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ABSTRACT

In this paper, an agroecosystem has been described as a network of flows of artificial energy both inside the system and input/output flows. The total input flow corresponds to an energy load on the agroecosystem, i.e., it is one of the main characteristics of anthropoghenic pressure. The network structure reflects the real structure of the agroecosystem. Entropy measures of information have been defined on this structure: the entropy increment ΔH and a redundancy index h. The degree of agricultural development from traditional agroecosystems up to agroindustrial production systems has been correlated with the density of energy inflow σ.

Using some general concepts of thermodynamics, we consider some speculative hypotheses about general properties of agroecosystems. The main task has been to establish the dependencies of these information criteria on the energy parameters of agroecosystems. The structure of energy flows and values of criteria were calculated for farms in Russia, Holland and Lithuania. The results indicate was that historically the value of ΔH has decreased while the density of artificial energy flow σ has increased with the level of technological development of agrosystems. An agroecosystem is considered stable in the thermodynamics sense if $\Delta H > 0$. The critical value of σ for agroecosystem's stability (the maximum energy load on the system) has been estimated from the condition that $\Delta H > 0$.

INTRODUCTION

Shannon and Brillouin's classical works on the theory of information, where the concept of the entropy as a measure of information, have been applied to ecology by Margalef (1958, 1968). He suggested to characterize ecosystem current state by the so-called "diversity" having practically no difference from the entropy measure of information. Diversity was defined by Margalef as:

$$D = -k \cdot \sum_{i=1}^{n} p_i \cdot \ln p_i , \tag{1}$$

where

$p_i = B_i \,/\, B$	is the frequency of the i-th species, k is a scaling factor.
$B = \sum_{i=1}^{n} B_i$	is the total size (biomass) of the community of n species ; and
B_i	is the population size (biomass) of the i-th species;

Multiple observations prove that in a succession process of developing from its initial point to climax the diversity (information entropy, information) of the community increases, tending to a maximum, and further, at the stage of degradation, begins to decrease (Svirezhev and Logofet, 1983). The information approach is appropriate if regarded as some *empirical generalization* (in accordance to Vernadsky). This approach in ecology was proven to be valid in various works (see, for instance, Puzachenko and Moshkin, 1981; Levich, 1982).

However, as shown by Svirezhev (1987), direct application of information concepts to ecological systems engenders paradoxes. Information entropy alone appears to be insufficient to describe the ecosystem state: the information description must be supplemented with an energy or (and) a matter description.

I. DESCRIPTION OF AGROECOSYSTEMS USING ENERGY FLOWS. ECOENERGETICS ANALYSIS

An agroecosystem is considered as a transformer of the input flow of "artificial" energy into the output flow of agricultural production (Pimentel et al., 1973; Deleage et al., 1979). This approach called "eco-energetics analysis" is based on:

1) categorizing of material and energy flows that are the most significant for agroecosystem;
2) determination of energy equivalents for these flows.

Thereby one can define the intensity levels for all the flows considered and estimate the flow intensities in general units - energy ones. This allows to compare the different flows and to calculate the ratio of outputs to inputs, i.e., the efficiency η of the transformer, in this case of the agroecosystem (Odum, 1983).

As a rule, η exceeds one for crop production systems, because the approach does not take into account the "natural" energy of the sun as an input flow into the system. Why is it so? The flows of different kinds of artificial energy are approximately of the same order of magnitude, but the solar energy flow and that of artificial energy are not comparable as the difference is two orders in favor of solar energy. So they can not be compared in calculating efficiency. Certainly, the "solar energy" item in the total energy flow might be taken as consisting of photosynthetic active energy only (~1% of the total solar energy), but in such a case uncertainty arises as to the exact measurement of photosynthesis efficiency. Therefore, eco-energetics analysis disregards "natural" solar energy.

Traditionally, the utilized energy of anthropogenic origin is divided into two types: direct and indirect energy. Direct energy input implies the flows of resources directly related to *energetics*: oil, coal, peat, electricity, etc. (Deleage et al., 1979). By indirect energy we denote the flows of resources which are not actually energetic but take part in the operation of the system. These flows involve mineral fertilizers, pesticides, machinery, agrosystems infrastructure and some other resources.

The energy content of the flows is estimated by taking into account the *total primary energy* expenses needed for their formation. Thus, for example, the energy content of electric energy is the heat equivalent of the fuel burnt at power stations to produce this amount of electricity. The most questionable elements in such an approach relate to the quantification of multiple processes participating in the production flow. For example, when estimating the flow "human labour", one can account for not only the calories of the nutrition necessary for maintaining the physical activities required, but one can also account for all the other"energetic" expenses to provide an adequate living standard (e.g., using gasoline for private motor-vehicle transport (Smile et al., 1983). In our paper the methodology and recalculation factors from Pimentel's book (1980) were used as it is still the most complete summary of the results including the most significant production processes in agriculture.

The method, having been described in details by Svirezhev et al. (1986), will be illustrated by the analysis of a farm from the Central Chernozem Region of Russia.

The following input flows were taken into account:

- direct energy - fuel (diesel, petroleum, oil), electric energy, human labour;
- indirect energy - fertilizers (N,P,K), agro-chemicals, agricultural machinery, infrastructure, combifodders.

By expenses for infrastructure we mean those for agricultural buildings and premises, roads and reclamation structures.

Energy flows for the agrosystem are shown in Fig. 1 and Tables 1,2. *The total input* of artificial energy is estimated at 268 TJ (TJ = 10^{12} joules), indirect energy input being equal to 184.5 TJ, or 69 per cent of total energy input. The input energy for crop production is equal to 217.4 TJ (an additional internal system's flow of manure from husbandry equals to 107 TJ). This energy is transformed into 442.3 TJ of crop production, subtracting the production used for seeds. Thus, crop production energy efficiency defined as outputs/inputs ratio in energy units equals 2.0; i.e., 2 unit energy of crop production per unit energy input. A part of crop production is used for feeds. It should be noted that in livestock production analysis the energy content is calculated as the quantity of energy necessary for producing the forage, rather than that contained in the forage. In this example, the energy expenses in forage production amount to 94 TJ. In Fig. 1 the value of 232 TJ corresponds to the forage production in caloric equivalent. The major output flows of the agroecosystem include: crop production - 209.9 TJ, and livestock production - 19 TJ.

