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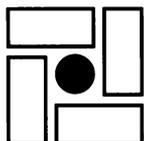
# **RUSSIAN JOURNAL OF ECOLOGY**

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## A New Approach to Estimating the Cost of Biotic Components of Ecosystems

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**Abstract**—A new approach to estimating the cost of biotic components of ecosystems taking into account their energy value is presented. A new method of calculating damage to ecosystems caused by human activities is considered. This method is based on the evaluation of the cost of energy necessary to maintain the ecosystems in a stationary state.

Man's expansion in the modern world is so wide that it is no longer possible to increase the load on ecosystems without serious demographic, social, and economic consequences for the society and the risk of destroying these ecosystems (Meadows *et al.*, 1994). Being a product of biological evolution, man can only exist within a narrow range of environmental characteristics controlled by the entire biospheric complex. There are living systems that control vital parameters, such as the constant gas composition of the atmosphere, global temperature characteristics, the level of the world's oceans, etc. (Gorshkov, 1988; Gorshkov and Kondrat'ev, 1990; Lovelock, 1979).

Therefore, it is necessary to develop systems for estimating the cost of the entire biocenosis as an elementary unit of the biosphere (including renewable resources important for the economy). These systems should be based on a *compensation principle* rather than on the consideration of a possibility of selling the resources, calculating net cost of exploitation and a possible profit. In other words, these estimates should answer the question as to what expenses should the society take in order to compensate losses in the regulatory function of the biosphere that can occur because of man-induced degradation of the ecosystems.

The existing methods of estimating the cost of the territory and damage do not allow such an approach. Moreover, our experience showed that the damage to renewable resources calculated by these methods is not commensurable with a profit that can be gained from, for example, development of oil and gas fields.

Economists use a so-called resource approach to evaluate renewable resources. That means that living components of the ecosystem can have a cost estimate only when they are somehow involved in the production process and are necessary for the everyday life of the society at the moment (Ekkel, 1985).

The main principles that were used to develop methods for estimating actual or possible damage to the

environment from the construction and operation of industrial facilities were as follows:

—compensation of expenditures for recovering damaged or destroyed natural resources;

—economy requirements and prevention of possible technogenic losses of natural resources (environmental control);

—the necessity of balancing economic conditions and the consequences of economic activities, compensation of economical losses (missed benefit).

Theoretical and practical issues of estimating damage to forests and other renewable resources (game resources, additional use of forests, etc.) are the least developed. For example, at the moment the fee does not depend on expenses for preparation and exploitation of forest resources and reforestation. Real expenditures and funds assigned for reforestation and forest management greatly differ (by dozens of times) under different conditions of forest growth and exploitation.

Procedures of calculation can also vary depending on the use of different approaches. Additional difficulties can arise in some branches. Thus, the game management service actually controlled only game animals rather than hunting grounds. Forests have always been controlled by the forestry service (in fact, now the situation is the same), being hunting grounds at the same time, and arable lands have been managed by agricultural authorities. Such a situation resulted in the development of methods for estimating damage to only game animals or game animals along with hunting grounds.

Two main problems arise when using the resource approach for the cost estimation. The first is a problem of the cost of a resource. There was no unified approach to the pricing in the Soviet Union (Ekkel', 1985), and damage was estimated in different ways. Thus, the following prices were proposed for evaluating damage to animals: (1) purchasing prices for game products (the method proposed by the Central Research Laboratory

of Glavokhota); (2) wholesale prices according to price list 46-01 (*Metodika opredeleniya stoimosti ...*, 1986); (3) wholesale prices for living animals according to price list 70-82-01 (Ravkin, 1989; Shilyaeva, 1989), and even (4) claim prices established by Glavokhota, order no. 1 of 04.01.88 (Ravkin, 1989; Shilyaeva, 1989). Nowadays, this problem has become more complicated because of inflation.

