1700, the global population of people has increased nearly 10-fold. Natural biological communities have been destroyed on most land areas of the world. For the first time, humankind is facing unfavorable environmental changes on a global scale. The available data on rates of environmental changes during different periods in the past show that present rates of global environmental change are also unprecedented. Such high rates of environmental change cannot be caused by natural phenomena and can only be explained by the increasing anthropogenic environmental impact of the growing economic activity of people. The very fact that global environmental change has begun means that the permissible threshold of perturbation of natural biological communities on land has been exceeded on a global scale. The remaining non-perturbed terrestrial biota is no longer able to cope with the human-induced degradation of the global environment.

Among the most serious global changes are pollution of rivers and coastal waters of seas and oceans, increasing atmospheric concentration of CO_2, changes in the ozone layer, acid rains, and increasing concentrations of heavy metals. People have begun to understand that the compensatory potential of nature is limited. A new branch of knowledge of the environment has come into existence—technological ecology (i.e. ecology of cities, industrial enterprises, agriculture, building). At present, in spite of its rapid development, this branch of knowledge does not have a clear strategy that could help avoid global ecological catastrophe **(see Section 6.2. The Future of Ecology as a Science)**.

Thus, dangerous environmental changes appeared as a result of the development of civilization. What determined the direction of this development? What should be done to change this direction in order to avoid the unfavorable consequences of environmental degradation?

The behavior of Homo sapiens, like that of all other mobile animals, is based on catering to positive emotions. That is, people always tend to do things that bring about positive emotions and that appear to improve their living standards. The whole system of positive emotions is programmed in the genome of Homo sapiens. So far, civilization has been developing spontaneously in the direction determined by the emotional program of people. The human brain has been continuously solving the problem of bringing about positive emotions. It is mainly this emotion-based spontaneous development of civilization that has resulted in the modern unfavorable situation. Moving further in the same direction, humankind could perish.

Emotions are usually considered characteristics of human behavior. Instincts are generally investigated in non-human animals. Both emotions and instincts can be measured only during relevant actions performed by an individual. Thus, instincts can be considered analogous to emotions in non-human animals.

The behavior of non-human mobile animals is also based on a hereditary genetic program of instincts. In the framework of a natural biological community, such a program ensures the correct work of a species in most effectively stabilizing the environment in concert with all other species of the community. But under distorted unnatural conditions (e.g. when certain species are placed in an alien biological community), the same genetic program may conflict with the programs of the aboriginal species. This leads to disintegration of the community, degradation of the environment, and, finally, the death of the alien species population. Examples of such local ecological catastrophes include the introduction of alien mammals (goats, rabbits) into the ecosystems of small islands. It is well known that in many countries with active foreign trade, the public are seriously concerned about the destructive influence on aboriginal natural biological communities of alien species that are imported into the country with purchased biological products.

Thus, the instinct-based behavior of mobile animals ensures the stable existence of species and biological communities under natural environmental conditions. Under disturbed conditions, instinct-based behavior can lead to self-destruction. Using ever accumulating cultural information, people significantly disturbed their original ecological niche. Under artificial environmental conditions, the emotion-based behavior of humans does not ensure their stable existence, but, on the contrary, leads to global destabilization.

However, during the process of cultural evolution people have discovered an important factor that allows the working out of emotion-independent strategies of behavior. This is the scientific approach. This method of exploring the environment formed the basis for the scientific and technological revolution of the nineteenth and twentieth centuries that ensured the current ecological problems of humankind. It could well be that scientists have already made all the major discoveries that can help people to transform their natural environment. This is presumably the reason for the evident decrease in enthusiasm of many governments to support fundamental scientific research. However, fundamental scientific research is the only method capable of helping people find a way out of the present ecological crisis. Firstly, using this method people can find out what Homo sapiens' optimal lifestyle is as a species. What is more favorable for people: living in an industrial landscape with all the modern conveniences of civilization but deprived of free communication with nature because of high population density and a high degree of industrialization, or living in natural biological communities with, possibly, lower levels of consumption? To answer these questions serious fundamental research is needed. At present, however, such questions are not even put forward. The dominant viewpoint in many countries is that priority should be given to high standards of living, which implies good food, clothes, and housing at expense of nature and global ecological safety, and the ethical requirements of people in respect to communication with nature. Yet only fundamental investigations of the above questions and working out an emotion-free but reason-based strategy of development of our civilization can prevent a global ecological catastrophe.

Let us consider the basic knowledge of the environment available to date.

3. Knowledge of Energy and Information

The environment that surrounds all living organisms on the planet consists of the atmosphere, the waters of oceans, rivers, and lakes, and a thin layer of soil on land. The environment is characterized by continuous cycling of various substances. The most important cycle in the environment is the water cycle. Water evaporates from oceans, rivers, and lakes, and descends again in the form of precipitation. A certain proportion of the water that evaporates from ocean surfaces precipitates on land and returns back to the ocean in the form of river run-off. Ocean water is circulating as well. In polar regions and on mountain tops water exists in the form of eternal ice.

Atmospheric air is also continuously cycling. Warm air masses drift from equatorial to polar regions and, having cooled down, return to low latitudes. Earth's rotation leads to air fluxes that cause differences in air pressure and the formation of cyclones. Pressure differentials are equalized by wind fluxes of air that achieve enormous speeds in hurricanes and tornadoes.

Cycling of substances in the environment represents highly ordered processes that are maintained at the expense of external highly ordered energy. On earth, solar energy generates all naturally ordered processes in the environment. All ordered processes in the environment are irreversible and represent processes of decay of certain initially ordered states. During the decay of ordered states, work is generated that governs corresponding ordered processes. The highly ordered energy of initially ordered states dissipates and finally converts to the low-ordered thermal energy of the chaotic movement of molecules. According to the law of energy conservation, discovered in the middle of the nineteenth century, the energy of initially highly ordered and finally low-ordered states is equal. Thus, during ordered processes energy retains its quantity but loses its orderliness.

An ordered state can be continuously maintained at the expense of external ordered energy that counteracts the continuous decrease of orderliness. Ordered states of this kind are called states of dynamic equilibrium. Cycles of all substances in the environment represent such states of dynamic equilibrium maintained at the expense of solar energy. Solar energy dissipates during cycling and finally converts to the quantitatively equal energy of thermal radiation of the earth, which is emitted back to space.

Why is solar energy highly ordered compared to the chaotic thermal energy of the earth? According to physics discoveries of the twentieth century, earth's solar radiation and thermal radiation both consists of particles—photons. Absolute temperature measured in degrees Kelvin (K; equal to > 273°C) is proportional to the average energy of particles. The absolute temperature of the sun is about T_S = 6000 K. Earth's absolute global average temperature is about T_E = 288 K (i.e. about 15°C; see
). Thus, the average energy of one solar photon is about T_S / T_E = 6000/288 ≈ 20 times larger than the average energy of one thermal photon of earth. According to the law of energy conservation, the cumulative energy of all solar photons coming to the earth is equal to the cumulative energy of thermal photons. This means that the number of thermal photons emitted by the earth to space is about 20 times greater than the number of solar photons reaching the surface of the earth. Consequently, one solar photon decays on average into 20 thermal photons. The decay of solar photons gives rise to all ordered processes on the earth.