Livestock receives 50.4 TJ of energy from outside the system and 94 TJ - as forage energy, internal system's flow of straw equals to 107 TJ. This energy is transformed into 19

TJ of energy in livestock products. Let us introduce the definition of energetic efficiency:

$$\eta = \frac{E_{out}}{E_{in}} \quad , \tag{2}$$

where E_{out} is the total output flow, E_{in} is the input flow; all the flows involved in the process of energy transformation are considered here. In this case E_{in} = 144.3 TJ, E_{out} = 19 TJ, so the livestock production energy efficiency is: η = 0.13.

The total production output equals to 228.9 TJ, and total energy efficiency of the system equals to 0.64.

It is clear that the values of energy efficiency may serve as comparative characteristics of different agricultural systems, the possible levels of system comparison varying from a single unit (a farm, collective farm) up to a whole country. In Table 3 values are given for the farm units of the Central Chernozem Region, Lithuania (Brovkin et.al., 1991), as well as for agricultural systems of Hungary (Denisenko et al., 1991), France, Israel, and the UK (Deleage et al., 1979).

2. ULANOWICZ'S "ASCENDANCY" AND FLOW DIVERSITY OF AGROECO-SYSTEM

Obviously, the agroecosystem description given above, as a system of energy flows, provides its natural structure, therefore the corresponding information measure can be defined for this structure. However, before formulating this definition, let us dwell on a new concept of "ascendancy" introduced by Ulanowicz (1986).

Ulanowicz postulates that a specific indicator, termed "ascendancy", can be considered as a measure of the ecosystem "organization level", proceeding, by intuition, from the postulate: the more a system is "organized", the more it is stable, resistant, able to compensate disturbing effects of the environment. It should be noted that this postulate is also an empirical generalization (Herendeen, 1989).

According to Ulanowicz, the expression for "ascendancy" can be written in the form:

$$A = \beta \sum_{i=0}^{n+2} \sum_{j=0}^{n+2} \frac{x_{ij}}{\beta} \cdot \ln\left(\frac{x_{ij}}{x_i} / \sum_{s=0}^{n+2} \frac{x_{sj}}{\beta}\right), \tag{3}$$

where

$$\beta = \sum_{i=0}^{n+2} x_i = \sum_{i=0}^{n+2} \sum_{j=0}^{n+2} x_{ij}$$

is the total flow through the system, and $x_i = \sum_{j=0}^{n+2} x_{ij}$ is the total flow through the i-th compartment, x_{ij} is the flow from compartment i to compartment j, n is the number of compartments in the system.

The ratio $p_{ij} = x_{ij} / x_i$ can be considered as the probability for the movement of energy or substance from the i-th compartment to the j-th one. Index i = 0 corresponds to the input flow, i = n+1 corresponds to the dissipation flow (for example, respiration) and i = n+2 corresponds to the output flow. It is evident from the definition that the Ulanowicz' "ascendancy" represents an information measure defined for the system, which is described by flows, the structure of the latter determines the structure of the system.

Here we encounter, for the first time, a different type of system description where instead of describing its state through the values of its components we achieve it by measuring the values of flows between compartments. This can be illustrated by the following example.

Let the system consist of n components, each being described by the value of z (for example, the amount of some substance in the i-th compartment). Then the system state is defined by vector $z = (z_1, \dots, z_n)$. We can calculate the quantity of information contained in the system for each of its states:

$$I_z = -\sum_{i=1}^{n} p_i \cdot \ln p_i ,$$

where $p_i = z_i \Big/ \sum_{j=0}^{n} z_j$. However, this measure does not reveal the relationship between the compartments, i.e., the system structure. It is clear that two different structures resulting in the same value of z vector, will have the same value of information measure I_z. To avoid this ambiguity, we can supplement the description with a dynamic model (giving additional n links by differential equations), e.g.:

$$\frac{dz_i}{dt} = q_{0i} - q_{i0} + \sum_{j=1}^{n} q_{ji} + \sum_{j=1}^{n} q_{ij} , \tag{4}$$

where q_{ij} is the matter flow from the i-th compartment to the j-th compartment, "0" indicates the position outside the system, i.e, q_{0i} the input and q_{i0} the output flows. Consequently, we can determine the system state, using the *flows matrix*:

$$Q = \left\| q_{ij} \right\|, \; i,j=0,1,\dots,n.$$

This matrix gives information about the system structure, and not only qualitative but also quantitative one. The information measure can be determined for this matrix in the following form:

$$I_q = -\sum_{i=0}^{n} \sum_{j=0}^{n} p_{ij} \cdot \ln p_{ij} , \tag{5}$$

where $p_{ij} = q_{ij} \Big/ \sum_{i=0}^{n} \sum_{j=0}^{n} q_{ij}$.

Comparing (4) and (5) we can see that "ascendancy" according to Ulanowicz, and the information measure determined on the set of all the system flows practically do not differ from each other. Let us show that if we describe the system in terms of flows, the information content is approximately twice that of a description in terms of states of the compartments. In fact, in case of a large n and more or less equal flows

$$I_z = -\sum_{i=1}^{n} p_i \cdot \ln p_i \approx \ln n .$$

But since

$$I_q = -\sum_{i=1}^{n} \sum_{j=1}^{n} p_{ij} \cdot \ln p_{ij} \approx \ln n^2 = 2 \cdot \ln n ,$$

then $I_q = 2 \cdot I_z$.