The second problem is that this resource approach does not take into account a vast variety of objects that do not have a consumer's value at the moment.

Such an approach is absurd because it actually involves calculation of the damage caused by one type of industrial activity (for example, oil and gas field development) to another type (forestry, fishery, game management), but not to the environment.

The society should rearrange the system of values by including the cost of nature expressed in a money equivalent. According to F. Saint-Marc (1977), "to introduce the concept of nature value, which was negligible before, to our economy means to make a revolution in it and to cause the greatest change similar to that caused by the appearance of machines in the 19th century" (cited from Ekkel', 1985).

The energy-related aspect of relationships between the human civilization and the environment was discussed previously (Podolinskii, 1880, cited from Ekkel', 1985; Popsuev and Tilichenko, 1972; Odum, 1978; Arbatov and Reteyum, 1979). Ravkin (1989) proposed to use a similar approach to estimating damage to the biotic components of ecosystems that do not have any commercial value. A specific feature of our approach (Korytin *et al.*, 1995; Kryazhimskii *et al.*, 1996) is that the costs of all the key components of an ecosystem are estimated. This allows us to accurately compare the work on maintaining the environmental stability performed by living ecosystem components, and human activities.

Basically, man and his industrial activities contradict the laws of environmental development. Evolution of the civilization generally leads to disturbances in the normal functioning of the biosphere, to global and local irreversible changes in the environment. Sooner or later, these changes may endanger the very existence of our civilization. Therefore, any industrial or other activity resulting in unfavorable consequences for the ecosystems should be estimated in common and general measures so that it would be possible to balance harm and profit.

The method described below provides the basis for assessing the consequences of anthropogenic impact and makes it possible to estimate the environment-forming function of the biosphere in some commensurable units (units of power or money). Although this approach does not allow us to evaluate all the negative consequences of human activities, we believe that it is urgent to introduce it into practice as soon as possible.

This method can also be used for calculating damage caused by one type of human activity to another.

Our idea is that it is necessary to separate the damage to the biosphere from the damage to industries exploiting renewable natural resources caused by the construction and operation of industrial objects in other branches of the economy.

Note that our method is not comprehensive; it is just the first step in a new approach. When we consider the problem of coexistence of mankind and other components of the biosphere, we realize that it is necessary to begin the work immediately, using the ideas that the developing ecological science can offer us today.

#### DESCRIPTION OF THE APPROACH AND TECHNIQUES USED FOR ESTIMATING THE VALUE OF THE BIOTIC ECOSYSTEM COMPONENTS

One of the most fundamental features of living systems is the need to constantly perform work for maintaining their orderliness. The ultimate energy source for this work is solar radiation. Thus, all the living systems (from the cell to the entire biosphere) possess a specific power that generally depends on the amount of solar energy (per unit time) necessary for maintaining their state and preventing them from sliding into the thermodynamic equilibrium (thermal chaos).

Obviously, the measurement of this power can provide the basis for estimating the cost of living systems. This estimation is based on the fundamental natural laws (the first and second thermodynamic laws), on one hand, and on the ecological concept of the biospheric function of man, on the other. The cost expressed in power units can be easily transformed into an equivalent of expenditures for obtaining the same amount of energy from the Sun by technological means. Note that recalculation into hydrocarbon fuel equivalent is unreasonable from the ecological standpoint because this fuel was formed as a result of a complex biospheric transformation of energy assimilated by living systems in the course of photosynthesis. A unit of a heterotrophic system requires much more energy than that of an autotrophic system because the "quality" of energy improves at higher trophic levels (Odum, 1986). Therefore, the use of hydrocarbon fuel units for assessing the cost of biological resources greatly leads to underestimation of their "actual" value (from the biospheric standpoint).