Table 2. Planetary energy and temperature characteristics (after Gorshkov et al. 2000)

I_S—flux of solar radiation incident upon the earth outside the atmosphere (solar constant); *A*—planetary albedo (fraction of solar radiation reflected by the earth back to space); ***a***—greenhouse effect (fraction of the earth’s thermal radiation reflected by the atmosphere back to Earth); *t*—temperature in degrees Celsius.

Orbital temperature t_O is uniquely determined by I_S (i.e. by the orbital position occupied by the planet in the solar system). Under the approximation of black body radiation I_S and t_O are connected by the expression $T_O = (I_S / 4s)^{0.25}$, where $T_O = t_O - 273$ (absolute orbital temperature in degrees Kelvin, $s = 5.67 \cdot 10^{-8}$ W m^{-2} K^{-4} (Stephan-Boltzmann constant). Meanwhile surface temperature t is mostly determined by values of planetary albedo and greenhouse effect: $T = T_O (1-A)^{0.25} (1-\alpha)^{-0.25}$ (here $T = t - 273$ is the absolute surface temperature in degrees Kelvin).

Planet	I_S **W m^{-2}**	**Orbital temperature (A = a = 0)** t_O, °C	**Average values at planetary surface**		
			A, %	α, %	t, °C
Mars	589	–48	15	7	–53
Venus	2613	+58	75	99	+460
Earth	1367	+5	30	40	+15
Earth, if total ice cover	1367	+5	80	7	**-84**
Earth, if total evaporation of oceans	1367	+5	75	99	**+350**

Consider an imaginary situation where the temperature of the sun gradually decreases while the total amount of solar energy reaching the earth's surface is kept constant. The temperature of the earth's surface would then remain the same, because it is completely determined by the total amount of energy coming from the sun. But cycles of all substances in the earth's environment would begin to slow down, because their rate is determined not by the total amount, but by the orderliness of incoming energy. If the sun's temperature were equal to that of Earth, all ordered processes on the earth would stop. Thus, it is not heat that is sent by the sun to Earth, as is often stated, but energy, whose primary characteristic is its high degree of orderliness as compared to the thermal radiation of the earth. Since the middle of the nineteenth century, the quantitative measure of disorderliness has been called entropy. In spite of a clear formal definition, this notion often remains vague for non-specialists.

In the middle of the twentieth century, orderliness was quantitatively tied to a more transparent notion of information, which became especially popular when people throughout the world began to use personal computers. Information may be characterized by the available number of memory cells N. If all cells are excited with equal probability and can contain only two possible values of a certain variable, then the total number of possible combinations of these values in all memory cells is 2^N. Such a memory system possesses the maximum possible amount of information equal to N bits when values of the measured variable are defined in all N memory cells. If states of N_1 cells remain unknown, the amount of information reduces to $N - N_1$. Finally, if the measured variable remains undefined in all memory cells, information becomes zero while entropy reaches maximum.

Solar photons interact with molecules of the earth's surface. Solar photons can excite molecules (i.e. impart a certain amount of energy to molecules and increase their energy as compared to the average thermal level). Molecules can be compared to memory cells. A good approximation is to assume that molecular memory cells are characterized by only two states: excited and non-excited compared to the average thermal level. During the process of decay, solar photons are able to excite molecules until their own energy becomes equal to the average energy of thermal photons of the earth. Each solar photon possesses an amount of energy equal to that of about 20 of the earth's thermal photons. Consequently, one solar photon can excite about 20 molecules (i.e. give information to about 20 molecular memory cells). Such a consideration makes it possible to estimate the amount of information (in bits $\sec^{-1}$) coming from the sun to Earth. It is equal to the number of thermal photons emitted from Earth to space, because each thermal photon is emitted from an excited molecule, which represents a memory cell containing one bit of information. The number of Earth's thermal photons emitted to space in a unit of time is equal to the power P ($P \approx 2 \cdot 10^{17}$ W) of solar radiation coming to Earth, divided by the energy e of one thermal photon, which is determined by the earth's temperature T_E, $e = kT$, where $T_E \approx 288$ K (Table 2); k is the Boltzmann constant, which is proportional to the reverse Avogadro number ($k = 1.4 \cdot 10^{-23}$ J K^{-1} molecule^{-1}). As far as one molecule represents a memory cell with two possible states, dimension molecule^{-1} in the Boltzmann constant corresponds to bit^{-1}. Thus, for the estimate of information flux F coming from the sun to Earth the following expression is obtained: $F = P/kT \approx 10^{38}$ bit $\sec^{-1}$. Note that the obtained expression for F is simply the traditional definition of the flux of entropy.

The distribution of solar energy over different kinds of ordered processes on the earth is given in Table 1. Global biota uses solar energy to ensure processes of photosynthesis (0.06% of the total energy flux coming from the sun) and transpiration (i.e. evaporation of water vapor by plant leaves, which is about 2%). When the value 0.06% is taken as a lower estimate, the global biota processes information flux equal $F_B \approx 0.0006 \cdot 10^{38}$ bit $\sec^{-1} \approx 10^{35}$ bit $\sec^{-1}$. Interestingly, taking into account that the global biosphere contains about 10^{27} living cells (several dozens of unicellular organisms per each square micron (10^{-12} m^2) of the earth's total surface, which is about $5 \cdot 10^{14}$ m^2), it is easy to show that one cell processes about $10^{35}/10^{27} = 10^8$ bit $\sec^{-1}$, which is equal to information fluxes in modern personal computers (PC). Even if all the people on earth (about 10^{10} people) each had one PC of a future generation capable of processing ten thousand times more information in a time unit than modern PCs (i.e. about 10^{12} bit $\sec^{-1}$), the total information flux processed by humankind would be equal to $F_H = 10^{10} \cdot 10^{12}$ bit $\sec^{-1} = 10^{22}$ bit $\sec^{-1}$. This is 13 orders of magnitude less than the information flux processed by natural biota, $F_H << F_B$.

A negligible part of ordered processes is generated by geothermal power and the power of tides. Tidal power is determined by the movement of a stationary wave of water masses across the ocean's surface. It is mostly caused by the gradient of the gravitational field of the Moon at a distance equal to Earth's radius. The corresponding impact of the sun is considerably smaller because the distance between Earth and the Sun is much larger than that between Earth and the Moon. Tidal power represents the ordered power of mechanical movement and can be converted into any other ordered process. Geothermal power is mainly represented by heat flux coming from the earth's core. Being lost in the total thermal radiation of the earth, it cannot generate ordered processes. A small part of geothermal power exists in a highly ordered state. It can be seen in volcanoes, geysers, and near oceanic rifts. But this part of geothermal power is very small and constitutes about one-millionth of solar radiation (see Table 1). Thus, life that uses ordered geothermal power in oceanic depths and is based on chemosynthesis is characterized by cumulative production about one million times lower than that of life based on photosynthesis. On a global scale, chemosynthesizing life is negligible and taken all together corresponds to photosynthesizing life on an island with an area of about 100 km^2.