In the previous section we have presented the method of describing an agroecosystem in terms of energy flows (both external input-output and internal ones). However, in contrast to Ulanowicz's formalism described above, this one has its specific feature: the input and output flows of energy are subdivided. If the flows are aggregated (considering total input and output flows) the information about the structure of agricultural system will be inevitibly lost. By the way, it is such loss of information that takes place in calculating the system's energy efficiency when the relationship of total flows is calculated. Therefore, the next chapter will be devoted to considering different information measures defined for special structures, such as the one shown in Fig. 1.

3. DIFFERENT INFORMATION MEASURES DEFINED ACCORDING TO THE TYPICAL STRUCTURE OF AN AGROECOSYSTEM

To represent a standard flow structure of an agroecosystem, a generalization of Fig. 1 (see Fig. 2) will be used. An agroecosystem consists of two compartments: crop production {1} and livestock {2}. Exchange of energy by flows takes place between these compartments: flows $X_1, \ldots, X_p$ from compartment 1 to 2; and $Y_1, \ldots, Y_q$ from compartment 2 to 1. The input flows: into compartment 1 are $U_1, \ldots, U_n$; into compartment 2 are $V_1, \ldots, V_m$. The output flows are $u_1, \ldots, u_e$ and $v_1, \ldots, v_s$, correspondingly.

In addition to the flows of artificial energy, solar energy, flow E_S is delivered to the input of compartment 1. Its flow is not controllable, and

$$E_s >> \sum_{i=1}^{n} U_i + \sum_{i=1}^{m} V_i ,$$

so that in the calculation of the information entropy the fraction corresponding to solar energy (from the total energy delivered to the system), is close to zero ($p_s \cong 1$, hence $p_s \cdot \ln p_s \cong 0$).

Therefore, this flow will not be taken into account in analyzing the structure. Though this can result in formal violation of the energy conservation law, such violation will not influence the qualitative conclusions. As a result of this (as we have already mentioned) the coefficient of energy efficiency in crop production can exceed 1.

Let us consider all of the agroecosystems in general. These can be described by vectors of energy flows:

$$U\{U_1,\ldots,U_n\},\quad V\{V_1,\ldots,V_m\},\quad X\{X_1,\ldots,X_p\},$$
$$Y\{Y_1,\ldots,Y_q\},\quad u\{u_1,\ldots,u_e\},\quad v\{v_1,\ldots,v_s\}.$$

All these flows contribute to the formation of the agroecosystem structure. So we shall use the sum of all the energy flows as its integral characteristics:

$$\mathrm{E}=\sum_{i=1}^{n}U_i+\sum_{i=1}^{m}V_i+\sum_{i=1}^{p}X_i+\sum_{i=1}^{q}Y_i+\sum_{i=1}^{e}u_i+\sum_{i=1}^{s}v_i\,,$$

and their frequency distribution $\mathrm{P}(P_1,\ldots,P_n)$, where

$$P_i=\begin{cases}U_i/\mathrm{E}; & i=1,\ldots,n\\ V_i/\mathrm{E}; & i=n+1,\ldots,n+m\\ X_i/\mathrm{E}; & i=n+m+1,\ldots,n+m+p\\ Y_i/\mathrm{E}; & i=n+m+p+1,\ldots,n+m+p+q\\ u_i/\mathrm{E}; & i=n+m+p+q+1,\ldots,n+m+p+q+e\\ v_i/\mathrm{E}; & i=n+m+p+q+e+1,\ldots,n+m+p+q+e+s\end{cases}$$

The system state will be described by the pair $\{\mathrm{E},\mathbf{P}\}$, where E is a scalar and $\mathbf{P}$ is a vector. Of course, when calculating the total energy characteristic E, we do not observe the energy conservation law since the input and output flows are simply summed, but in our case we are interested in the system's structure (branching of flows, their different orientations, etc.), rather than in its efficiency. Furthermore, in order to compare different systems, we shall use the energy density per unit of land, i.e. E/S, where S is the area of the system. Note that functions *defined on* $\mathbf{P}$ do not depend on S_k. Let us define on $\mathbf{P}$ the function:

$$H=-\sum_{i=1}^{N}p_i\cdot\ln p_i\,, \tag{6}$$

which can be considered as either the information entropy of the system or its flow diversity, i.e., a function analogous to (1) but defined on the energy flows. As a matter of fact, function H is equivalent to Ulanowicz's ascendancy, but it is defined in a more formal way.

Since the maximum value of H equals $\ln N$, where N is the total number of flows, then, by implication, the value of H depends on this number. However, it is desirable to characterize the system's structure using a function independent of N. Information theory as well as its applications in biology and geography uses the so-called *redundancy index* (or informational index of connection ability by Ferster (1964) or by Puzachenko and Moshkin (1981)) which equals to

$$h=\frac{H_{\max}-H}{H_{\max}}=1-\frac{H}{H_{\max}},\qquad 0\le h\le 1. \tag{7}$$

Using the value of $\ln N$ as H_{max}, i.e., considering entropy to be maximal in systems with homogenous distribution, we obtain

$$h = 1 - \frac{\sum_{i=1}^{N} p_i \cdot \ln p_i}{\ln N}, \qquad 0 \le h \le 1. \tag{8}$$

Formula (8) shows that the more homogenous energy allocation is among the flows and the more aligned the hierarchy of the flow, the smaller is the redundancy index. We observe that the redundancy index h reduces along with a reduction of the system's hierarchical organization. Therefore, the value of h may be considered as an index for the description of the degree of system hierarchy. Introducing some additional flows always result in increased h, and making the system more homogeneous reduces it.

Considering the above, we shall characterize the state of a system, say the k-th system ε_k by a pair of values: $\varepsilon_k = (E_k / S_k, h_k)$ representing its state by a point on plane: $\{\varepsilon, h\}$. Our hypothesis is the following: *on plane* $\{\varepsilon_k, h_k\}$ *there exists a curve* $h = f(\varepsilon)$ *along which the agroecosystem evolution is realized,* i.e., the values of h and ε, which are the information and energetic indices occuring in reality, are connected. This curve can be called *the curve of structural evolution for agroecosystems.*

The existence of this connection is our speculative hypothesis, however, based on general thermodynamic concepts. Entropy and energy are known to be connected in thermodynamics, this connection being none other than reflection of some general laws of nature (Zommerfeld, 1955). We shall try to determine the form of the curve empirically.

