in these forests is represented by natural fires, among which ground fires dominate (Korovin, 1996; Furyaev, 1996). The overwhelming majority of forest communities in these regions exist in a stationary stable state or close to that, Figures 6.19–1,2a.

In the rest of the European part of Russia, perturbations of forests are mainly due to clear-cuttings and, to a lesser degree, to fires (Forest Fund of Russia, 1995). Under such pressure forest communities may only occasionally reach the climax state (Figure 6.19–2b).

In the developed countries, territories previously covered by forests are represented now by artificially managed agricultural or silvicultural systems (Figure 6.19–3,4). In such a case, the natural stationary stable of community capable of biotic regulation is never reached. It should be noted that long-term land use is inherently unstable and leads to complete soil degradation in about two hundred years (Dokuchayev, 1954; Kovda and Rozanov, 1988; Zonn, 1991; Doran *et al.*, 1998). Intensive forest management can be also characterised as unstable due to substantial loss of biogens observed at early stages of recovery (Bormann and Likens, 1994). This loss has no time to be compensated over the too short process of recovery (50–60 years) during which the tree stand achieves the prescribed industrial standard and is cut down.

Summing up, the performed analysis of available experimental data on organisation and recovery dynamics of forest communities after strong perturbations show that the biota is able to completely compensate (up to a certain limit) even such strong perturbations of the environment as total fires, windfalls and others. This constitutes important empirical evidence in favour of the biotic regulation concept.

Anthropogenic activities seriously affect the functioning of natural ecological communities and, by doing so, undermine environmental stability on local and global scales.

7

Energy and Information

It is not heat that is sent by the Sun to the Earth, but highly ordered energy corresponding to a huge flux of information, which generates ordered physical processes and life of the biota on the Earth's surface. The natural biota absorbs solar radiation and processes it in molecular memory cells. Fluxes of information processed by the biota are used to support functioning of the mechanism of biotic regulation of the environment. Biotic information fluxes exceed by 20 orders of magnitude the information-processing capacity of modern civilisation. It follows that the existing natural biotic mechanism of maintenance of suitable-for-life environment is absolutely unique and cannot be replicated and replaced by technology however advanced the stage of technological progress.

7.1 ORDER AND DECAY

Ordered macroscopic processes surround us in our everyday life. Wind, formation of clouds, precipitation and flow of rivers are examples of ordered macroscopic processes of physical nature. The orderliness of these processes means that molecules of the involved substances move in a correlated fashion. For example, all molecules of water in a river have a downstream velocity component. During turbulent flow in whirlpools macroscopic groups of molecules feature identical angular velocities. The phenomenon of wind means that all the molecules of air have a common velocity component. Ordered motion of molecules can be opposed to their chaotic (non-correlated) thermal motion.

Molecules taking part in macroscopic motion interact with other molecules of the medium in which such motion occurs. Interaction of two molecules may produce a great number of final states. For example, during elastic collision a molecule may change the direction of its motion, while during inelastic collision it may transmit the whole of its energy to a molecule of the medium. Different final states of two interacting molecules are approximately equally probable. Thus, after interaction

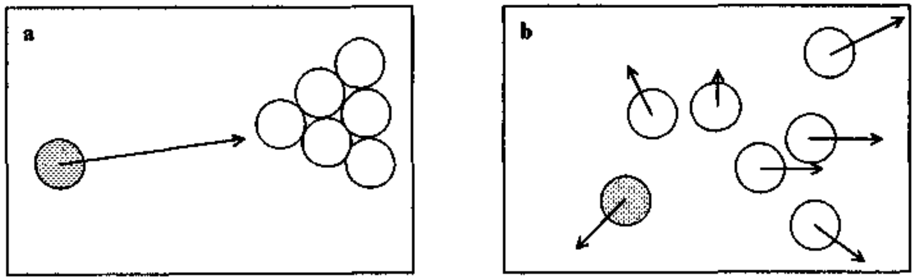

Figure 7.1. Highly-ordered energy of the rectilinear motion of the grey ball (a) converts (decays) to low-ordered energy of chaotically moving balls after collision (b). The energy (and impulse) quantity of the system remains the same; it is the energy (and impulse) quality that changes. Note that the reverse process (b → a) is improbable.

with the medium only an infinitely small fraction of molecules retain the characteristics of their initial ordered motion. Hence, an ordered correlated motion decays into disordered chaotic movement of molecules. It is the possibility of transition from a definite initial state to a large number of various final states that makes decay both possible, inevitable and irreversible.

Phenomena of this kind are well known from everyday experience. If a ball in billiards is given rectilinear motion in a definite direction (which is an ordered process, Figure 7.1) and collides with a group of motionless balls, the latter will move chaotically in different directions. As a result, the ordered motion of the first ball is terminated. The cumulative energy of chaotically moving balls after collision is equal to the energy of the initial ordered motion. Such a process is irreversible, because it is highly improbable that a few independent balls move in such a way that when they all meet, all but one of them stop and their cumulative energy is conveyed to a single ball that continues motion in a prescribed direction.