4. Knowledge of Environmental Stability

Dynamic equilibrium of cycling substances consists in the fact that masses and concentrations of all substances remain, on average, constant in all local areas of the environment in spite of the continuous exchange of substances between different areas generated by solar radiation. This means that, for all substances, sources are equal to sinks in all areas of the environment. If this equality is broken, masses and concentrations of corresponding substances begin to change. Rates of such changes are determined by processes in corresponding sources and sinks.

Atmospheric oxygen and CO_2 are in physical thermodynamic equilibrium with oxygen and CO_2 dissolved in rivers, lakes, seas, and oceans. On average, water solutions of these two substances are saturated. Solubility of these two gases increases with decreasing temperature. Thus, in polar regions there is a net flux of these gases from the atmosphere to the ocean, while in equatorial regions there is a reverse flux of gases from the ocean to the atmosphere. Physical cycles of oxygen and CO_2 depend mainly on the average temperature of the earth's surface and the difference between average temperatures of polar and equatorial regions. These two parameters are determined by the total amount of energy received from the sun and in practice do not depend on the difference between the earth's and the sun's temperatures. Thus, on a global scale, physical cycling of oxygen and CO_2 can be described by traditional thermodynamics.

Water is present in the biosphere in all three possible phases—solid, liquid, and gaseous. Conditions for thermodynamic equilibrium between different water phases are met only in very small local areas. On a global scale, the three phases of water are not in physical thermodynamic equilibrium. Residence time of water molecules in the atmosphere is of the order of ten days. Global average time of latitudinal and longitudinal atmospheric mixing is of the order of one month and one year, respectively. As a result, density of water vapor in the atmosphere is extremely non-uniform in contrast to the rather uniform densities of atmospheric oxygen and CO_2, which change hundreds of times in different regions of the planet. The uneven distribution of atmospheric water vapor over the earth's surface is conditioned by the orderliness of solar radiation and therefore depends on differences between the earth's and the sun's temperatures.

Thus, for some substances (e.g. oxygen and CO_2) dynamic equilibrium of cycling is close to physical thermodynamic equilibrium and is totally determined by the earth's average temperature and atmospheric pressure. For other substances (e.g. water), dynamic equilibrium is far from physical thermodynamic equilibrium. Cycling of such substances is a highly ordered process and depends on the degree of orderliness of solar energy.

The orbital position occupied by Earth in the solar system determines the flux of solar energy incident upon the earth outside the atmosphere. This is called the solar constant (Table 2). About one-third of this flux is reflected back to space, predominantly by clouds in the atmosphere and ice cover at the earth's surface (Table 2). The relative part of solar radiation reflected back to space is called planetary albedo. Due to non-zero albedo, Earth and other planets of the solar system are visible in space. Part of the solar radiation absorbed by the earth's surface through generating of cycling processes in the biosphere finally converts into thermal radiation. In the atmosphere, thermal radiation of the earth's surface is trapped by what are called greenhouse gases. Molecules of the greenhouse gases emit thermal photons in all possible directions, so that about half of this radiation returns to the earth's surface where it is again emitted to the atmosphere and so forth. This phenomenon is called the greenhouse effect and can be quantified as the relative part of thermal radiation of the earth's surface that is effectively reflected back to the earth by the atmosphere. The modern atmosphere of the earth reflects about 40% of thermal radiation, while on Venus this value is about 99% (Table 2).

The temperature of the earth's surface is uniquely determined by the cumulative flux of thermal radiation from its surface. Irrespective of what orbital position is occupied by the planet, this flux is totally determined by planetary albedo and greenhouse effect. Thus, surface temperature can assume almost arbitrary values depending on values of albedo and greenhouse effect that are completely determined by various environmental characteristics of the planet (Table 2).

When values of albedo and greenhouse effect are constant and temperature-independent, surface temperature of the planet $T = T_0$ is stable and determined by the balance of the absorbed solar radiation and emitted thermal radiation. The stability of temperature T_0 is ensured by negative feedback. When the surface temperature accidentally increases, $T > T_0$, the emitted flux of thermal radiation increases as well, so that the planet loses more energy than it receives. As a result, the planet cools down back to T_0. When the surface temperature decreases, $T < T_0$, the planet loses less energy than it receives. As a result, temperature increases back to T_0.

There are two physically stable states where values of albedo and greenhouse effect remain constant in a wide temperature interval. These states are total glaciation of the earth's surface at temperatures about –80°C, and total evaporation of the earth's oceans at temperatures close to 350°C (Table 2). In both states, life is impossible. Constancy of albedo and greenhouse effect in these states is determined by the fact that in both states water exists predominantly in only one phase—solid at low and gaseous at high temperatures.

Under modern climatic conditions, water exists in all three phases. Values of albedo and greenhouse effect change with changing temperature (e.g. with increasing temperature ice cover melts and albedo decreases). The kind of temperature dependencies of the global mean values of albedo and greenhouse effect remains unclear. At present there are no known physical barriers that could prevent the earth's climate from descending to one of the two stable but life-incompatible states. However, the stable existence of life over the last four billion years provides unambiguous evidence that the modern state of the earth's climate that is favorable for life is stable and that spontaneous transitions to both lifeless states are forbidden. This fact can be only explained under the assumption of the biotic nature of climate stability. This means that using solar energy, global biota of the earth generates directional processes that have a stabilizing effect on global environment and counteract spontaneous deviations from the favorable-for-life state.

5. Knowledge of the Natural Biota of the Earth

5.1. Internal and External Milieu

Each organism is characterized by an internal milieu and exists in an external milieu, which differ drastically from one another. This is possible because each organism has a natural envelope that protects and separates it from external milieu: trees have bark, mammals have skin and hair, birds have skin and feathers, etc. Thus, it is possible to maintain sharp differences between external and internal milieu. The internal environment of an organism is maintained by the well-coordinated work of its internal organs. Failure of any of internal organs leads either to death or to deterioration of the internal milieu and general condition of the organism.

Functioning of internal organs is not possible without consumption of nutrients and energy from external milieu, which is called the environment. In the organism, nutrients are decomposed, their chemical composition is changed, and they are excreted from the organism together with thermal energy that is released in metabolic processes. As a result, the environment changes. Each organism is characterized by a rather narrow interval of environmental conditions in which it can live (temperature, humidity, air pressure, availability of nutrients, low concentration of harmful substances, etc.). If an organism’s environment is not continuously supplied with nutrients and it is not cleared of excrement, it soon becomes unfit for life for any organism. Thus, it is evident that in any environment species cannot exist sustainably in isolation from other species.