To illustrate the possibilities of using the power as the first approximation to a realistic ecological and economic estimation of biological resources, let us discuss energy flows through a stable ecological system (figure). The total biomass of this system and the biomass of its components remain relatively stable over a long period of time. The system consists of four trophic levels and each level is represented by populations of different species. These populations play different roles in

the general cycle of matter and energy: some of them (usually dominant and fairly abundant species) form the core of the biocenosis, whereas others (satellite species) add some specific features to the ecosystem (Shvarts, 1971). It is seen from the figure that any ecological system is open, i.e., it interchanges energy and matter flows with the environment. Thus, the state of the ecosystem is stationary and dynamic at the same time: free energy expenditures for irreversible processes are compensated by energy input from the Sun.

In the figure, symbols  $A_k$  and  $R_k$  show the input and output energy flows, respectively. Dimensions of the rectangles reflect the difference in biomass of the species belonging to a certain trophic level. According to the first thermodynamic law, the system remains stationary if:

$$A_1 = \sum_{k=1}^n R_k. \quad (1)$$

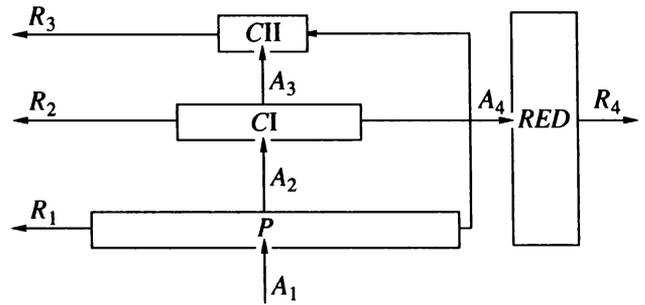
As indices  $R_k$  show energy expenditures per unit time (i.e., power), the state of the ecosystem can be integrally estimated by summarizing the powers of its main components. The result shows the amount of solar energy consumed by the system per unit time.

Although the assumption that the system is stationary can be regarded as a rough approximation, it meets the requirement for the simplicity and expediency of ecological and economic estimation methods and generally corresponds to the knowledge that can be used in practice. Anyway, this estimation is more valid from the scientific standpoint than most of the methods mentioned above. Our method leaves many details to be elaborated, but the essence of this is obvious and consists in taking into account the processes of development (first of all, successional processes).

Let us discuss now possible approaches to estimating the power of ecosystem components on the basis of the ideology described above. These approaches differ in complexity and require different amounts of information about the ecosystems. We have analyzed these approaches and can recommend one of them as basic, taking into account availability of certain information at the moment. Meanwhile, we do not reject more complicated approaches as they are likely to give better results when it is possible to use them in practice.

One of the most ecologically sound approaches consists in obtaining integral (systemic) estimates based on equation (1), where the cost of components belonging to the upper links of the food chains includes the cost of maintaining all the lower links:

$$C_k = Q_k \Xi_k + R_k + \left[ \sum_{i=1}^n (Q_i \Xi_i + R_i) D_i - \sum_{j=k+1}^n (Q_j \Xi_j + R_j) D_j \right] / D_k, \quad (2)$$



Scheme of energy flows through a four-level ecosystem: P are producers; CI are the first-order consumers; CII are the second-order consumers; RED are reducers;  $A_k$  and  $R_k$  are the input and output energy flows for the  $k$ -th trophic level, respectively.

where  $C_k$  is the cost of an individual (or a biomass unit) of the  $k$ -th component;  $Q_k$  is the energy content of an individual (or a biomass unit);  $\Xi_k$  is the turnover rate;  $R_k$  is the maintenance power;  $D_k$  is the population density of the  $k$ -th component of the food chain;  $n$  is the total number of the food chain components. Such an estimation is very difficult because it is necessary to know the structure and quantitative characteristics of all (or, at least, the main) components of the ecosystem. Cost evaluation of any resource requires plotting graphs that show the structure of trophic chains (networks) in the ecosystem and typical densities of all the ecosystem components. Then, the cost of the resources at the upper trophic levels is estimated from this cost at the lower levels.