Biogeochemical cycles taking place in the Earth's environment present examples of ordered processes of chemical nature. Orderliness of these processes means that among all possible biochemical reactions, only a few strictly-defined reactions actually take place. This situation can be vividly illustrated when comparing a living and a dead organism. In a living organism all biochemical reactions are strictly defined and aimed at maintenance of biological homeostasis. Any deviation from the prescribed direction of any process in the living body leads to dysfunction of various parts of the organism, i.e. to disease. After death of the organism, its ordered biochemical reactions are stopped. The highly-ordered energy of the organic matter dissipates and converts to low-ordered thermal energy of the molecules. **According to the law of energy conservation, energies of the initial highly-ordered and final low-ordered states are equal. Thus, during ordered processes energy retains its quantity but loses its orderliness.**

All the diverse macroscopic processes observed on Earth are but various forms of decay of highly-ordered states of matter and of dissipation of highly-ordered energy they contain. The energy resources of Earth are formed by the totality of energy-rich states of matter on Earth. These resources exist in the form of kinetic or potential

energy. Kinetic energy is the energy of correlated motion of particles, e.g. solar radiation, hydraulic energy of rivers and oceanic waves, energy of sea tide, energy of wind. Potential energy is the energy of correlated bonds between various parts of the matter, e.g. gravitational energy, chemical energy of organic matter, nuclear energy. Other forms of potential energy include the existing temperature gradient between the polar and equatorial regions of the Earth's surface and between surface and deep waters of the world ocean. The nuclear energy, the gravitational energy of redistribution of matter in the Earth's interior and the energy of sea tides, are all preserved since the time of the formation of the solar system. All the other forms of energy resources available on Earth are generated by solar radiation.

Decay processes are characterised by a certain direction and time of duration. The majority of phenomena either observed in everyday life or detected in the course of scientific experiments are irreversible processes of decay of certain initial state. In the absence of decay, no observable events develop in time. For example, the absolute geochronology of the Earth is only known because of the decay of unstable isotopes of chemical elements. **Thus, time only acquires a physical meaning when a process starts fading (decaying), i.e. when the considered process has a start and a finish.**

7.2 SOLAR ENERGY

Since decay and dissipation of energy go on permanently, any ordered process may be supported only if there exists an influx of ordered energy to it from another ordered process. On Earth it is solar energy that generates all natural ordered processes in the environment and dissipates finally converting to quantitatively equal energy of thermal radiation of Earth, which is emitted back to space.

Why is solar energy ordered compared with the chaotic thermal energy of Earth? Both solar radiation and thermal radiation of Earth consists of particles—photons. Absolute temperature measured in degrees Kelvin is proportional to the average energy of a single photon. Absolute temperature of the Sun is about $T_S = 6000\,\mathrm{K}$ (Newkirk, 1980). Absolute global average temperature of Earth is about $T_E = 288\,\mathrm{K}$ (i.e. about 15°C). Thus, average energy of one solar photon is about $T_S/T_E = 6000/288 \approx 20$ times larger than average energy of one thermal photon of Earth. According to the law of energy conservation, the cumulative energy of all solar photons coming to Earth is equal to the cumulative energy of thermal photons emitted by the Earth into space. It means that the number of thermal photons emitted by Earth into space is about 20 times larger than the number of solar photons reaching Earth's surface. Consequently, one solar photon decays on average into 20 thermal photons. Decay of solar photons gives rise to all ordered processes on Earth.

Imagine that we decrease gradually the temperature of the Sun but keep constant the total amount of solar energy reaching the Earth's surface. 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 Earth's environment would begin to slow down, because their rate is determined not by the total amount, but by the orderliness of the incoming energy. If the Sun's temperature were equal to that of Earth, all ordered processes on Earth would stop. Thus, it is not heat that is sent by Sun to Earth, as it is often stated, but energy, the primary characteristic of which is its high degree of orderliness as compared with the thermal radiation of Earth.

Since the middle of the 19th century the quantitative measure of disorderliness has been called entropy. In spite of its clear formal definition, this notion often remains vague for non-specialists. In the middle of the 20th century orderliness was quantitatively tied to a more transparent notion of information (see, for instance, Brillouin, 1956), which became especially popular when people throughout the world began to use personal computers widely. Information capacity of a system may be characterised by the available number of memory cells N. If all memory cells can be characterised by only two possible values of a certain variable, 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, the information becomes zero while the entropy of the system reaches its maximum.

Solar photons interact with molecules of the Earth's surface that can be viewed as elementary memory cells of the environment. Solar photons can excite molecules, i.e. impart a certain amount of energy to molecules and increase their energy above the average thermal level. A good approximation is to assume that molecular memory cells are characterised by two states—excited (a definite state) and non-excited (indefinite chaotic state) compared with the average chaotic 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's surface. Each solar photon possesses an amount of energy equal to that of about 20 thermal photons of Earth. Consequently, one solar photon can excite about 20 molecules, i.e. impart information to about 20 molecular memory cells. Such consideration makes it possible to estimate the amount of information (in bit sec^{-1}) coming from the Sun to Earth. It is roughly equal to the number of thermal photons emitted from the 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 Q ($Q \approx 2 \cdot 10^{17}$ W) of solar radiation reaching the Earth divided by the energy ε of one thermal photon, which is determined by the Earth's temperature T_E, $\varepsilon = k_B T_E$, where $T_E \approx 288$ K, k_B – Boltzmann constant, which is proportional to the reverse Avogadro number ($k_B = 1.4 \cdot 10^{-23}$ J K^{-1} molecule^{-1}). As far as one molecule represents a memory cell with two possible states, dimension molecule^{-1} in Boltzmann constant corresponds to bit^{-1}. Thus, for the estimate of information flux F coming from the Sun to Earth we obtain $F = Q/k_B T_E \approx 10^{38}$ bit sec^{-1} (Thribus and McIrvine, 1971; Nicolis, 1986). Note that the obtained expression for F is simply the traditional definition of the flux of entropy.