Life for individuals of any species is only possible in coordinated interaction with other species of the biota. Consequently, natural biota consists of biological communities of species. Excrement of one species becomes nutrients for another and vice versa. Only then can the environment in principle remain stable. But this is *guaranteed* only if the functioning of all species in the community is rigidly correlated, similarly to the work of internal organs inside an organism.

5.2. Communities of Natural Biota

Any living organism represents a super-ordered internally correlated structure existing in a flux of external energy. The degree of orderliness of any living organism is much higher than that of the energy it consumes. Thus, all living organisms, as highly ordered objects, are subject to inevitable decay (death).

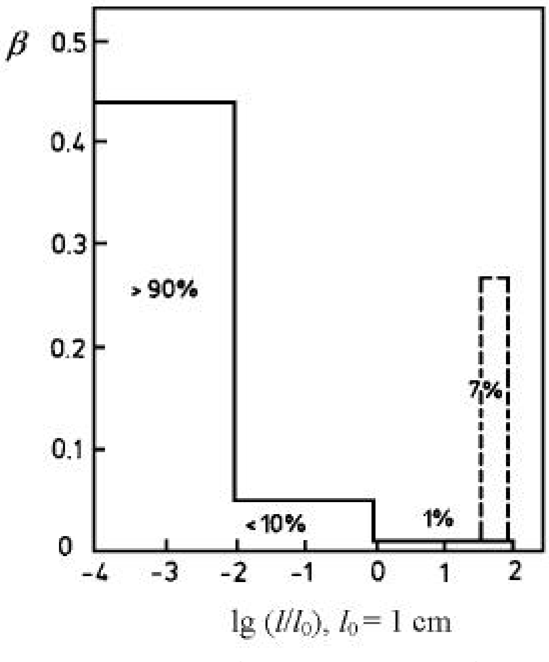
However, in spite of the decay of all individual organisms, the high degree of orderliness of life as a whole does not decrease; it even increases in the course of evolution. To support the high degree of orderliness, life uses the principle of stabilizing selection, a unique characteristic of living matter. Each biological species consists of one or more populations, consisting of uniform organisms. Not a single species exists in the form of one or two organisms. Individuals inside populations compete aggressively with each other. During the process of competitive interaction, decaying individuals (i.e. those with physical, genetic, or any other defects) are forced out of the population. The remaining organisms are all characterized by equal competitiveness, and, consequently, a high degree of orderliness. The necessary condition is the absence of correlation between competing organisms, so that removal of any individual from the population does not influence other individuals. Such a process can maintain any desirable degree of orderliness. Moreover, this is the only way to maintain the very high degrees of orderliness that are characteristic of all living objects.

Each organism is characterized by a strictly specified set of internal organs and a strictly specified distribution of fluxes of nutrients and energy going through different organs. Similarly, each community is characterized by a strictly specified species composition and a strictly specified distribution of fluxes of matter and energy going through different species in the community. Stability of the internal organization of organisms can only be maintained by means of competitive interaction of independent organisms. Similarly, stability of internal organization of communities can only be maintained by competitive interactions of independent communities.

Correlation of different organisms belonging to the same community is characterized by a certain radius (i.e. it becomes weaker with distance and dies out at a certain critical value of radius). Therefore, biological communities, as do all internally correlated objects (e.g. bodies of organisms), have finite sizes. Two neighboring communities compete with each other just as two individuals compete with each other inside a population. Communities that maintain their environment in a close to optimum state are the most competitive. Evidently, neighboring communities can stand the competition only if they regulate the environment as well as the most competitive ones, and maintain the same optimal values of all parameters of the environment. Otherwise they are forced out by the most competitive communities.

One of the main characteristics of a species is the average body size of its individuals. Figure 2 gives the distribution of consumption of the primary production of plants over heterotrophs of different body sizes. This distribution is based on published data for different natural terrestrial ecosystems and is universal for all natural communities.

Figure 2. Distribution of the relative rate of consumption of organic matter over body size of organisms-heterotrophs (bacteria, fungi, animals) (after Gorshkov et al. 2000)



$\beta \equiv P^-(l) \ / \ P^+$. $P^-(l)$ is the spectral density of consumption performed by all organisms with body size l. P^+ is net primary production of terrestrial plants. The solid line gives the universal distribution found in all non-perturbed terrestrial ecosystems. The area enveloped by the solid curve is equal to unity. Percentage figures give the relative input of different parts of the histogram. The dashed line describes violation of the natural distribution caused by the present-day anthropogenic perturbation of the environment. Area under the anthropogenic peak (7%) corresponds to humans' food, cattle fodder, and consumption of wood.

The distribution of consumed production over different heterotrophs is arranged in such a way that the smallest part of consumed energy is allocated to organisms characterized by the largest relative fluctuations of consumption. In other words, the environmental impact of a single large animal is very substantial and sometimes can even lead to degradation of a community on a local scale. To prevent such a situation on a larger scale, population densities of large animals are kept low in natural communities, so that the cumulative impact of large animals is small. Absolute fluctuations of consumption are therefore kept small in all species of the community.

Production of organic matter in the community is for the most part determined by photosynthesizing plants, many of them having rather large body sizes (e.g. trees). Each tree, however, has a large number of weakly correlated (i.e. nearly independent) small photosynthesizing organs—leaves or needles. In this sense, a tree can be compared to a colony of small photosynthesizing organisms. Such a structure of green plants decreases fluctuations of production in the community. When fluctuations of production and consumption are low, it is possible to keep production exactly equal to consumption and maintain the whole community in a state of equilibrium. Thus a low level of fluctuations of production and consumption means stability of a community and its environment.

Properties of major global types of biological communities and their environments are given in Table 3.

Table 3. The net primary production and living biomass of the biosphere (after Gorshkov 1995)

1 ha = 10^4 m^2; 1 Gt = 10^9 t = 10^{12} kg.
S—area occupied by the ecosystem;
p—net primary productivity of the ecosystem;
P—net primary production of the ecosystem ($P \equiv p\,S$);
b—density of organic carbon in the ecosystem;
B—total biomass of organic carbon in the ecosystem ($B \equiv b\,S$);
τ—residence time of carbon in living biomass ($\tau = B / P = b / p$);
d—leaf area index (the ratio of the total area occupied by photosynthesizing organs of plants to their projection area upon the earth's surface).

Bogs, marshes and swamps cover about 10% of the area occupied by forests. They are joined with forests because these ecosystems feature similar productivities and biomass. Tundra occupying an area of about 10% of that of deserts is joined with the latter for the same reason.