Estimation (2) requires comprehensive knowledge about the ecosystem composition and the density of animal and plant species (or, at least, about its biocenotic core). The cost estimation of each component involves estimations of all the others. This approach is the most ecologically valid because it takes into account both direct (trophic) and indirect interactions in the ecosystems. However, its practical application is rather difficult because it requires a very careful preliminary study of each particular ecosystem. However, estimates of this type are sometimes possible to obtain, and we recommend this approach (in a simplified variant, as described below) for estimating the cost of rare and protected satellite species that cannot exist outside specific types of ecosystems.

From the thermodynamic standpoint, the cost of the  $k$ -th object can also be estimated as follows:

$$C_k = Q_k \Xi_k + R_k \left( 1 + \sum_{i=1}^m p_{ik} \frac{C_i - Q_i}{M_{ik} Q_i} \right), \quad (3)$$

where  $p_{ik}$  is the role of the  $i$ -th object in the feeding of the  $k$ -th object,  $M_{ik}$  is the coefficient of energy utilization by the  $k$ -th object feeding on the  $i$ -th object,  $m$  is

the total number of food items consumed by the  $k$ -th object. Estimation (3) assumes that

$$\sum_{i=1}^n p_{ik} = 1. \quad (4)$$

In this case, it is unnecessary to know the density of every object of the food chain in order to estimate the energy value of an individual or a biomass unit. Only energy (food) requirements of every object are taken into consideration. Although this estimation is more simplified than (2), it requires knowledge of food chains (networks) and diets of all heterotrophic species. Hence, this estimation should be further simplified because the greater part of ecosystems has not been studied in sufficient detail. The simplest variant is as follows:

$$C_k = Q_k \Xi_k + R_k / \prod_{j=1}^k p_j, \quad (5)$$

where  $C_{k(1)}$  is the cost of the  $k$ -th species (kW/g or kJ/g per year),  $Q_k$  is the energy value of tissues (kJ),  $\Xi_k$  is the period of energy turnover in tissues (biomass),  $R_k$  is the basal respiration rate (kW/g or kJ/g per year),  $p_j$  is the coefficient of energy assimilation upon transfer from  $j-1$ -th to  $j$ -th trophic level.

To obtain estimation (5), we need the following data: the list of species composing the ecosystem (at a certain approximation level), each with corresponding values of  $Q_k$  (the energy content of an individual or a biomass unit),  $\Xi_k$  (the rate of biomass turnover),  $R_k$  (maintenance energy), and  $p_k$  (a coefficient related to the trophic level of a given species).

For using estimations (2) and (3), it is necessary to have a square matrix with  $n \times n$  dimensions (where  $n$  is the number of objects in the ecosystem) that contains transfer coefficients  $\lambda_{ik} = p_{ik}/M_{ik}$ , which describe the trophic structure of this ecosystem. We also need to know characteristics of fecundity of the objects. For example, when assessing the cost of granivorous animals, we need to extrapolate the quantity of seeds to the total maintenance energy of the plants.

Calculations (3) and (5) reveal only a decrease in energy efficiency upon transfer from one trophic level to another and result in underestimations when applied to an individual or a population, however, the result obtained after summation (while evaluating the cost of a unit of the territory occupied by a given ecosystem) is similar to the integral estimation (5). Moreover, preliminary calculations demonstrated that estimations (3) and (5) at a permissible approximation level are close to one another. Estimation (5) is much simpler to calculate and requires less information: actually, it is only necessary to determine the trophic level and coefficients of energy assimilation.