The obtained estimate of the amount of information sent by the Sun to Earth is based on the assumption that all thermal photons emitted by Earth come from excited molecules. In fact, if one solar photon possesses energy equal to that of $T_S/T_E \approx 20$ thermal photons, the maximum number of molecules it can excite is $T_S/T_E - 1 \approx 19$, because after 19 acts of excitation its energy becomes equal to that of one thermal photon. After that it cannot impart additional energy to molecules and, therefore, cannot excite them. So, only $(T_S/T_E - 1)/(T_S/T_E) \cdot 100\% = (T_S - T_E)/T_S \cdot 100\% \approx (19/20) \cdot 100\% = 95\%$ of Earth's thermal photons come from excited molecules and characterise information flux coming from the Sun to Earth. Note that the ratio $(T_S - T_E)/T_S$ characterises the well-known Carnot efficiency of the solar radiation on Earth. If the Sun's temperature were equal to that of Earth, solar photons would have the same energy as thermal photons of Earth and could not excite any molecules on the Earth's surface. Evidently, in such a case the information flux from Sun to Earth would be equal to zero. Although the total number of Earth's thermal photons would then remain the same, none of them would come from excited molecules.

Distribution of available energy over different kinds of ordered processes on Earth is given in Table 7.1. Note that only a negligible part of ordered processes is generated by geothermal power and power of tides. Tidal power is determined by movement of a stationary wave of water masses across oceanic surface. It is mostly caused by the gradient of gravitational field of the Moon at the distance equal to Earth's radius. The corresponding impact of the Sun is considerably smaller owing to a considerably larger distance between Earth and the Sun as compared to that between Earth and Moon. Tidal power represents ordered power of mechanic movement and can be converted into any other ordered processes. Geothermal power is mainly represented by heat flux coming from the Earth's interior. Being lost in the total thermal radiation of Earth, it cannot generate ordered processes. Only a small part of the geothermal power exists in a highly-ordered state, e.g. in volcanoes, geysers and in the vicinity of oceanic rifts. The ordered part of geothermal power constitutes about one millionth of the solar radiation (Table 7.1). Thus, life that uses ordered geothermal power in oceanic depths and is based on chemosynthesis is characterised by cumulative production which is about one million times lower than that of life based on sunlight and photosynthesis. On a global scale, chemosynthesising life is negligibly small and taken altogether corresponds to photosynthesising life on an island with an area of about 10 km × 10 km.

7.3 STORES AND FLUXES OF INFORMATION IN NATURAL BIOTA AND CIVILISATION

Today there is little doubt that the global environment as well as the natural biota of Earth are degrading under the increasing pressure of anthropogenic activities. Until very lately, however, the observed adverse changes of the environment and human-induced degradation of the natural biota have been envisaged as two independent processes, although having a common cause. A common view has been that people should fight on the two fronts simultaneously. People should both restore the

Table 7.1. Energy fluxes at the Earth's surface.

Power source/sink	Power 10^{12} W	Power Relative to the solar power	References
Solar Power and Processes of its Dissipation			
Total solar power coming from Sun to Earth	$1.7 \cdot 10^5$	1.0	[1]
Solar power absorbed by the Earth's surfaces[a]	$8 \cdot 10^4$	0.47	[2], [3]
Evaporation from the total Earth's surface	$4 \cdot 10^4$	0.24	[2], [3]
Evaporation from land (evapotranspiration)	$5 \cdot 10^3$	$3 \cdot 10^{-2}$	[4], [5]
Heat fluxes from equator to the poles:			[6], [7], [8]
atmospheric	$3 \cdot 10^3$	$2 \cdot 10^{-2}$	
oceanic	$2 \cdot 10^3$	10^{-2}	
Wind power	$2 \cdot 10^3$	10^{-2}	[5], [9]
Oceanic waves	10^3	$6 \cdot 10^{-3}$	[5]
Maximum hydraulic power of rivers	3	$6 \cdot 10^{-5}$	[4], [10]
Available for humans			
wind and rivers' hydraulic power	1	$6 \cdot 10^{-6}$	[5], [9], [10]
Moonlight	0.5	$3 \cdot 10^{-6}$	[15]
Biota			
Transpiration	$3 \cdot 10^3$	$2 \cdot 10^{-2}$	[5]
Photosynthesis	10^2	$6 \cdot 10^{-4}$	[11]
Non-solar Sources of Power			
Total flux of geothermal heat	30	$2 \cdot 10^{-4}$	[10], [12], [13]
volcanoes and geysers	0.3	$2 \cdot 10^{-6}$	
chemosynthesising life	10^{-4}	$6 \cdot 10^{-10}$	
Tidal power	1	$6 \cdot 10^{-6}$	[14]
Humankind in the end of the 20th century			
Energy consumption (fossil fuel combustion mostly)	10	$6 \cdot 10^{-5}$	[10], [16]
Consumption of the net primary production of the biosphere	9	$6 \cdot 10^{-5}$	[17]

[a] Solar power absorbed by the Earth's surface is equal to the total solar power coming from the Sun to Earth minus solar power reflected by Earth back to space minus solar power absorbed by the atmosphere.

References: [1] Willson, 1984; [2] Ramanathan, 1987; [3] Schneider, 1989; [4] Lvovitch, 1974; [5] Brutsaert, 1982; [6] Kellogg and Schneider, 1974; [7] Peixoto and Oort, 1984; [8] Chahine, 1992; [9] Gustavson, 1979; [10] Skinner, 1986; [11] Whittaker and Likens, 1975; [12] Berman, 1975; [13] Starr, 1971; [14] Hubbert, 1971; [15] Allen, 1955; [16] Starke, 1987, 1990; [17] Gorshkov, 1995; Figure 1.1.

environment eliminating industrial wastes and help the natural biota preventing loss of biodiversity.

Such setting of the problem has resulted in endless discussions about how to feed the growing population, stop the global changes and prevent extinction of endangered species. Those who think that all these issues can be (easily) settled, are called *optimists*. People who question the solvability of this task are labelled *pessimists* and *alarmists*. As we demonstrate here, the very setting of the problem is incorrect. In reality—fortunately—we do not need to save the environment and biota each taken separately, which is indeed impossible. The only thing to be done is to lessen the burden of anthropogenic impact currently imposed on the natural biota. After that the latter will be able to restore and further maintain an environment suitable for humans.