4. CHANGE OF INFORMATION ENTROPY IN AGROECOSYSTEMS: ARTIFICIAL ENERGY LOAD AND STABILITY

Let us consider a system characterized by input and output flows (see Fig. 3). Changes of information entropy in passing of energy flows through the system will be equal to:

$$\begin{aligned} \Delta H = H_{out} - H_{in} &= [-\sum_{i=1}^{m} \frac{u_i}{l} \cdot \ln \frac{u_i}{l}] - [-\sum_{i=1}^{n} \frac{U_i}{L} \cdot \ln \frac{U_i}{L}] = \\ &= \sum_{i=1}^{n} \frac{U_i}{L} \cdot \ln \frac{U_i}{L} - \sum_{i=1}^{m} \frac{u_i}{l} \cdot \ln \frac{u_i}{l}, \end{aligned} \tag{9}$$

where $l = \sum_{i=1}^{m} u_i$, $L = \sum_{i=1}^{n} U_i$.

This linear additive operation for a non-linear function such as entropy is, of course, not quite correct but we have no alternative, since the usually applied measure of information entropy increment has been defined only for $m = n$ (Volkenshtein, 1988). For systems that do not cause significant changes in the quantity of information, formula (9) is acceptable.

Let the system shown in Fig. 3 be an agroecosystem. For a primitive agroecosystem using as energy input only the flow of solar energy (human labour and livestock exploitation are considered as flows inside the system) the diversity of output flows is usually very large (which is inherent for subsistence economy), $\Delta H > 0$. In fact, since $m >> 1$ and $n = 1$ (see Fig. 4a), then

$$\Delta H = H_{out} - (H_{in} = 0) = -\sum_{i=1}^{m} \frac{u_i}{l} \cdot \ln \frac{u_i}{l} > 0. \tag{10}$$

Since the entropy increment is positive, the system is thermodynamically stable. Its stability is provided by solar energy dissipated by different components of a primitive agroecosystem - thus it is provided by its species diversity.

Now let us consider an extreme case of an industrial agroecosystem with different types of artificial energy being supplied as input and with only a single energy type as output (single crop) (Fig. 4b). (An industrial agroecosystem producing only a single crop is, of course, a theoretical abstraction, but as we said above, it is an extreme case that we consider.) Then $m = 1, n >> 1$:

$$\Delta H = (H_{out} = 0) - H_{in} = \sum_{i=1}^{n} \frac{U_i}{L} \cdot \ln \frac{U_i}{L} < 0. \tag{11}$$

Note since the flow of artificial energy is much less than that of solar energy, the corresponding term can be excluded from the formula (11) (see above Ch.3).

From inequality (11) it follows that an industrial agroecosystem producing "negative" entropy must be thermodynamically unstable. The only way of making it stable is to dissipate some definite quantity of artificial energy inside the system so that total entropy production inside it (taking into account a dissipation of artificial energy) would be positive. From this point of view the role of diversity of artificial energy flows in industrial agroecosystems as the main factor for their stabilization becomes clear.

Now let the agroecosystem state be described by two parameters: the value of information entropy increment, i.e., that of information entropy produced by the agroecosystem (ΔH) and the density of artificial energy input flow ($\sigma = E_{in}/S$, where S is the agroecosystem area) characterizing dissipation of this energy inside the agroecosystem. Its state can be described by a point on the plane $\{\sigma, \Delta H\}$. The general concepts clearly show that if σ increases then ΔH is reduced and even becomes negative. As in the previous chapter, we hypothesize that a definite relationship exists between ΔH and σ which is described by curve $\Delta H = f(\sigma)$ on the plane $\{\sigma, \Delta H\}$ along which agroecosystems evolution from primitive to industrial ones proceeds. To estimate the form of this curve we shall use experimental data on energy flows of different farm types.

5. FARMS: ENERGY AND INFORMATION CHARACTERISTICS

Above we have considered the structure of the energy flows of a contemporary farm from Central Chernozem Region (near Kursk city, Russia, so we call it Kursk farm). In addition, data on energy structure will be given for three other farms: a farm in Holland in 1800 (primitive agroecosystem), a farm in Holland in 1965, and a collective farm in Lithuania in 1985 (industrial agroecosystems). The data about Dutch farms in 1800 and 1965 were taken from Tooming (1984), those on the Lithuanian farm from Brovkin et. al. (1991). All of them are represented in Figs. 5-7.

The values of the redundancy index h and the density of total energy flow $\varepsilon = E/S$ were estimated using the data from the observed farms. As can be seen in Table 4, the redundancy index h decreases with increased density of total energy flow ε. It is interesting that h is smallest for the most industrialized agroecosystem (Dutch farm, 1965). It is approximately the same for the two farms of the former USSR (from Kursk and Lithuania), though they are situated in different regions. For the primitive agroecosystem (Holland, 1800) this index is largest. The energy index behavior characterizing total quantity of energy flowing through the system and circulating inside it is *vice versa*, it increases when going over from a primitive agroecosystem to an industrial one. Then the trajectory describing the connection between h and ε, can be plotted by these points (see Fig. 8). This curve can be considered as the trajectory of evolution from primitive to industrial agroecosystems.

This evolution inherently involves an increase in artificial energy flowing through the system and its circulation inside. But it is interesting that the redundancy index concomitantly reduces. This reduction indicates that the evolution is accompanied by increased branching of artificial energy flows and an increase of homogenization of energy flows. The degree of *hierarchical structuring* reduces, all the flows become equally important, and no one of them can be excluded in a modern farm without causing damage for the agroecosystem functioning. In other words, the more industrialized the system is, the more homogeneous its energetic structure becomes.