Therefore, we recommend the use of estimation (5) at the first stage. However, this method does not take into account the specific role of rare species. For the latter, we propose a simplified method based on approach (2). To estimate their cost, the correction for the cost of all the lower trophic levels should be made:

$$C_{k(p)} = Q_{k(p)} \Xi_{k(p)} + R_{k(p)} + \left[ \sum_{i=1}^n C_i - \sum_{j=k+1}^n C_j \right] / D_{k(p)}, \quad (6)$$

where  $C_{k(p)}$ ,  $Q_{k(p)}$ ,  $\Xi_{k(p)}$ ,  $R_{k(p)}$ , and  $D_{k(p)}$  are the cost of an individual, energy content, turnover rate, maintenance power, and the density of a rare species per individual or a biomass unit, respectively;  $n$  is the total number of trophic levels in the food chain to which the rare species belong; and  $C_i$  are estimations of the cost of the other food chain components that were obtained by method (5).

#### CALCULATING PARAMETERS OF EQUATION (5)

(1) *Energy content in tissues ( $Q_k$ )*. Literature sources provide ample data on heat capacity (energy content) of different tissues, obtained by direct calorimetry (Table 1). These data can be used for estimating the energy cost of biological objects:  $Q_k$  is calculated by multiplying heat capacity of a unit of tissue weight by the body weight of an individual:

$$Q_k = q_k W_k, \quad (7)$$

where  $q_k$  is heat capacity and  $W_k$  is body weight of an individual. According to the standardization requirements, heat capacity should be measured in J or kJ.

(2) *Turnover rate ( $\Xi_k$ )*. This characteristic is measured in units that are reciprocal of time. In order to express power in W or kW,  $\Xi_k$  should be expressed in  $s^{-1}$ . The turnover rate is inversely proportional to the average generation period, which can be roughly estimated at approximately one-third of the maximal individual lifespan. Note that populations of the same species in different ecosystems can have different generation periods and, hence, different turnover rates. If the data on lifespan of homoiothermal animals are absent, the value of  $\Xi_k$  can be approximately estimated from body weight (the bigger the animal, the longer its lifespan).

Thus, the lifespan of captive mammals is calculated by the equation:

$$L_k = 366 \times 10^6 W^{0.2}, \quad (8)$$

where  $L_k$  is lifespan, s;  $W$  is body weight, kg (Sacher, 1959; Lindstedt and Calder, 1981). The corresponding equation for birds has different coefficients (Lindstedt and Calder, 1976, 1981):

$$L_k = 894 \times 10^6 W^{0.19}. \quad (9)$$

**Table 1.** Energy contents of tissues

Biological objects	Specific heat capacity, kJ/g dry weight	Reference
Terrestrial plants (total)	18.9	Odum, 1986
Only seeds	21.84	Odum, 1986
Algae	20.58	Odum, 1986
Invertebrates (without insects)	21.00	Odum, 1986
Worms	22.11	Prus, 1970
Crustaceans	17.80	Polishchuk <i>et al.</i> , 1978; Wallwork, 1975
Mollusks	20.28	Ashkenazie, Safriel, 1979; Ol'shvang, 1980
Insects	22.68	Vtorov, 1963, 1967
Fish	22.15	Dol'nik <i>et al.</i> , 1983
Amphibians	17.17	The same
Reptiles	19.68	"
Birds	23.32	"
Eggs of altricial birds	21.73	"
Eggs of nidifugous birds	25.75	"
Mammals	20.43	"

**Table 2.** Parameters of the allometric equation describing the relationship between basal metabolism (kJ/day) and body weight (g) in terrestrial vertebrates

Group	<i>a</i>	<i>b</i>	Reference
Passerine birds (summer)	3.727	0.69	Kendeigh <i>et al.</i> , 1977
Passerine birds (winter)	4.642	0.66	Kendeigh <i>et al.</i> , 1977
Nonpasserine birds (summer)	2.371	0.73	Kendeigh <i>et al.</i> , 1977
Nonpasserine birds (winter)	2.724	0.70	Kendeigh <i>et al.</i> , 1977
Mammals	1.855	0.74	Kleiber, 1961
Lizards (30°C)	0.106	0.83	Bennett, Dawson, 1976
Snakes (30°C)	0.034	0.86	Galvao <i>et al.</i> , 1965
Amphibians (25°C)	0.035	0.66	Ultsch, 1974

Correspondingly,  $\Xi_k$  can be expressed as:

$$\Xi_k = aL_k^{-1}, \tag{10}$$

where the coefficient of proportionality *a* can vary depending on ecosystem. In rough calculations, *a* = 3. The lifespan of poikilotherms largely depends on the temperature of the environment; hence, it must be determined for each species separately. The same applies to perennial plants.