In order to show that this is the only possibility to ensure environmental stability, let us compare quantitative information characteristics of the natural biota and modern civilisation.

The maximum rate of information processing by the human brain does not exceed 100 bit sec^{-1} (short-term memory).[1] Rate of information acquisition in the long-term memory is lower and does not presumably exceed 10 bit sec^{-1} (Ninio, 1998). Information is acquired most actively during the first 20 years of life of the individual, i.e. during about $6 \cdot 10^8$ sec. It can be safely assumed that the amount of information acquired later in life does not change the order of magnitude of the total store. Thus, the amount of information stored in human memory can be estimated as $6 \cdot 10^8\ \text{sec} \cdot 10\ \text{bit sec}^{-1} = 6 \cdot 10^9$ bit.

Processing and storage of information are inevitably linked to certain material carriers. Information about the surrounding world acquired by our brain is read from macroscopic natural memory cells, that are defined by the brain itself. When we look at a rose, for example, we can perceive and remember it as an integral unit (flower) or, at a closer look, as an assemblage of petals. But we cannot see and remember a rose as an assemblage of atoms, because our organs of sense (and, therefore, our brain) do not give us such a possibility. In the brains of animals (including humans) storage and processing of information that is read from macroscopic memory cells is performed in microscopic memory cells of molecular size. In the brain, therefore, macroscopic processes that take place in the environment and organism itself are imitated on a microscopic scale and are detached from their macroscopic natural material carriers. Such a situation may give an impression of independence of the world that is created by our brain from the real world. As a result, the idea of *soul* which is independent of the body, emerges. Thus, soul can be defined as the cumulative non-genetic information acquired during one's life-span and stored in the individual memory.

The unique ability of *Homo sapiens* to transmit the information acquired in memory to further generations forms the basis for such notions as *immortal soul* and *the future life*. Memory information (i.e. soul in the above definition) of people who contributed considerably to the cultural heritage continue to exist in memories of people of further generations. Memory information of people who did not make

[1] The minimum time interval that can be discerned by human organs of sense is not less than 10^{-2} sec. Among organs of sense, vision is characterised by the largest rate of information processing. Perception of visual information in humans is based on innate and acquired symbols stored in the long-term memory cells. Acquisition of visual information is based on successive perception of symbols of different level of specificity (Loftus and Bell, 1975), e.g. forest → tree → leaf. Thus, it is a good approximation to assume that at every moment only one symbol (bit) is perceived. Therefore, the maximum rate of acquisition of information does not exceed 100 bit sec^{-1}.

such contributions and were forgotten by their offspring dies (vanishes) as soon as the last person who remembers those people dies. Note that 'soul' in the above definition is a property of all locomotive animals that have memory and the ability to learn. However, the soul of all animals except humans inevitably decays with death of the organism. Only humans are able to transmit part of their memory information to further generations. Thus, *immortal soul* is a unique property of people.

Cultural information of civilisation is, for the most part, represented by information about an artificial human-created environment. Information stored in books and computers is lost unless it is contained in the memory of certain living members of the society. Thus, the amount of cultural information stored by civilisation can be estimated as the sum of non-overlapping elements of memory of all living people. An upper estimate of the amount of cultural information of modern civilisation can be obtained by multiplying the current population of Earth ($\sim 6 \cdot 10^9$ people) by the average individual memory store of information ($\sim 6 \cdot 10^9$ bit), which gives a value of about 10^{19} bit. This figure is evidently a gross overestimate of the real value, because the majority of memory information is the same in all contemporary people. The unique non-overlapping information of civilisation is stored in memories of *specialists*—scientists, craftsmen, writers, musicians, artists. Working specialists constitute not more than about 10% of the whole population (multiplier 10^{-1}). Each field of knowledge can exist sustainably with no less than 100 specialists working in this field and sharing the same memory information (multiplier 10^{-2}). Thus, the real value of information store of modern civilisation can be obtained by multiplying the upper estimate by 10^{-3}, which gives about 10^{16} bit.

Note that the amount of individual memory information of animals coincides by the order of magnitude with that of humans. Large animals live longer but perceive information more slowly due to lower rates of metabolism (Section 3.2). Small animals are characterised by shorter lifespans, but higher metabolic rates and, consequently, higher rates of information acquisition. Thus, human society differs from a herd of animals not by the absolute amount of individual memory of its members, but by the presence of differentiation of information over memories of different members, that is, by the presence of specialists (professionals). It may be argued that social insects, for example ants, are also characterised by a high degree of specialisation. The critical difference between specialisation in humans and other animals lies in the fact that humans continuously increase the amount of cultural information in each field of specialisation, while in animals the amount of information does not change from generation to generation. If we compare, for example, architectural knowledge of humans and ants, we realise that ants of a certain species always make the same type of anthills. A particular anthill construction is one of the genetically encoded species-specific characteristics. Meanwhile the modern architecture of humans differs greatly from what our ancestors used to build. Modern architecture comprises both traditional and newly-acquired knowledge.

Let us now estimate the store of genetic information in the biota. Genetic information of most species of the biosphere is written in polymer double-strand

molecules of DNA, which represent various sequences of the existing four different monomer units – nucleotide base pairs (bp). That is, the genetic alphabet consists of four different letters. Human genome contains $G = 3 \cdot 10^9$ bp (Lewin, 1987), i.e. $3 \cdot 10^9$ memory cells each of which can be characterised by one of the four different values. The store of genetic information in the human genome is equal to $\log_2 4^G = 2G = 6 \cdot 10^9$ bit. Note that the stores of genetic and non-genetic (memory) information in humans are of the same order of magnitude.