Kursk and Lithuanian farms occupy very close locations on the plane $\{\varepsilon, h\}$ though they are situated in geographically different regions. This means that the integral indices used characterize farm structure, and type of agroecosystem organization, rather than geographical location.

The last point: our hypothesis of the existence of an agroecosystem evolution curve is an empirical generalization, rather than a strong logical conclusion.

If the hypothesis is correct, we can use the curve in Fig. 8 for prognosis of future agroecosystems organization from evolutionary point of view. For example, if a future agroecosystem will be at point A in Fig. 8, we can conclude that it is inadequately organized from an evolutionary viewpoint. Therefore, the structure of its energy flows should be changed, so that the new location on the plane be somewhere near the evolutionary curve (e.g., at point B).

6. CHANGE OF INFORMATION ENTROPY AND ENERGY LOAD

Using data of Figs. 1, 5-7 we can, for different farms (see Table 5), calculate the information entropy increment ΔH, as well as the energy load for the system (σ) using formula (9). On the plane $\{\sigma, \Delta H\}$ the corresponding points are plotted and the linear regression is drawn. It is interesting to note that Kursk and Lithuanian farms are differed by the values of energy flows (Fig. 1 and 7) but have close locations on the plane. It can be explained by some general regularities defined by internal organization of the system rather than by natural conditions. So their closeness in terms of the criteria σ and ΔH indicates their similar organization. The thermodynamic origin of these criteria and the fact that thermodynamic laws are the general laws of Nature allow us to believe that these criteria can determine the degree of organization and energy efficiency of agroecosystems. We can assume that in the course of agroecosystems industrialization they evolve along the curve shown in Fig. 9. The increase of energy load results in decreased entropy production by the system at the expense of it's environmental degradation. But this growth is limited since the influence of a degrading environment can cause the degradation of the agroecosystem. As an maximum load assessment the value of σ' can be determined by equation $\Delta H=0$. The boundary $\Delta H=0$ can be considered as that of system stability. From Fig. 9 it follows that $\sigma'=18$ GJ/ha.

If we compare this value with other estimates obtained from different considerations (see, e.g., Bulatkin,1982, where $\sigma'=14$ GJ/ha; or Novikov,1984, where $\sigma'=15$ GJ/ha) we shall see that they are very close.

The positive value of ΔH for an industrial Dutch farm in 1965 can be explained by the following: at this farm the optional energy load has been chosen ($\sigma = 16$ GJ/ha $<\sigma'$).

CONCLUSIONS

Considering all the above we conclude that a continued increase of the energy density of an agroecosystem (as compared to the farms in Central Russia and Lithuania) must eventually result in a corresponding increase of negative entropy production: this causes increased risk of system degradation. To avoid such a development, the energy load must be reduced to $\sigma < \sigma'$, simultaneously changing the structure of input and output flows so that information entropy production by this system remains positive, i.e., that the system is maintained.

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TABLE 1

An energy budget of crop production (farm from Central Chernozem Region, 1985).

Input		Output	
Resource	Energy equivalent, TJ	Production	Energy equivalent, TJ
Fuel	65.0	Cereals	214.1
Machinery	52.9	Sown grass	108.6
Fertilizers	47.0	Silage corn	52.4
Infrastructure	41.3	Sugar beets	44.2
Toxic chemicals	11.2	Food roots	15.8
		Potatoes	7.2
Total	217.4		442.3

TABLE 2

An energy budget of livestock (farm from Central Chernozem Region, 1985).

Input		Output	
Resource	Energy equivalent, TJ	Production	Energy equivalent, TJ
Forage	101.7	Milk	12.6
Infrastructure	20.1	Beef	4.9
Electricity	16.9	Pork	1.5
Mashinery	4.2		
Fuel	1.0		
Human labour	0.4		
Total	144.3		19.0

TABLE 3

Energy efficiency of different agroecosystems.

Agroecosystem	η
Hungary	0.87
France	0.69
Kursk farm	0.64
Farm from Lithuania	0.61
Israel	0.40
UK	0.34

TABLE 4

Redundancy index and energy flow density for different agroecosystems.

Agroecosystem	h	ε, GJ/ha
Dutch farm,1800	0.35	55
Dutch farm,1965	0.19	135
Lithuanian farm,1985	0.23	80
Kursk farm,1985	0.25	85

TABLE 5

Information entropy indices and energy load for different agroecosystems.

Agroecosystem	H_{in}	H_{out}	ΔH	σ, GJ/ha
Dutch farm,1800	0	1.10	1.10	0.8
Dutch farm,1965	1.18	1.64	0.46	16.0
Lithuanian farm,1985	2.06	1.22	-0.84	25.7
Kursk farm,1985	1.68	0.92	-0.76	27.0

