Russian Journal of Ecology, Vol. 29, No. 5, 1998, pp. 297–305. Translated from Ekologiya, No. 5, 1998, pp. 339–348.
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A New Approach to Estimating the Cost of Biotic Components of Ecosystems

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Received April 28, 1998

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

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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:

$$A_1 = \sum_{k=1}^{n} R_k. \tag{1}$$

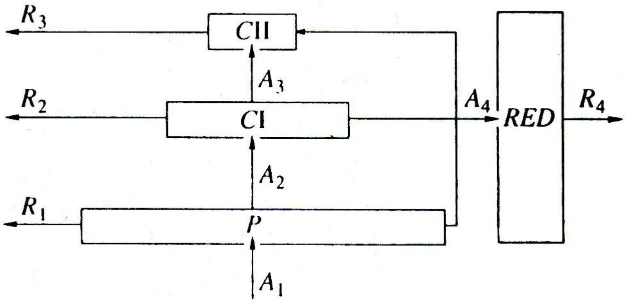
As indices R_k show energy expenditures per unit time (i.e., power), the state of the ecosystem can be integrally estimated by summarizing the powers of its main components. The result shows the amount of solar energy consumed by the system per unit time.

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:

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



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); Ξ_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:

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

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

$$\sum_{i=1}^{n} p_{ik} = 1. \tag{4}$$

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:

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

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), Ξ_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), Ξ_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:

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

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:

$$Q_k = q_k W_k, \tag{7}$$

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* (Ξ_k). This characteristic is measured in units that are reciprocal of time. In order to express power in W or kW, Ξ_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 Ξ_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:

$$L_k = 366 \times 10^6 W^{0.2}, \tag{8}$$

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):

$$L_k = 894 \times 10^6 W^{0.19}. \tag{9}$$