Ecosystem	***S*** **10^9 ha**	***p*** **t ha^{-1} yr^{-1}**	***P*** **Gt yr^{-1}**	***b*** **t ha^{-1}**	***B*** **Gt**	**t** **yr**	***d***
Forest, bogs, swamps, marshes	3.5	8.0	30.0	150.00	500.0	19.00	8.0
Grasslands, shrubs	4.7	4.0	20.0	17.00	70.0	4.00	4.0
Arable lands	1.4	3.0	5.0	3.00	5.0	1.00	4.0
Lakes, rivers	0.2	2.0	0.5	0.40	0.1	0.20	2.0
Deserts, tundras	5.2	0.2	1.0	0.40	2.0	2.00	0.7
Continents, total	15.0	4.0	60.0	50.00	600.0	13.00	4.0
Open oceans (pelageal)	33.0	1.0	30.0	0.01	0.5	0.01	0.6
Coastal waters (shelf)	3.0	3.0	8.0	0.10	1.5	0.20	2.0
Ocean, total	36.0	1.0	40.0	0.06	2.0	0.05	0.8
Earth, total	51.0	2.0	100.0	16.00	600.0	8.00	2.0

Arbitrary changes of the two main characteristics of natural communities—species composition and distribution of energy fluxes over different species—result in disintegration of correlated functioning of organisms of different species. This inevitably leads to unfavorable changes in the environment.

An internally correlated biological community together with its environment is called a local ecosystem. The main difference between an organism and a local ecosystem is that the latter does not have an envelope that would delimit the ecosystem's internal milieu (living area of all organisms of the community, their environment) from the local ecosystem's external milieu (area where there are no living objects).

Whether biota adapts to external milieu that changes arbitrarily due to random physical, chemical, and biological processes or whether biota forms and maintains its environment itself is currently a widely discussed question in biology.

5.3. Adaptation to or Regulation of the Environment?

The concept of adaptation to changing environment forms the basis of the Darwinian theory of evolution. In the first half of the eighteenth century, Carolus Linnaeus (Carl von Linné) created his famous classification of biological species that was based on morphological similarities and differences. Linnaeus thought that all species do not change with time. Charles Darwin used paleodata to put forward the statement that similar species had a common origin in the global process of biological evolution. No modern biologist would deny this statement. Darwin further assumed that the evolutionary process represents a continuous accumulation of hereditary changes in each individual and natural selection of individuals that are best adapted to the existing environment (i.e. that leave in this environment the greatest number of progeny). Darwin thought that natural selection is absolutely analogous to the artificial selection that is performed by people to create new breeds of animals and sorts of plants.

When the genetic nature of hereditary changes became evident, the Darwinian approach yielded new practical applications. It is well known that individuals of the same species differ genetically from each other. For example, the human genome consists of about $3 \cdot 10^9$ base pairs—genetic "letters." If the genomes of two people are compared, on average one comparison in a thousand will discover different letters. This means that the total number of differences is about $3 \cdot 10^6$. Intraspecific genetic variability appears to be due to mutations—genetic "misprints"—that mostly arise in the process of copying the genetic material. In light of the Darwinian approach, the more genetic variability a species has, the more easily it can adapt to an unpredictably changing environment. That is, the more genetic variability, the more chance a species has to survive in a changing environment, because when there are many genetic variants, the probability that one of them will fit a future environment is higher than when there is only one genetic variant (i.e. when all individuals are genetically uniform). Thus, many conservation biologists are seriously concerned that many endangered species exhibit very low levels of genetic variability. Accordingly, for conservation breeding programs populations with high genetic variability are generally preferred.

To date, however, ample evidence has been accumulated that contradicts such a view. Paleodata show that most species do not change morphologically (and, consequently, genetically) during the whole time of that species' existence, which is several million years. This means that extinct species appeared in discrete forms, there were no transitional forms between successive species. The extant species also demonstrate discreteness. No processes of transition between species are observed. All this suggests that formation of new species is not a continuous, but a punctuated, process, which can hardly be explained by adaptation to continuously changing environments. New species are formed during very short periods of time compared to the whole period of its species existence. For most of their existence, species are characterized by morphological and genetic stability.

The observed genetic variability can then be considered not as adaptational potential, but, rather, as random deviations from normal genetic programs of species. All the meaningful genetic information is the same in all individuals of the same species. Random genetic deviations accumulate due to the mutational process and erase the genetic information of a species. Thus, the total number of such deviations cannot increase indefinitely, but is limited by natural selection. In the process of natural selection individuals with too many genetic deviations are forced out of the population. Thus, under natural conditions the genetic program of species is prevented from decay.

However, in distorted conditions individuals with genetic defects can accumulate. Artificial selection uses this fact to create new breeds of economically important plants and animals. Thus, domestic animals and agricultural plants represent genetic monsters. Under natural conditions they cannot compete with normal individuals of the corresponding species, because those hereditary properties that make them useful for humans (high productivity of milk, high degree of fat, extremely large size of edible parts of plants) are disadvantageous under natural conditions. Unlike evolutionary changes, many artificially created genetic changes are reversible. When placed in natural conditions, many domestic species recover their normal (wild-type) genetic program, which assures maximum competitiveness of individuals. For example, doves living in cities have rather uniform morphology and are practically identical with wild doves, though urban doves descend from various domesticated breeds of doves that differ drastically from one another and from wild doves.

In some cases when two genetically different populations of the same species live in different environmental conditions, individuals taken from one population and placed on the territory of the other appear poorly fitted to the alien environment and lose in competition with aboriginal individuals. Such facts are interpreted as an argument for the existence of genetic adaptation. However, the possibility of the existence of a normal and distorted environment is ignored in such considerations. Suppose that, in a normal environment, individuals of a certain species need both to swim and to walk. In one distorted environment they need only to walk, in another only to swim. In both cases, individuals will lose one of the two abilities, because competitive interaction in distorted environments will not be able to support both hereditary abilities. Individuals that are able to walk in the environment where swimming is the only requirement will have no advantage, so this ability will finally vanish. So, in the first environment individuals will only be able to walk, and in the second one they will only be able to swim. Then after changing their environment, they will die in both cases. But their genetic differences are not an example of adaptation (i.e. acquiring new information about a changed environment). On the contrary, genetic differences between the two hypothetical populations represent erosion of original genetic information.

The above shows that all empirical data that could be explained without the notion of continuous genetic adaptation to changing environments. Rather, the assumption about the existence of this process contradicts some important evidence concerning, for example, the mode and tempo of the evolutionary process.

An alternative view on the nature of biota-environment interaction is that natural biota forms and maintains an environment favorable for life. This is the essence of the biotic regulation of the environment.

5.4. Biotic Regulation of the Environment

If the physical instability of the earth’s climate discussed above is considered a proven fact, then the existence of the biotic regulation of the environment needs no further proof. It follows unambiguously from the fact of existence of biota over a long period of time, by far exceeding characteristic times of spontaneous transition of the earth’s climate to stable states of total glaciation or total evaporation of oceans where no life is possible. However, many other facts testify to the existence of biotic regulation of the environment.