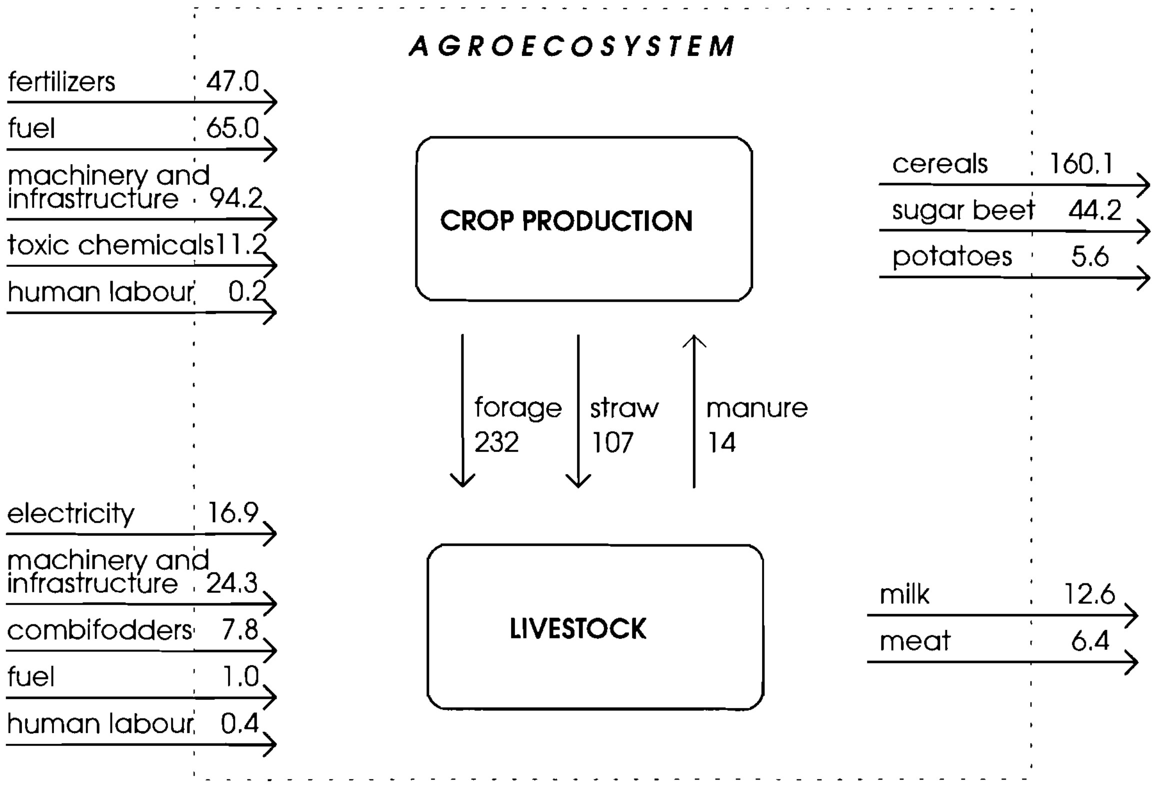


Fig. 1. The structure of energy flows in an agroecosystem (farm from Central-Chernozem region, 1985, units: TJ)

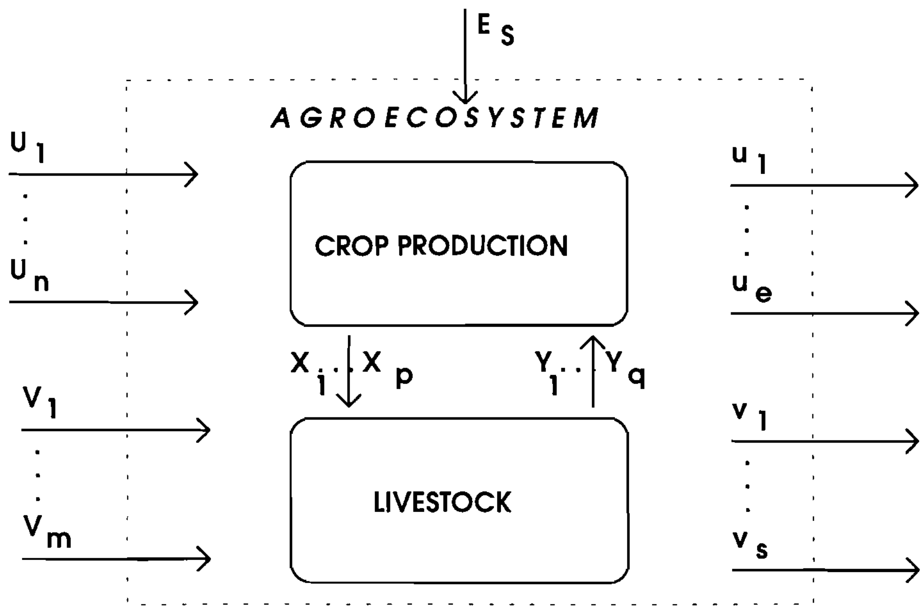


Fig. 2. Typical flow structure of agroecosystem

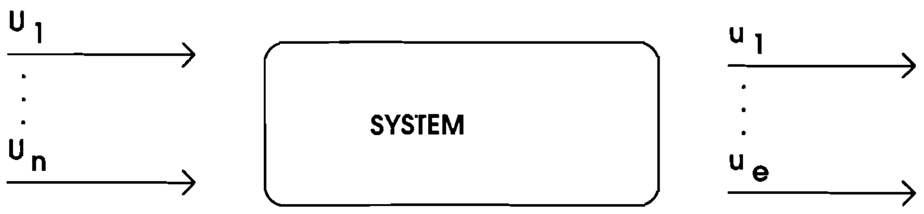
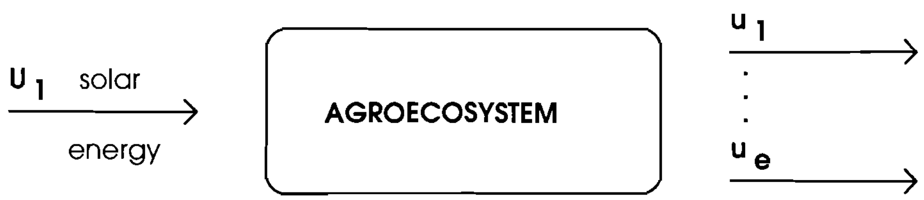
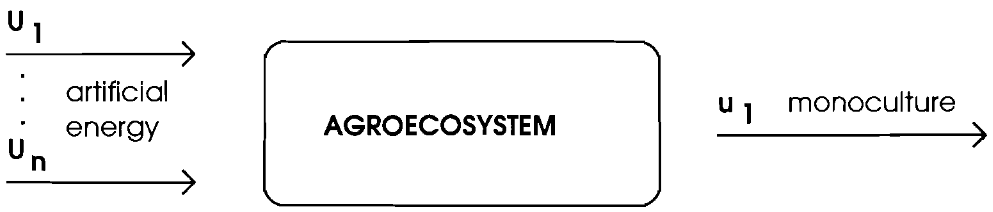


Fig. 3. System described by energy flows



(a)



(b)

Fig. 4. Structure of input and output energy flows for primitive (a) and industrial (b) agroecosystems