(3) *Maintenance power (R<sub>k</sub>)*. Numerous experimental studies (Brody, 1945; Golley, 1961; Dol'nik, 1982) and theoretical works (Kryazhimskii, 1988, 1994) showed that the energy of self-maintenance (i.e., the flow of energy assimilated from food and necessary for maintaining a constant body weight) of most homoiothermal animals is twice as great as the level of basal metabolism, i.e., metabolism in the resting state under conditions excluding additional energy expenditures for thermoregulation. The basal metabolism of homoiothermal animals (as well as the maintenance energy

of poikilothermal animals) depends on body weight. This dependence is adequately described by allometric equations such as  $Y = aW^b$ . The coefficients *a* and *b* are known for most groups of animals, which allows us to calculate the maintenance power from animal body weight (Tables 2, 3).

The maintenance power for plants is calculated by the formulas of photosynthesis and respiration. For example, energy expenditures for respiration can be calculated from the rate of oxygen consumption in the dark phase using the following formula (Kuperman and Khitrovo, 1977):

$$R_e = q\eta \frac{(D_{t_1, t_m^o} + D_{t_2, t_m^o})RM_{av}}{273 + t_{av}^o} Q_{10}^{0.1(t_{av}^o - t_m^o)}, \tag{11}$$

where *q* is the energy content of tissues (kJ/mg);  $\eta$  is the proportionality coefficient of 180° mg/ml; *D* is the rate of O<sub>2</sub> assimilation (ml/g per hour); *t*<sub>1</sub> is the time of the beginning of measurements; *t*<sub>2</sub> is the time of the end

**Table 3.** Parameters of the allometric equation describing the relationship between daily metabolism and body weight (g) in different animal groups (from Dol'nik, 1978)

Class or type	a		b
	cal	kJ	
Protozoa	2.02	$8.48 \times 10^{-3}$	0.75
Infusoria	0.08	$3.36 \times 10^{-4}$	0.75
Porifera	7.00	$2.94 \times 10^{-2}$	0.75
Coelenterata	3.36	$1.41 \times 10^{-2}$	0.74
Turbellaria	14.62	$6.14 \times 10^{-2}$	0.82
Polychaeta	15.53	$6.52 \times 10^{-2}$	0.81
Oligochaeta	10.94	$4.59 \times 10^{-2}$	0.86
Hirudinea	12.28	$5.16 \times 10^{-2}$	0.82
Crustacea	14.40	$6.05 \times 10^{-2}$	0.76
Insecta (aquatic larvae)	74.00	$3.11 \times 10^{-1}$	0.82
Mollusca (Bivalvia)	7.85	$3.30 \times 10^{-2}$	0.72
Mollusca (Gastropoda)	23.80	$1.00 \times 10^{-1}$	0.75
Echinodermata	8.34	$3.50 \times 10^{-2}$	0.70
Tunicata	6.00	$2.52 \times 10^{-2}$	0.60
Pisces	34.20	$1.44 \times 10^{-1}$	0.81
Amphibia	33.50	$1.41 \times 10^{-1}$	0.76
Reptilia	39.60	$1.66 \times 10^{-1}$	0.78
Aves (Nonpasseriformes)	500.20	2.10	0.72
Aves (Passeriformes)	868.20	3.65	0.72
Mammalia	443.60	1.86	0.73