1. (a) According to the ice core data from the Antarctic, masses m of inorganic (CO_2) and organic (biota) carbon in the biosphere were about the same and changed less than by an order of magnitude, $m \approx 10^3$ GtC (1 GtC $\equiv 10^9$ tons of carbon), during a time period of recent $\tau = 10^4$ years. Rates of synthesis (P^+) and destruction (P^-) of organic matter by global biota are of the order of 100 GtC yr^{-1} (see Table 3). These figures mean that global fluxes of synthesis and destruction coincide with an accuracy of four digits.

(b) Inorganic carbon is continuously emitted from the earth's core to the atmosphere. The net rate of emission is $F^- = 10^{-2}$ GtC yr^{-1} for the last billion years ($T = 10^9$ years). Thus during this period the atmosphere could have accumulated about $F^-T = 10^7$ GtC (i.e. ten thousand times the observed value of $m \approx 10^3$ GtC). Then the greenhouse effect would have increased catastrophically (note that at present humankind is seriously worried by a 30% increase of CO_2 concentrations). Direct observations show, however, that an equal quantity of carbon (10^7 GtC) was accumulated in organic form in sediments. Under the reasonable assumption that the total mass of atmospheric CO_2 did not change its order of magnitude during $T = 10^9$ years, the following inequality is true:

$$(F^+ - F^-)\, T \pounds M$$

Here $(F^+ - F^-)T$ is mass of carbon really accumulating in the atmosphere during time period T. Then $(F^+ - F^-)/F^+ \le M/F^+T \approx 10^{-4}$. This means that F^+ and F^- coincide with an accuracy of four digits.

F^+ is equal to the difference in biotic organic synthesis (net primary production) and destruction, $F^+ = P^+ - P^-$. So the two biological values (P^+ and P^-) coincide in four digits and the difference between them coincides with an independent physical F^- value in four digits. This means that biota controls both synthesis and destruction to an accuracy of eight digits. Random coincidence with such accuracy is improbable, so this fact unambiguously points to the existence of the biotic regulation of the environment—biota is able to change synthesis and destruction of organic matter in any direction so that any difference between them will precisely compensate for external perturbations.

2. Molar inorganic ratios of most important dissolved inorganic nutrients ($C/N/P/O_2$) (Redfield ratios) in the ocean available for biota are exactly the same as the corresponding ratios in the production of oceanic biota. This is an indication that ocean concentrations of nutrients are formed and maintained by oceanic biota.

3. River run-off from land to the ocean is equal to the amount of precipitation brought by air masses from the ocean. On the other hand, river run-off is about three times lower than the total precipitation on land. Thus, two-thirds of precipitation on land is determined by evaporation from vegetation cover and soil. Without land, biota land climate would be three times drier. Thus, the water cycle on land is also under biotic control.

4. Modern data on the change of oxygen and CO_2 content in the atmosphere indicate that weakly perturbed biota of the ocean absorbs excessive atmospheric CO_2 and thus partially compensates for negative anthropogenic changes of the environment. Anthropogenically destroyed land biota has lost its stabilizing ability and at present adds to anthropogenic perturbation of the environment.

5. Atmospheric CO_2 concentration coincides with the average global concentration of the dissolved CO_2 in the surface ocean layer and is three times lower than the CO_2 concentration at depth. Such a difference is maintained by the biological pump—diffusion flux of inorganic carbon from depth to the

surface is counteracted by synthesis of organic carbon at the surface and sinking of newly synthesized organic carbon down to depth where it is decomposed. As a result, oceanic biota maintains atmospheric CO_2 concentrations three times lower than it was in the absence of biota.

6. One of the most vivid examples of mechanisms of biotic regulation is the process of recovery of biological communities after external disturbances (e.g. fire, cutting). This process is called succession. It can be compared to the process of healing or regeneration of injured organs of an organism. During the process of succession, a biological community is able to change unfavorable values of major environmental characteristics very significantly. For example, large-scale cutting of forests results in substantial degradation of soil. During succession processes, biological communities of forests restore all components of soil, changing concentrations of some of them by orders of magnitude.

During succession, dominant species of plants and heterotrophs succeed each other in a certain non-random order until the initial stationary (climax) composition of species in the community is restored. Climax community remains further unchanged unless another external disturbance occurs. The difference between the final (climax) and intermediate stages of succession lies in the fact that intermediate stages are not stationary. Once succession begins, they replace each other even in the absence of external disturbances. This happens because at each intermediate stage of succession dominant plant and animal components of the community change their local environment in an direction that is unfavorable for themselves but prepare environmental conditions favorable for the dominant species of the next stage. In taiga forests, for example, at first stages of succession the community is dominated by various herbs and shrubs; later on, there appear trees like birch and aspen that force out previous dominants. Finally, climax communities are dominated by spruce and pine, while species of all intermediate stages exist in climate communities in low densities.

In contrast to intermediate stages, the final climax stage is stationary and remains unchanged for indefinite periods of time. Correlated functioning of all species of the climax community ensures maintenance of an environment that is suitable for the whole community.

5.5. Mechanism of Biotic Regulation of the Environment

Many factors that are important for the global environment on Earth cannot be influenced by biota. Global biota is not able to change solar activity, Earth's orbital radius, the rate of Earth's rotation, or the angle between the axis of rotation and the orbit plane that determines alternation of seasons on the planet. To all these characteristics of the global environment, biota is genetically adapted. Similarly, biological communities of temperate or polar zones cannot maintain constant values of temperature or humidity all year round. They can only smooth out sharp fluctuations of temperature and humidity. To seasonal fluctuations of these characteristics, all species of the community are adapted. This adaptation represents a species-specific characteristic and is thus written down in species' genomes. It remains constant during the whole time of the species existence and does not depend on random environmental changes.

However, global biota consumes enough solar energy to control and maintain at a certain optimal level major determinants of the global environment (e.g. atmospheric concentrations of all greenhouse gases). Transpiration of water by continuous vegetation cover and storage of soil moisture by natural ecosystems of forests and bogs totally determines the water regime on land. Reflecting properties of continuous vegetation cover to a considerable extent determine the earth's albedo. Regulation of greenhouse effect and albedo makes it possible for biota to control average surface temperature.

To regulate the environment, biota uses processes of synthesis (production) and decomposition (destruction) of organic matter. In the absence of external physical fluxes of biogens to and from the ecosystem, their concentrations inside the ecosystem will remain stable only if biological synthesis of organic matter is precisely compensated for by biological destruction. This determines the degree of closeness of biological cycles inside the ecosystem.

If external physical fluxes of certain biogens are smaller than biological productivity (and, consequently, destructivity) of the community, the community is able to form and maintain concentrations of these biogens inside the ecosystem at a level that can differ significantly from that in the external milieu. For example, concentrations of various elements in soil differ drastically from corresponding concentrations in the earth's crust or atmosphere. This means that in natural ecosystems the rate of physical and chemical degradation of soil (soil erosion) is substantially lower than the rate of the compensating process of soil recovery that is performed by species of the biological community. In the case of soil in the forest and in other similar cases, biogens are regulated by local biological communities.