To quantify the store of the genetic information of the natural biota as a whole it is necessary to multiply the information content of an average genome by the total number of species in the biosphere, which is equal to about 10^7 species (Thomas, 1990). The average genome size can be taken equal to 10^9 bp, which is the average genome size of insects that constitute the majority of species in the biosphere. Intraspecific genetic variability is for the most part represented by decay changes of the genome (i.e. loss of information, Chapters 9 and 10) and cannot influence the obtained estimate. **Thus, the total amount of genetic information stored in the natural biota is of the order of 10^{16} bit and coincides in the order of magnitude with the information store of the modern civilisation.**

The amount of information that can be stored in a modern PC is of the order of 10^9 bit, i.e. it coincides by the order of magnitude with the amounts of genetic and individual memory information of one person. The cumulative memory capacity of modern computer technologies is large enough to store both the cultural information of modern civilisation and the genetic information of the natural biota.

Thus, when it comes to *stores of information* and memory capacity, modern civilisation is not inferior to the natural biota (Figure 7.2). However, life is a process. It is characterised by *fluxes of information* and the amount of work that can be performed in a unit of time by living organisms interacting with the environment. As far as the temporal characteristics of information are concerned, there exists an insurmountable quantitative gap between the natural biota and civilisation. We show this below.

Let us now estimate the major information fluxes. The species composition of the natural biota changes with evolutionary transitions of old species to new related ones. The genetic information of the biosphere changes in the course of evolution. Closely related species differ from each other in about 1% of their genetic information (Lewin, 1987). The average species life-span is about three million years (Chapter 11). Thus, 1% of the genetic information changes in a single act of speciation every $3 \cdot 10^6$ years. Consequently, a complete turnover of the genetic information of the natural biota (which we estimate as 10^{16} bit, Figure 7.2) takes about $3 \cdot 10^8$ years, i.e. about 10^{16} sec. Thus, the rate of evolution (i.e. the rate of change of genetic information of the natural biota in the course of evolution) is approximately equal to 10^{16} bit/10^{16} sec $= 1$ bit sec^{-1} (Figure 7.2). This extremely low rate of information change has been sufficient to ensure sustainable development of the biosphere, that is, to support evolution of the natural biota in such a manner that the latter has been able to compensate directional adverse environmental changes of cosmic and geophysical nature during the whole period of life existence, i.e. during nearly four billion years (Hayes, 1996).

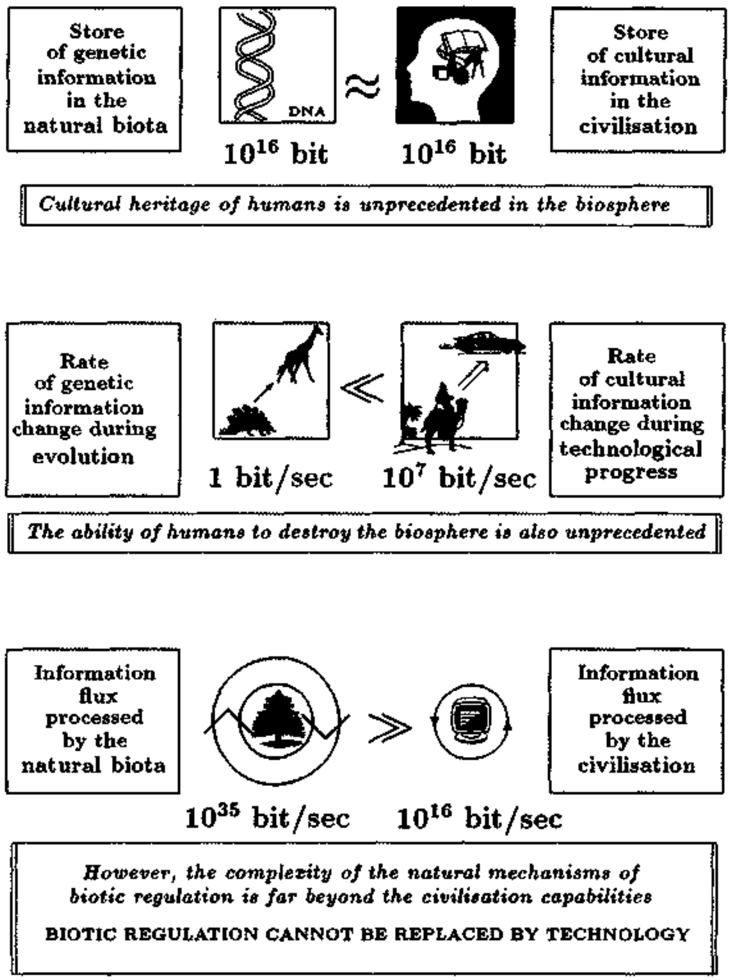

Figure 7.2. Major informational characteristics of the natural biota and modern civilisation.

The rate of information change during the technological progress of civilisation is determined by the ability of people to generate and assimilate new cultural information. According to the above estimates, the present-day population of Earth can assimilate no more than $6 \cdot 10^9 \cdot 10\,\text{bit}\,\text{sec}^{-1} = 6 \cdot 10^{10}\,\text{bit}\,\text{sec}^{-1}$. The present-day rate of technological progress depends on the average time of renewal of modern technological systems, which is of the order of 10 years, i.e. about $3 \cdot 10^8$ sec. Given that the store of information of modern civilisation is of the order of 10^{16} bit, the modern rate of civilisation progress is about $10^{16}\,\text{bit}/3 \cdot 10^8\,\text{sec} \approx 3 \cdot 10^7\,\text{bit}\,\text{sec}^{-1}$. (This estimate is obtained under the reasonable assumption that the majority of cultural information of modern civilisation is represented by information stored in the memory of specialists dealing with modern technologies.) Thus, the ratio of the amount of newly-generated information to the amount of assimilated information for modern people does not exceed $3 \cdot 10^7/6 \cdot 10^{10} \approx 10^{-3}$. Note that the same value characterises the average ratio of the amount of unique non-overlapping cultural information to the whole amount of the cultural information stored in the individual memory (see above).