**Table 4.** Wood density ( $\rho$ ) in different tree species, kg/m<sup>3</sup> (Poluboyarinov, 1976)

Species	$\rho_{12}$	$\rho_0$	$\rho_{nom}$
Larch	660	630	520
Pine	500	470	400
Spruce	445	420	360
Siberian pine	435	410	350
Fir	375	350	300
Oak	690	650	550
Birch	630	600	500
Beech	670	640	530
Aspen	495	470	400
Alder	520	490	420

Note:  $\rho_{12}$  is density at standard humidity (12%);  $\rho_0$  is the density of absolutely dry wood;  $\rho_{nom}$  is nominal density (ratio of the weight of absolutely dry wood to the volume of fresh or newly cut wood).

of measurements;  $t_m^\circ$  is the temperature of measurements, °C;  $R$  is the duration of the dark period, hours;  $M_{av}$  is mean body weight, mg;  $t_{av}^\circ$  is the average temperature during the period of study.

The assimilation of CO<sub>2</sub> is recalculated into energy units by the photosynthesis formula: 477 kJ of energy is fixed per gram-atom of assimilated carbon dioxide. As this takes place, 0.68 g of CH<sub>2</sub>O (hydrocarbons) is formed, and 0.36 g of O<sub>2</sub> is released with energy assimilation of 2.55 kcal (10.71 kJ) per gram of assimilated CO<sub>2</sub>. When calculating the maintenance power for plants, one should bear in mind that the ecological energetics of plant communities is developed insufficiently. At the same time, the ratios of the total productivity (assimilation) to net productivity (energy accumulated in the biomass) are available. For example, this ratio for the vegetation of the North equals 0.75, i.e., the maintenance power relates to the productivity (the rate of energy accumulation in plant tissues) as 1 to 3; hence, energy consumption can be roughly estimated from average productivity. The accuracy of calculations should be determined in each particular case.

For example, to calculate the maintenance power (the total productivity) of forest communities, one can use the following (fairly rough) relationships that were determined empirically (Utkin, 1975; Molchanov, 1983):

(1) the annual production is about 5 % of the total biomass;

(2) the total biomass includes the underground biomass (25 %), trunks determining the stand volume (40 %), and also branches and foliage and/or needle (35 %).

The growing stock is the most common parameter characterizing the density of forest biomass. Thus, we can roughly estimate the maintenance energy (kJ/m<sup>3</sup> per year) of the forest communities per m<sup>3</sup> of stand volume.

$$R_k(\text{year}) = 0.0417\rho q, \quad (12)$$

where  $\rho$  is nominal wood density (the ratio of absolutely dry weight to the volume of fresh wood),  $q$  is the combustion heat per unit weight. The values of the nominal density for different tree species are cited in Table 4; the combustion heat per kg of absolutely dry weight is similar in different species and varies from 19.6 to 21.4 kJ/g, averaging at about 20 kJ/g (Chudinov, 1968; Ugolev, 1975). The conversion into standard units of power (1 kW = 1 kJ/s) is achieved by multiplying  $R_k(\text{year})$  by 0.032.

The maintenance power per m<sup>3</sup> of stand volume (in kW) is roughly estimated as follows:

$$R_k(f) = 0.0013344\rho q. \quad (13)$$

Of course, this estimation is the least preferable; it is much better to have the data on the actual photosynthetic productivity of trees, which greatly varies in forests of different types. Consequently, the method should be improved to give more realistic results. In particular, the initial stage consists in classifying the maintenance power (or, at least, biological productivity) for different forest types of a given area with respect to species composition, humidity, etc.

(4) *Coefficients of the energy utilization ( $M_k$ )*. The coefficient of utilization of energy received with food is about 0.8 for most carnivorous and granivorous animals (Table 1). The animals feeding on coarse green forage utilize the energy by approximately 60% ( $M_k = 0.6$ ).