In many cases, external fluxes of biogens are considerably larger than a community's productivity. For example, physical mixing in the atmosphere and ocean is so large that it is not possible to discriminate between the ecosystem's environment and external milieu. In such situations, optimal concentrations of biogens are maintained by a large number of uniform biological communities occupying large territories of the earth's surface. Such biogens, for example atmospheric CO_2, may be called "globally regulated."

If the external concentration of a certain globally regulated biogen differs from the community's optimum, then biota of the community activates processes aimed at compensating for this difference. The direction and rates of these processes are the same in all communities of equal competitiveness. Compensating processes can be based on increasing productivity as compared to destructivity, or vice versa. For example, if the global atmospheric concentration of CO_2 is larger than the optimal for the biological community, then the community can try to decrease the internal CO_2 concentration of the ecosystem, depositing excessive CO_2 in organic form. This will induce a local physical influx of CO_2 into the ecosystem.

If such a local change gives the community an advantage (i.e. makes it more competitive), it can force out other communities that cannot perform such a change. As a result, all neighboring communities will perform the same flux. Thus there will be a global flux of CO_2 to biota until the atmospheric CO_2 concentration becomes equal to the optimal concentration of the community. As a result, excessive atmospheric CO_2—an active greenhouse gas—will be deposited in organic form and can be stored in tree trunks or dead organic forest litter and humus. Thus, small relative changes of concentration of biogens performed by local communities may lead to large absolute changes in the global environment.

6. Knowledge of Human-Biota Interaction

6.1. Climatic, Biological, and Ecological Limits to Anthropogenic Energy Consumption

The use of external sources of energy by humans at the earth's surface means transformation of all kinds of highly ordered energy into low-ordered thermal energy. The generation of additional thermal energy inevitably increases the earth's surface temperature in accordance with the Stephan-Boltzmann law (i.e. proportionality of the heat flux to the fourth degree of temperature). According to this fundamental physical law, it is in principle impossible to evacuate used waste thermal energy from the earth's surface without additional heating of it. Only the highly ordered energy can be evacuated from the earth's surface without changing the surface temperature. For example, part of the solar energy may be reflected back to space by increasing the planetary albedo. The reflected energy will initiate no processes at the earth's surface, that is, it will not be used in any way. It is only possible to cool the earth's surface at a fixed level of heat production by reducing the greenhouse effect, that is, by changing the existing composition of the atmosphere. This is inadmissible from the point of view of life in general and humans in particular.

Present-day energy consumption by humankind has reached 10 TW (1 TW = 10^{12} W) (see Table 1). Anthropogenic emission of 10 TW of thermal energy is equivalent to heating the earth's surface by 0.01°C. On a global scale, heating of the earth's surface by 0.1°C (i.e. ten times more) can in principle lead to unfavorable environmental changes. Thus, present energy consumption may still be increased by a factor of about ten above the present level up to about 100 TW. This is the climatic limit.

However, most of the released thermal energy originates from fossil fuel, which is necessarily accompanied by emissions of CO_2, one of the major greenhouse gases. Growth of atmospheric CO_2 concentrations leads to an increase of the greenhouse effect and heating of the planet. The present anthropogenic change in the greenhouse effect is equal to direct emission of about 1 000 TW of thermal energy (Table 2), which is one hundred times more than the present level of energy consumption and ten times more than the climatic limit. Therefore the build-up of the greenhouse effect is a much more serious factor than direct emission of heat resulting from anthropogenic energy consumption. Not surprisingly, this has caused the most concern among climatologists, whom politicians of many countries have lately started to listen to.

Production of global biota is based on consumption of about 100 TW of solar power (Table 1), which is close to the climatic limit. This is not a random coincidence—the power of the biosphere has reached the top power limit yet has remained compatible with climate stability. Peculiarities of the process of plant photosynthesis makes it possible to increase biotic power by at least an order of magnitude by using in agriculture exclusively the most productive plants like corn and sugar cane. But an increase of the average power of photosynthesis on a global scale by an order of magnitude means a catastrophic restructuring of the solar radiation budget on the planet and is, possibly, more dangerous than direct consumption of excessive external energy. Therefore, within the present climate, the total biospheric power of the global biota cannot be increased.

According to the law of energy conservation, no more than the total power of the global biota (i.e. of 100 TW), may be transferred into the anthropogenic channel. That corresponds to increasing the share of anthropogenic consumption of human food, cattle fodder, and wood by about an order of magnitude above the present level. This is the biological limit.

The increase of the anthropogenic share of consumption of biospheric production goes hand in hand with growth of the total energy consumption by humans. At present, the latter is far ahead of the former. This is an indication of how strongly the biota resists the destructive force of humans. The increase in the greenhouse effect is produced by the increased concentration of atmospheric CO_2. This effect is traditionally related to combustion of fossil fuel. As a result of anthropogenic perturbation of the greenhouse effect, the climatic limit has already been exceeded ten times over. That is why both climatologists and politicians see the main thrust in their struggle for preservation of the global environment to be reducing emissions of fossil carbon and transferring to alternative ecologically sound sources of energy. After implementing such a transition and stopping emissions of fossil fuel into the atmosphere, one might expect with help of an energy saving regime to return below the climatic limit and to reach the biological limit earlier than the climatic limit during the subsequent economic growth.

In fact, however, none of these limits, repeatedly discussed in various publications, describes the real situation. The actual existing limit to humankind's growth is the ecological one. It is determined by the condition of environmental stability and functioning of the biotic regulation of the environment on a global scale.

Human-induced transformations of that part of environment controlled by global biota brings about changes in the greenhouse gases and in humidity and temperature regimes of the planet. That, in its turn, breaks up climatic stability, affecting life conditions of both the biota in general and humans in particular. Both the climatic and biological limits are then automatically violated.

6.2. The Future of Ecology as a Science

Most mobile animals substantially change their local environment in certain areas of their feeding territories. Examples of such animal-induced transformations of the environment are nests of birds, burrows of rodents, beehives, anthills, etc. These objects, however, usually occupy very limited space and do not disintegrate the mechanism of the biotic regulation of the environment.

At present, humans spend most of their lives in cities and villages that are connected by networks of railways and roads. The total area occupied by cities, villages, railways, and roads is not very large and does not exceed the total area occupied by the rivers and lakes of all continents (Table 3). The problems of local pollution and utilization of wastes have always existed in all human settlements. For many centuries, the conventional solution of these problems was to pour out the wastes into the local environment, mostly into rivers and lakes, but also into the atmosphere. In these reservoirs, concentrations of wastes rapidly decreased thanks to the activity of biological communities of the biosphere. Finally, most of wastes were deposited in the form of inactive sediments.

During the pre-industrial era, the science of ecology as we know it today did not exist. Studies of organism-environment interactions were performed in the framework of biology and bore no relation to the ecological problems of humankind, which at that time were of a local character and minor importance.