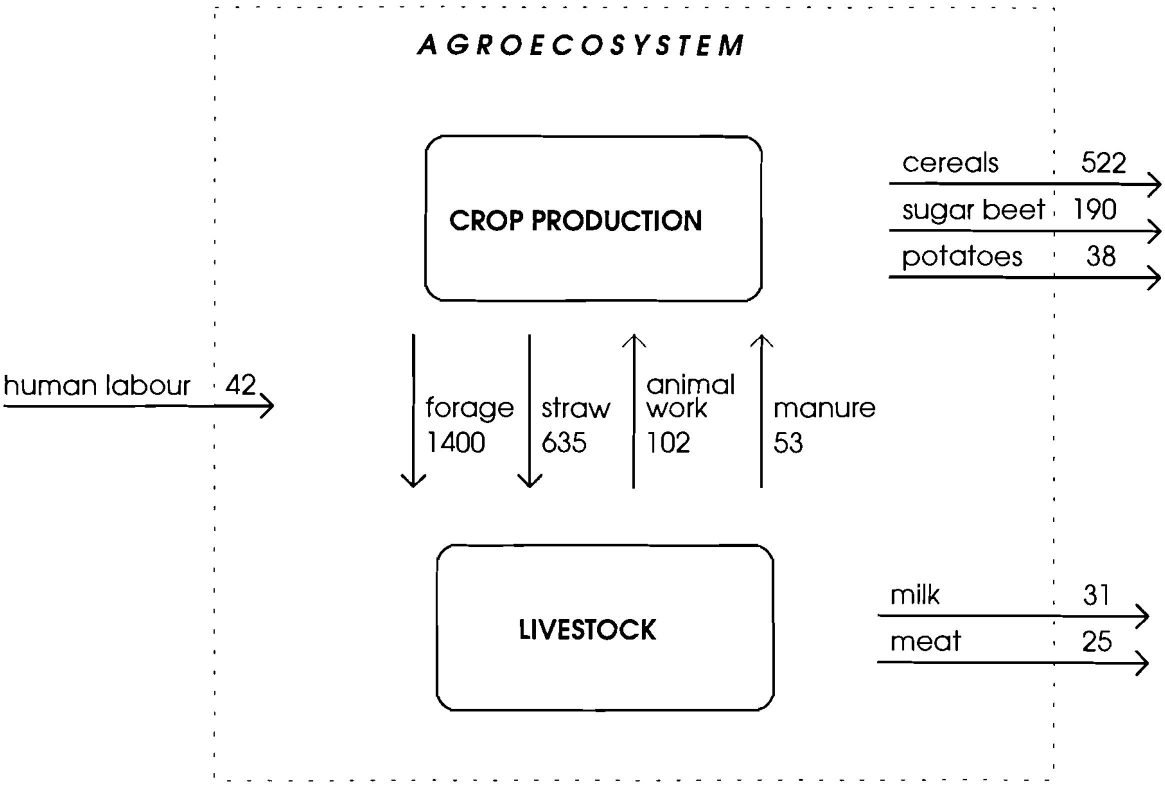


Fig. 5. The structure of energy flows of agroecosystem (farm from Holland, 1800, units: GJ)

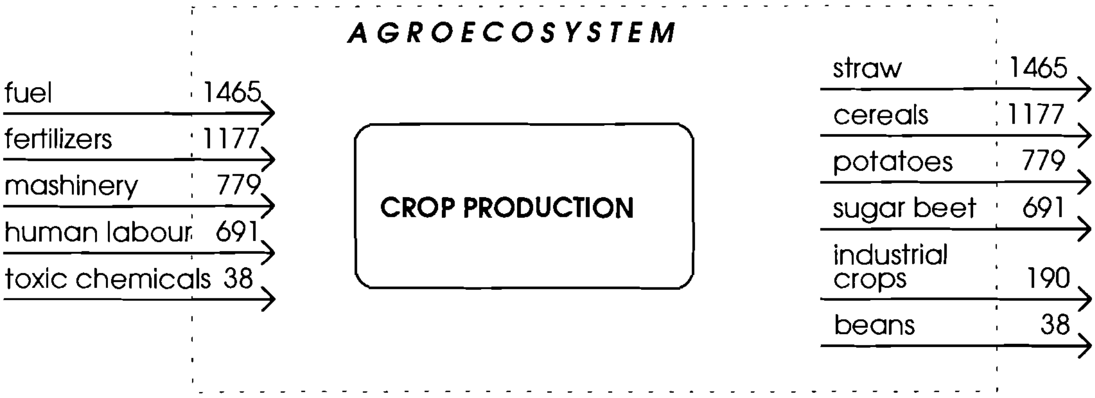


Fig. 6. The structure of energy flows of agroecosystem (farm from Holland, 1965, units: GJ)