#### JUSTIFICATION OF THE NEW APPROACH TO DETERMINING THE PRICE PER UNIT OF THE ENERGY EQUIVALENT OF COST

The approach to determining the price per unit of the energy equivalent of cost is based on the following. In our opinion, the ecologically cleanest method of converting solar energy into electric power by photoelectric (solar) cells is comparable to the utilization of solar energy by autotrophic organisms. This method is fairly expensive at the moment: in 1986, the price of a solar cell reached \$5.25 per watt even in the United States, the most developed country (*Mir vos'mide-syatykh ...*, 1989). We propose to use this price as the first approximation for calculating the cost of biotic ecosystem components: the cost of estimated damage will decrease together with the cost of energy generated in this way. This is likely to occur because the development of ecologically cleaner power, without exploiting resources of the biosphere, is a criterion and proof of changes in the prevailing attitude towards relationships in the man-nature system.

#### CALCULATING COST AND DAMAGE

To estimate the cost of biological resources in power units by simplified method (5), we need the following data: (1) energy content per gram of matter; (2) average body weight of an individual (for animals); (3) generation period (biomass turnover rate); (4) basal respiration (maintenance energy); (5) the trophic level, food specialization, and energy utilization coefficient; (6) population or biomass density (net primary or secondary production).

To estimate the cost of a territory, it is necessary to have data on the density of all the main groups of resources. The absence of at least approximate data on one of these groups will result in a considerable underestimation of the energy cost of the territory. For terrestrial ecosystems, these groups are: (1) soil invertebrates; (2) ground vegetation (mosses, lichens, herbage); (3) shrubs and trees; (4) invertebrates inhabiting ground surface, especially insects; (5) vertebrates (amphibians, reptiles, birds, mammals). For freshwater ecosystems we need the data on: (1) benthos (bottom invertebrates); (2) zooplankton (crustaceans and other invertebrates); (3) phytoplankton; (4) higher aquatic plants; (5) water vertebrates (primarily fishes).

Using these data and formula (5), the price of a certain resource per individual (mainly for animals) or biomass unit (for plants) is calculated. After this cost is estimated for all the species composing the biocenotic

core of the ecosystem (Shvarts, 1971), we can calculate the price of rare species by formula (6) using the data on the density of these species. Then, the cost of the territory or water area per unit density is computed:

$$C_t = \sum_{i=1}^n (C_i D_i), \quad (14)$$

where  $C_t$  is the energy cost of the territory (kW/ha or kW/km<sup>2</sup>);  $C_i$  is the price of an individual or a biomass unit of the  $i$ -th species;  $n$  is the total number of species, and  $D$  is the density of the  $i$ -th species. As mentioned above, estimation (14) is easy to express in money equivalent, multiplying it by the production cost of 1 kW of energy.

Note that these estimations are only the first step on the way to developing an ecologically sound system of assessing natural resources. They do not take into account information flows and qualitative transformations of energy upon transition from one trophic level to another.

The damage is calculated by multiplying the cost of biotic components per territory unit by the time lag. We propose to determine the duration of this lag on a biological rather than economic basis, using as a criterion the time necessary for the recovery of a deteriorated ecosystem to the initial state (or close to it). Thus, a 100-year lag is acceptable for many forest or tundra ecosystems. The duration of the lag is not a principal point: when assessing the prospective damage caused by temporary or constant land use, this parameter can differ in each particular case depending on expert evaluation.

A control calculation was made using the data collected with the aid of our colleagues (S.V. Paskhal'nyi, V.F. Sosin, M.G. Golovatin, N.L. Dobrinskii, M.S. Chep-rakov, V.G. Shtro, Yu.M. Malafeev, L.N. Dobrinskii). It concerned the cost of a typical tundra area in the Yamal Peninsula. The cost of this territory (without water area) was estimated at \$45 930 per ha. Consequently, the damage caused by irrevocable alienation of this territory (taking into account a 100-year time lag) is \$4593000 per ha.

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