The obtained information rate of the progress of modern civilisation, $3 \cdot 10^7\,\text{bit}\,\text{sec}^{-1}$, exceeds the information rate of evolution, $1\,\text{bit}\,\text{sec}^{-1}$, by more than seven orders of magnitude (Figure 7.2). This provides an explanation for the unprecedented (as compared to all other extant and extinct species) 'competitiveness' of *Homo sapiens*, as far as its potential to destroy the environment is concerned.

An estimate of the total information flux going through all modern computers can be obtained by multiplying the average information flux in one PC, $\sim 10^8\,\text{bit}\,\text{sec}^{-1}$, by the total number of people owning computers. Assuming that at present there is one PC for every hundred people we obtain that the total flux of information in computers of modern civilisation is of the order of $10^{16}\,\text{bit}\,\text{sec}^{-1}$. This figure will hardly ever increase by more than six orders of magnitude (by providing computers for all people on the planet and ensuring a four orders of magnitude's increase of information flux in each PC), i.e. up to $10^{22}\,\text{bit}\,\text{sec}^{-1}$.

Note, however, that even the present-day global computer information flux, $10^{16}\,\text{bit}\,\text{sec}^{-1}$, exceeds the assimilation capacity of the brain of modern people, $10^{10}\,\text{bit}\,\text{sec}^{-1}$, by a factor of a million. Computers work on the basis of programs designed by people and significantly speed up processing of information. But this only makes sense while people are still able to check and control the outgoing flux of information. All the information that is generated by computers and other mass-media devices (TV, cinema, video, theatre, music, etc.) above that threshold is nothing else but informational pollution of the environment (Gore, 1992). Informational pollution affects all the five organs of sense and, of the various types of pollution, presents the most dangerous threat to the mental health of humans.

Let us now estimate fluxes of information processed by living objects. In humans, metabolic power of existence in adults is equal to $q = 140\,\text{W}$ (Section 3.1). The body temperature of humans is approximately equal to $T_b \approx 37°\text{C} = 310\,\text{K}$. The average thermal energy of molecules in the human body is equal to $k_B T_b$, where k_B is the Boltzmann constant ($k_B = 1.4 \cdot 10^{-23}\,\text{J}\,\text{K}^{-1}$). Thus, $k_B T_b$ gives the order of the average amount of energy necessary to excite a molecule, i.e. the additional energy committed to a molecule as compared with the average thermal level. Assuming as above that one molecule corresponds to one memory cell with two possible states (excited and non-excited), i.e. 1 molecule $\approx$ 1 bit, we obtain that the information flux going through all living cells of the human body is equal to $q/k_B T_b \approx 3 \cdot 10^{22}\,\text{bit}\,\text{sec}^{-1}$. This value exceeds the asymptotic information power of possible future computers and by more than 12 orders of magnitude exceeds the assimilation capacity of modern humanity.

The human body contains about 10^{14} living cells. Thus, every living cell processes on average about $3 \cdot 10^{22}/10^{14} \approx 10^8\,\text{bit}\,\text{sec}^{-1}$, which is equal to information flux realised in a modern PC. The biosphere contains about 10^{28} living cells (Section 3.8).

Thus, the natural biota of Earth as a whole processes about $10^8 \cdot 10^{27} = 10^{35}$ bit $\sec^{-1}$, which is about 20 orders of magnitude more than the information flux of all computers of modern civilisation (Figure 7.2). Unlike computers, molecular memory cells of living cells are directly coupled with the environment. Thus, the whole flux of information processed by biota is immediately used for correct interaction with the environment.

Energy consumption of modern humankind is equal to 10^{13} W, which is only an order of magnitude less than the photosynthetic power of the natural biota (Table 7.1). It may seem that people only need to increase their energy consumption tenfold to be able to perform the same amount of work on regulation of the environment as the natural biota does. In reality, however, due to the huge difference in the rates of information processing between the natural biota and civilisation, any kind of anthropogenic energy use is inevitably characterised by remarkably low efficiency. By *low efficiency* we do not mean here a high percentage of energy loss. Modern technologies permit to minimise energy loss and achieve high efficiency coefficients when transporting energy or converting it to kinetic energy of working devices. Rather, *low efficiency* refers to the low information content of most processes generated by humankind with help of energy use.

Indeed, humankind spends a large portion of its energy on transport, i.e. moving macroscopic objects—cars, trains, people, etc. Motion of a macroscopic object is totally determined by only four figures—its mass and three co-ordinates of the velocity vector. Thus, motion of macroscopic objects can be fully described by a very small amount of information coded in corresponding macroscopic memory cells. It is in principle possible to convert efficiently the kinetic energy of moving macroscopic objects to gravitational or electric energy that could be further used for generation of complex correlated molecular processes similar to those taking place in a living cell. In fact, however, the kinetic energy of transported objects does not generate any ordered, information-rich processes. It is spent on friction, and finally dissipates, converting to heat.

Note that macroscopic motion can be found in the natural biota as well (e.g. locomotive animals). However, the amount of energy allocated by the natural biota to this low-efficient channel of energy use does not exceed 1% of the total biotic energy consumption (Section 3.7, Figure 3.3). Meanwhile people spend on transport more than one-third of the consumed energy. The remaining part of anthropogenically-utilised energy is spent even more wastefully with respect to the information content of the generated processes (e.g. heating of buildings).