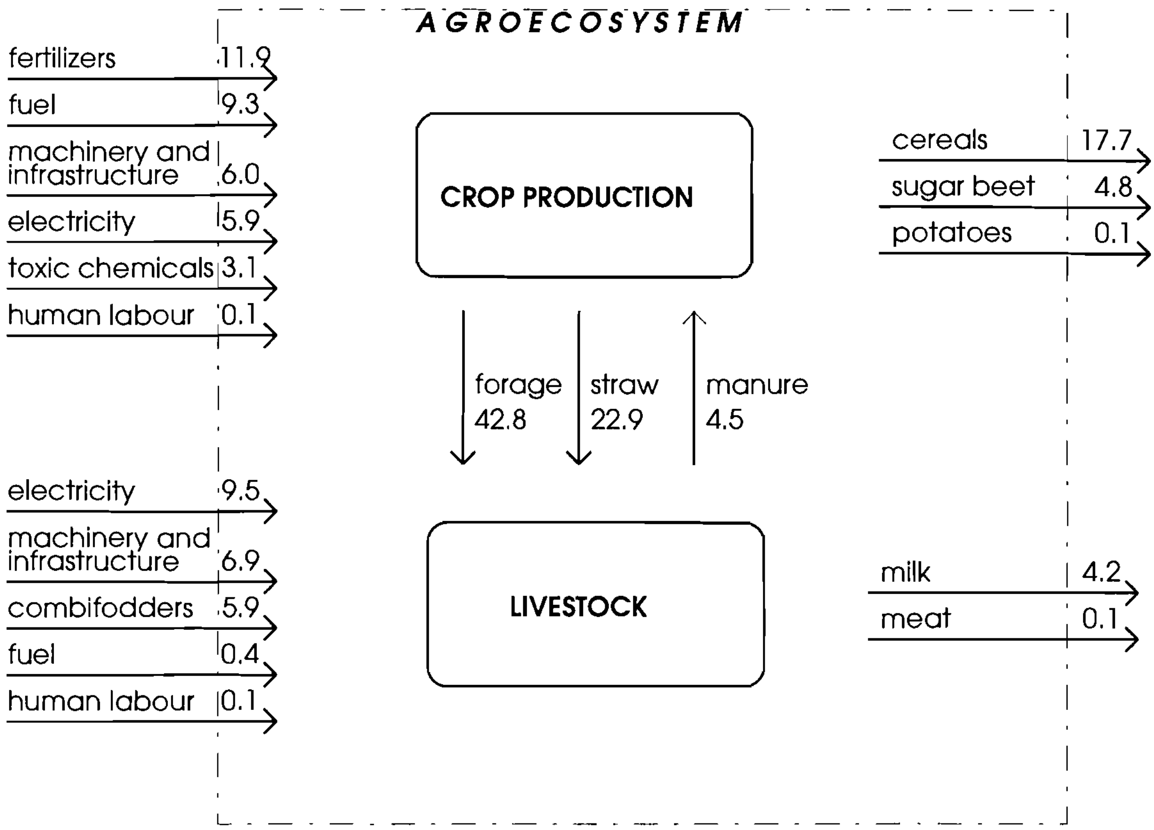


Fig. 7. The structure of energy flows of agroecosystem (Lithuanian farm, 1985, units: TJ)

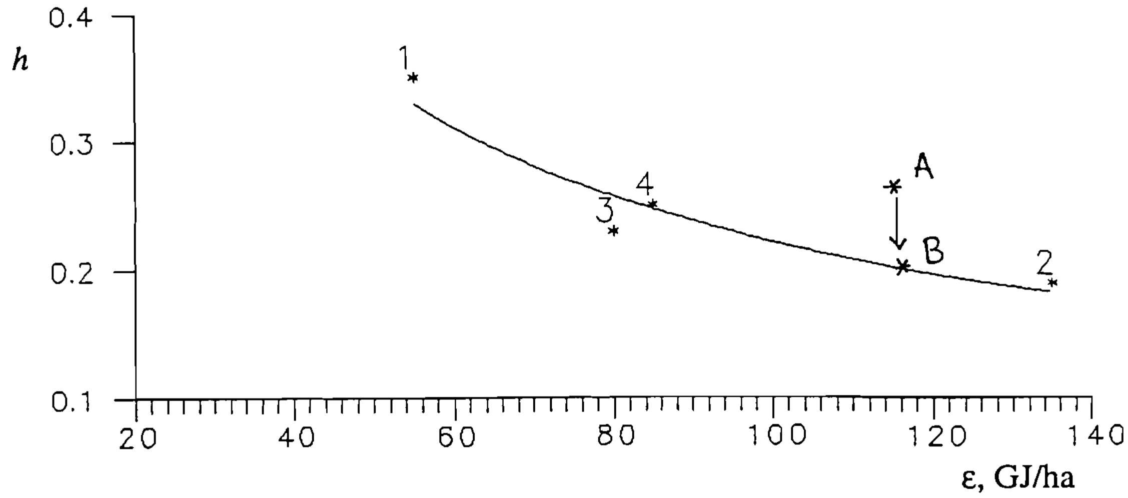


Fig. 8. Dependence of redundance index *h* on the energy flow density ε

1 - Dutch farm, 1800
2 - Dutch farm, 1965
3 - Lithuanian farm, 1985
4 - Kursk farm, 1985

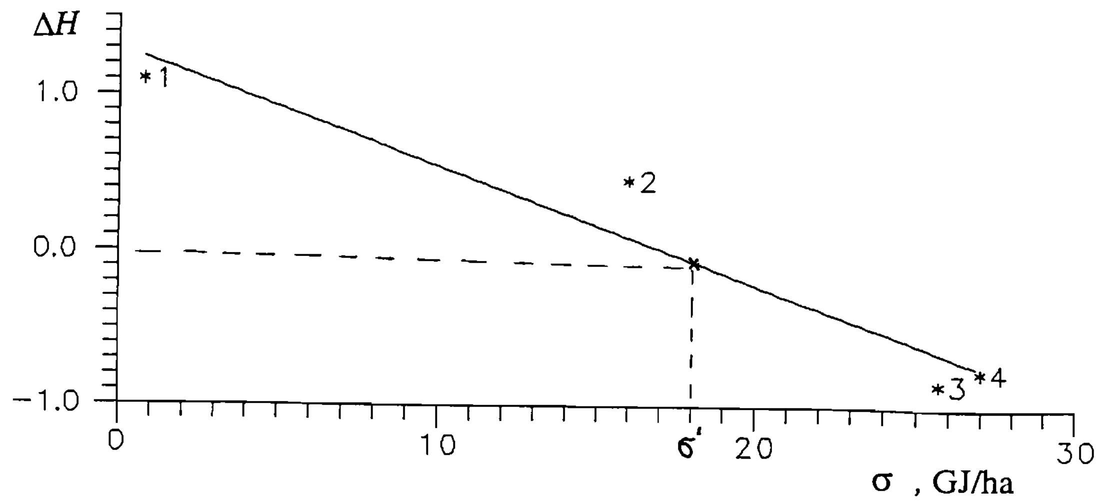


Fig. 9. Dependence of information entropy increment Δ*H* on the energy load σ