The rapid development of civilization caused the rate of anthropogenic pollution to exceed the stabilizing capacity of natural biota. Local pollution began seriously to threaten people’s health. Thus, the notion of ecology began to comprise various non-biological fields such as the creation of no-waste technologies and cleaning facilities. Naturally, this new technological meaning of ecology has little to do with ecology in its conventional sense. Knowledge of how organisms of natural species interact with the natural environment seem to be of little help when the most important problem is to prevent or repair dangerous human-induced environmental pollution that is occurring at a growing rate and poses an immediate threat to human health. Thus, it is not surprising that while traditional (biological) ecology in general retains its modest place in biology textbooks, more and more attention is being paid to the development of the new technology-based dimension of ecological science (technological ecology). More and more money is being allocated to technological stabilization of the environment. According to various forecasts, in the first half of the twenty-first century the average share of the gross national product allocated to technology-based solutions of environmental problems in various countries is expected to reach 40% to 50%.

There has been considerable progress in technological ecology. Modern technological processes ensure almost total purification of waste and do not cause local pollution. Further progress in science and technology may create a technological system that will be able to regulate the environment on a global scale and replace the existing natural mechanism of biotic regulation. On closer inspection, however, such a possibility proves to be highly improbable. To ensure global biotic regulation of the environment, natural biota processes information fluxes by more than ten orders of magnitude, exceeding information fluxes that can ever be processed by civilization. Every living cell represents an ultra-complex system that both monitors and influences the environment. The whole biosphere of

Earth consists of more than 10^{27} living cells, each working as a modern PC. To make a technological system that would be able to perform the same regulatory functions as the biosphere does, it would be necessary to build computers with memory cells of molecular size and to cover the earth's surface with a continuous network of such computers; in other words, to re-create the virgin biota in its pre-industrial state. The creation of such a system is impossible. The unambiguous conclusion that follows is that the natural biota is the only mechanism capable of forming and stabilizing a global environment and climate that is suitable for life.

Thus, while technological ecology is indispensable for solving problems of local human-induced pollution, biological ecology that studies natural biotic mechanisms of environmental stability is necessary when solving problems of the long-term sustainability of human existence. Thus, it is very important to ensure that policy makers in all countries realize how vital are serious fundamental studies of the ecology of natural biological communities, and that they are no less important (and in the long-term are far more important) than the development of new technologies.

6.3. Scientific Bases for Nature Conservation

Through much of the development of civilization, the natural species of the biosphere have been classified as useful for people, useless for people, or harmful to people. Useful species were those few species that were actively used by people, while harmful species were those that interfered with anthropogenic activities. Useful species were protected, harmful species were contended with. The rest of the biosphere species, of no interest to humankind, were not protected and could be done away with if conserving them hindered the progress of civilization.

Many scientific and public movements for the conservation of biodiversity have been born recently. Yet there are still no commonly accepted scientific arguments for the conservation of biodiversity. Arguments that are put forward are based on aesthetics or are an appeal to preserve the unique nature of species genomes and the impossibility of restoring them should the species become extinct. Until now, however, humans have been using about one hundred species of the existing ten million and the number of widely used species is shrinking. There are no reasonable grounds to expect that all ten million will ever be used by humankind. Thus, it remains unclear to people why they should protect them. It is not surprising that decision makers in all countries are unwilling to sacrifice economic progress to a poorly argued task of biodiversity conservation.

The concept of the biotic regulation of the environment provides a sound scientific base for the necessity of biodiversity conservation. Natural species of the biosphere are not aesthetic objects for humans to look at, they are not hypothetical genetic resources for humankind, or potential forest pests. They are indispensable parts of the working mechanism for maintaining an environment that is favorable for humans. Each species inside the community performs strictly specified work on stabilizing the environment. The program of this work is determined by species genomes. And the unique nature of species genomes means that this work cannot be done by any other species.

Species in the community carry out different amounts of work. On average, the amount of work is determined by species body size and the observed distribution of consumption of the net primary production over heterotrophs with different body sizes (see Figure 3). All large animals, mostly mammals, carry out the smallest amount of work in a community and consume less than 1% of the net primary production in all terrestrial ecosystems.

The combined consumption of the net primary production by all mammal species of similar body size drops abruptly with increasing body size because the number of species of similar body size decreases with increasing body size (there are more species with small body size than with large body size). However, on average the share of consumption of net primary production that is allocated to one mammal species as a whole does not depend on body size. Mammals maintain constant body temperature and need to compensate for loss of heat from their body surface. Therefore, the consumption of mammals per unit area of body surface is nearly similar for all species. The ratio between body volume and body surface grows linearly with increasing body size. Thus, given constant consumption per unit area of body surface and constant consumption per species as a whole, the total biomass of a single mammal species (i.e. biomass of mammals per unit area of ecosystem surface) grows linearly with body size. In other words, the larger the animal, the larger biomass of this species in the community. This creates the illusion that large animals play a leading role in the community. That is why most conservation efforts are concentrated on protecting large animals. In reality, however, the relative amount of work carried out by each species of large animals constitutes less than 0.1% of the work performed by inconspicuous small organisms.

The significance of each species of a community is determined not only by the relative amount of work it carries out (i.e. the relative amount of the consumed net primary production). Interaction between some species features a trigger effect: consuming relatively small amounts of the net primary production, such species may regulate distribution of energy fluxes between the dominant species (e.g. insects pollinating flowering plants).

Summing up, the work of all natural species of biological communities is important for stabilizing environmental conditions. All natural species of a community should be preserved not as potential genetic resources but as unique parts of the working mechanism of maintaining an environment that is favorable for life. Obviously, it is necessary to preserve not separate species, but the whole community. Moreover, not single communities but a set of uniform competing communities covering large territories of the earth's surface the size of continents must be preserved in order to ensure global biotic regulation of the environment and guarantee ecological safety for future generations.

Glossary

Biota: Earth's natural flora and fauna.
Biogens: Chemical substances participating in the metabolism of living organisms.
Biosphere: The global biota and its environment.
Heterotroph: An organism that obtains the energy it needs to live by consuming other organisms or organic detritis. All animals and fungi, as well as many bacteria, are heterotrophs.

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Victor Gorshkov was born on July 12, 1935 in Leningrad, Russia, and graduated in 1958 from Leningrad (St. Petersburg) State University's Faculty of Physics. He was awarded a Ph.D. in nuclear physics by Leningrad State University in 1963, and a Doctor of Science (nuclear physics) by the Physical Technical Institute, Leningrad, in 1973. He was appointed in 1991 to a professorship in the Department of Biophysics, St. Petersburg State Technical University, and is currently a leading scientific researcher at the Theoretical Department of Petersburg Nuclear Physics Institute, St. Petersburg, Russia. In 1997 he was made an Academician of the Russian Academy of Noosphere, and an Academician of the Russian Ecological Academy.

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