A similar wasteful character of energy expenditure is observed in such phenomena as hurricanes, tornadoes, earthquakes, falls of large meteorites, etc. In all these phenomena huge amounts of energy are released and dissipate in a non-controllable fashion, breaking down ordered structures in the natural biota, civilisation and environment. For this reason, all these phenomena present a serious hazard to people and are called *natural calamities*. **For the same reason, the non-controllable dissipation of anthropogenically-utilised huge fluxes of energy is becoming an *anthropogenic calamity* for the natural biota, global environment of Earth and, ultimately, for people themselves.**

Thus, the *total amount of energy* consumed by humankind does not characterise the amount of work that can be done by people in order to stabilise the environment. We have seen that of critical importance here is the *total flux of information* that can be processed by modern civilisation. And, as far as information fluxes are concerned, modern civilisation is hopelessly inferior to the natural biota (Figure 7.2).

As noted above, the information flux gap between the natural biota and civilisation will hardly ever be reduced by more than six orders of magnitude and become less than 10^{14} bit $\sec^{-1}$. But even if we imagine that the gap is surmounted, and people have somehow been able to process as much information as the natural biota, it is easy to show that it is impossible to create a technological operating system equivalent to that of the biotic regulation of the environment. This becomes evident from the analysis of the well-known problem of automatic and manual control.

Manual control of technological processes is performed on the basis of genetic and cultural information of people. It consists in creation of feedback loops connecting the human brain and external fluxes of information. The rate of manual control is limited by the maximum rate of acquisition of information by the human brain, which is determined genetically as well as by all other major properties of the human organism. Automatic control functions on the basis of computer programs. Rate of automatic control is limited by technological properties of computers and can exceed the rate of manual control by millions of times.

However, the automatic control can be safely used in only those cases when the basic computer program leans upon well-developed theories. Such theories have been tested in so many independent experiments that people are absolutely sure in their predictions and do not need to check the results of automatic control. So, for example, the known exact physical laws allow the automatic control of space flights. But any unexpected situation not accounted for in the computer program inevitably forces the astronaut to switch the systems from automatic to manual control, the rate of all operations being immediately reduced by millions of times. Creation of any programme of automatic control is a very time-consuming process. Before it can be put into operation, all aspects of the work of all its elements need to be carefully tested by people, which is performed slowly by manual control.

Biotic regulation of the environment is equivalent to an operating system where the characteristic rate of information processing exceeds the maximum possible rate of manual control by 34 orders of magnitude and by 20 orders of magnitude—the rate of automatic control provided by all computers of modern civilisation. Biotic regulation is based on genetic programmes of biological species of the biosphere. Thus, from an anthropocentric standpoint, biotic regulation can be viewed as an automatically-controlled operating system where the programme of automatic control has been tested for reliability in an experiment lasting for several billion years (during the whole period of life existence). Humankind is unable to create adequate mathematical models of the natural biota. It is impossible to create a technological system equivalent to the natural biota, where each micron of the Earth's surface is controlled by dozens of independently functioning unicellular and multicellular organisms, each living cell processing an information flux similar to that of a modern PC. Finally, the genetic programme of the natural biota cannot be substituted by any technological programme of automatic control (even if this technological programme is characterised by fluxes of energy and information similar to those in the natural biota), because the search for appropriate technological decisions and their testing is performed by people and can take billions of years.

It follows unambiguously from the above that people are in principle unable to perform management of the natural biota, to improve or intensify its regulatory mechanism. Such attempts could be compared to the attempts of a domesticated animal (e.g. a cow) to improve functioning of a computer that governs its food supply. In very much the same manner as non-human animals are incapable of acquiring cultural knowledge of civilisation, humans are unable to manage fluxes of information similar to those processed by the natural biota. It is impossible to manage natural forests and wetlands to make them regulate the environment 'better' than they do. Humans are only able to manage artificial biological systems that are completely deprived of the regulatory ability, e.g. agricultural fields, where the only characteristic to be controlled is the productivity of the planted culture. Note also that even such primitive management always occurs at the expense of environmental stability, i.e. all other environmental characteristics (except for the productivity) change in a direction unfavourable for humans.

Genetic information of the natural biota totally changes every $3 \cdot 10^8$ years (see above). Thus, during the whole period of life existence ($3.8 \cdot 10^9$ years) there were no more than a dozen completely different programmes of biotic regulation of the environment. A working programme of biotic regulation is presumably unique for each particular epoch. Evolution of the biotic regulatory programme is possible due to acting geophysical and cosmic processes. That is, directional changes in parameters that cannot in principle be controlled by biota (e.g. solar activity) may lead to a situation when the old regulatory programme is no longer the most effective one. As a result, there opens a possibility for a new, more effective regulatory programme of the biota to establish as a result of genetic modifications (i.e. appearance of new species) in the old programme. New regulatory programmes appearing in the course of evolution are exposed to a thorough experimental testing.

The relative degree of *unsteadiness* in the work of a computer can be defined as the ratio of the rate of human-induced changes in the computer program to the total flux of information processed by the computer. The relative unsteadiness of the regulatory programme of the natural biota, similarly defined, is fantastically low, $1\ \text{bit sec}^{-1}/10^{35}\ \text{bit sec}^{-1} = 10^{-35}$. (Rate of programme change corresponds to the rate of information change in the course of evolution, $1\ \text{bit sec}^{-1}$. The total information flux processed by the natural biota is equal to $10^{35}\ \text{bit sec}^{-1}$, Figure 7.2.) It means that each working regulatory programme is maintained by the natural biota in a steady state for the maximum possible periods of time.

Summing up, we have seen that while the store of cultural information of modern civilisation is of the same order of magnitude as the store of genetic information in the natural biota, the natural biota is able to process 20 orders of magnitude more information in a time unit than modern civilisation (Figure 7.2). There is no sense in attempting to substitute the reliable working mechanism of the biotic regulation of

the environment by a technological system. All such attempts are doomed to fail, as shown above and, which is more, the very setting of such a goal is dangerous. The only promising strategy for modern humankind is the strategy of preservation of the remaining natural biota and restoration of its global regulatory potential.

7.4 ECOLOGICAL INFORMATION OF LARGE ANIMALS

In unicellular organisms, nearly all cellular processes have an immediate impact on the external environment. Some multicellular organisms (plants mostly) have also preserved this quality thanks to a very large effective surface area of their organs—leaves, branches, roots. In large locomotive animals, on the contrary, most metabolic processes take place in the internal organs that do not have direct contact with the external environment. The regulatory biotic impact on the environment is evidently proportional to the surface area of metabolically active (living) biomass. The ratio of the surface area of living biomass to the territory occupied by the organism is proportional to the projection area index (leaf area index)[2] (Section 3.8). This index is of the order of 10 for immobile organisms (plants, bacteria, fungi) (Section 3.3) and of the order of 10^{-7} for large locomotive animals (Sections 3.7 and 3.8). Thus, the regulatory potential of large animals is a hundred million times weaker than that of plants, bacteria and fungi. With increasing body size the variety of the organism's possible interactions with the environment becomes poorer. Complex metabolic processes taking place in the internal milieu of a large organism are mostly aimed at converting metabolic power of the organism to the mechanical power of locomotion, feeding (consuming biomass) and work of excretory organs. These relatively simple (information-poor) actions do not require the high complexity of biochemical organisation of cellular processes that was inherited by multicellular organisms from their unicellular predecessors. The same work could be easily performed by artificial devices, far more primitive than organisms of large animals. Meanwhile small animals specialise in very fine and complex (information-rich) interactions with vegetation, that cannot be performed by any technological means of civilisation (e.g. pollination of plants by insects). Thus, contrary to common opinion, large animals represent the most primitive part of the natural biota with respect to environmental control.

Natural biota is from time to time exposed to various catastrophes of abiotic as well as of biotic nature (e.g. fires, windfalls, volcanic eruptions, occasional invasions of alien species, etc.). Thus, natural biota must include as its integral part a certain set of species that could ensure recovery of the ecosystem after such disturbances. It

[2] For trees the projection area index is roughly equal to the average number of times the tree's leaves overlap each other along a vertical axis (leaf area index), i.e. how thick (in terms of leaves) would be the tree's foliage when all the leaves are put on the projection area of the tree. Note that for plants the ratio of the surface area of metabolically active biomass to the territory occupied by the organism is roughly equal to leaf area index multiplied by a factor of two (taking into account the upper and lower surfaces of a leaf). For locomotive animals the projection area index is equal to the ratio of the area of the organism's projection on the Earth's surface to the feeding territory of the organism.

is natural to call such species *species-repairers* (see Section 6.7). Evidently, species-repairers should achieve high population numbers and high population density immediately after disturbances and exist in lower numbers in the absence of disturbances. External disturbances do not occur at regular intervals. If a time interval between two consecutive disturbances (e.g. fires) becomes too long, the 'unemployed' species-repairers may lose their genetic stability, as soon as the process of stabilising selection is most efficient in dense populations. Thus, in order to 'train' species-repairers, natural biota has to support *species-disturbers* that disturb the ecosystem at regular intervals and, by doing so, periodically activate species-repairers, preventing them from genetic decay. Primitive man was among such species-disturbers together with many other large animals (e.g. elephants making large lawns amidst tropical forests). This issue has been previously discussed in Sections 4.7 and 6.7.

Homo sapiens has preserved the strategy of behaviour based on the genetic programme of positive and negative emotions inherited from large animals. Natural ecological role of man in the biosphere was to use fire and other means (e.g. stubbing up trees to get arable land) in order to introduce periodical disturbances of local ecosystems and activate species-repairers. Thus, the genetically-based programme of environmental impact of humans is aimed towards transformation of the natural environmental conditions (e.g. forest) into more favourable artificial ones (e.g. field), i.e. creation of an artificial 'internal' environment forcing out a less favourable external environment. This can be regarded as a further advancement of the principle of large body size (i.e. when more and more space is occupied by the internal milieu of the organism), which, as explained above, reduces the ability of *Homo sapiens* as a species to regulate the external environment. Cultural information accumulated by humankind in the course of historical development of civilisation has enabled people to impose a huge impact on the biosphere. But, as ever, the strategy of this impact is confined to the genetic programme of behaviour of *Homo sapiens*. Thus, most human–environment interactions result in large-scale perturbations of the natural biota and the forcing out of the natural 'wild' environment. It is this unprecedented scale of these processes that is now threatening the future existence of humanity.

8

Unique Nature of Climate Stability on Earth

In this chapter evidence is presented in favour of the statement that Earth's modern climate is physically unstable. In the absence of natural biota it should change spontaneously to one of the two possible physically stable states—that of complete glaciation of the Earth's surface and that of complete evaporation of the Earth's hydrosphere, both of which are life-incompatible. The existing climate has remained suitable for life during the last four billion years. It means that natural biota of Earth is the only mechanism that keeps the Earth's climate in a state suitable for life.

8.1 MAJOR CLIMATIC CHARACTERISTICS OF EARTH

All biogeochemical cycles in the environment represent steady ordered processes maintained at the expense of solar energy. A steady state of all substances cycling in the environment means that masses and concentrations of all substances remain, on average, constant in all local areas of the environment despite continuous exchange of substances between different areas. It 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 properties of the corresponding sources and sinks.

Atmospheric oxygen and carbon dioxide are in physical thermodynamic equilibrium with oxygen and carbon dioxide 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 carbon dioxide depend mainly on the average temperature of the Earth's surface and on 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 informational characteristics of solar energy that are determined by the difference between temperatures of Earth and Sun