Energy-based measuring of ecological and economic effectiveness of agroecosystems

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Abstract. In the paper the study’s results of energy-based measuring of ecological and economic effectiveness of agroecosystems are given. The principles and provisions of the methodology of geosystems self-organization are presented, the short algorithm of energy analysis of geosystems is proposed. The results of agroecosystems energy evaluation in different climatic conditions are shown, that allows assessing and comparing the energy efficiency of natural-climatic and economic resources. In particular, based on analysis of energy efficiency of functioning of farm Tomsk region the flow-oriented model of the agroecosystem as operationally closed structure has been developed. Under the proposed methodology some calculations carried out. With use science-based and rational-based management system optimization of energy costs in the AGES of the Tomsk region can be reduced. Based on analysis of energy efficiency of functioning of agro-ecosystems of a steppe zone of Kazakhstan practical results have been obtained. For the steppe zone of Kazakhstan the natural savings of energy generated through precipitation has been defined. The most real value of organic fertilizer to maintain the fertility of dark chestnut soils in the energy measurement is assessed. The energy efficiency of biogas technology implementation in the functioning of the economy based on the use of organic waste of agriculture with the simultaneous production of organo-mineral fertilizers have been showed. The use of energy assessment, in combination with economic, objectively reflects the essence of the ongoing social-economic processes and reveals the true labor costs of production. The most promising is the transition to managing agro-ecosystems as complex self-organizing structure working on the principles of operational introversion. The challenges for further research are set.

1. Introduction
It is a well-known fact that the science and practice of economy do not take into account the contribution of Nature to material goods production. Meanwhile, life has shown that economic activity of people becomes profitable only if it is greatly helped by Nature: it concentrates energy and substances, transforming them into other forms serving as a base for newly created various geosystems; resumes the consumed supplies of matter and energy, thus maintaining the achieved state of dynamic equilibrium. But the efficiency of business operations is usually measured by such parameters as cost to market price ratio; profit to cost ratio, profit to land ratio; etc. With such an approach, labor productivity, in comparison with overall system efficiency, is overestimated, which leads to paradoxical results – market price of goods, despite of increased energy amounts consumed in
the course of their production, decreases, making us think of a highly efficient production, which is quite opposite to the reality.

According to the theory of market economy, the price of goods and services is determined by the supply/demand ratio, where the costs of labor (energy) are indirectly taken into account. Market advantage, thus, belongs to businesses, who, given the same market price, enjoy the minimum production costs. In reality, the possibility to lower production costs is often based to a large extent on a high productivity of natural resources, or, in other words, on the amount of useful elements (i.e. energy) contained in these resources, plus the amount of energy spent during the commodity production. Progressive social-economic development objectively implies a non-linear increase in the energy consumption levels.

The entire experience of civilization development shows that GDP of every country increases in proportion with the energy consumption in its economy. In economically developed countries, energy consumption per person per day exceeds $1.13\times10^9$ joules [1]; the total energy consumption of humanity is estimated as $2.7$ to $4.5\times10^{20}$ J per year [2] and continues to grow.

The article describes the results of the analysis of agroecosystems, conducted using the energy-based measure (J) of human labor. This includes technogenic input and the contribution of natural energy resources – both from internal resources of the agroecosystem and external energy supply (coming mainly from solar energy and other climatic sources).

2. Basic provisions of the energy-based analysis of agroecosystems and the problem statement

Energy is the driving force of dynamic processes. The spatial flows of energy determine the essence of thermodynamics processes – the irreversible movement of energy from the sources of its accumulation to the sources of dissipation. A universal, scientifically proofed assessment of labor, including “the labor of nature”, should consider the energy-based measure which does not depend on market conditions or political realities.

The use of a unified energy-based measure allows us to conduct a comparative analysis of nature versus human labor contributions into material goods production and to perform the energy-based assessment of the ecological capacity of ecosystems existing in different environmental and climatic conditions.

The method is based on the analysis of natural and anthropogenically transformed energy flows. The purpose of such analysis is to calculate the energy-based budget required for the successful operation of the considered farm.

As it is known, the sources of natural energy sources can be divided into permanent ones (solar energy, thermal energy of the Earth, energy of tides and ebbs), renewable sources (energy of atmospheric precipitation, kinetic energy of flowing waters and wind currents, biomass energy, soil fertility energy), and non-renewable sources (energy of hydrocarbons and nuclear disintegration), etc. A separate group consists of alternative energy sources, mainly based on the waste of agricultural production and other industries.

To analyze the flows of natural energy used in agroecosystems, energy density maps were compiled, based on the spatial distribution of natural energy [3]. Then, the requirements for the natural energy of various agroecosystems were determined and an actual energy balance was calculated, taking into account, on the one hand, human needs (in joules/year), and on the other hand, objectively existing natural energy flows allowing to satisfy these needs to a greater or lesser extent.

3. Energy-based measuring of ecological and economic efficiency of agroecosystems (AES)

The study was conducted on the example of agricultural farms located in two different climatic zones: taiga (Tomsk Oblast) and steppe (Kazakhstan, Karaganda Oblast). The work uses the results of previous studies conducted under the federal fundamental research programs of SB RAS: Project VII.63.1.3. and Project VIII.77.1.4.
3.1. Agroecosystems from Tomsk Oblast

Based on the analysis of energy efficiency of a functioning farm located in Tomsk Oblast, a flow-based model of an agroecosystem as an operationally closed structure was built [4]. The structure was built as a system of objects, each possessing own inherent properties and functions. The basic principle is that the AES constituents (plant growing, cattle breeding modules, etc.), its management body and infrastructure are connected with each other, with their own output and with the external environment by the flows of energy, matter, and information. Thus, the change in the parameters of any part of the agroecosystem causes the change in the parameters of all other functionally related elements. The elements output in the form of waste and by-products are fed into the corresponding processing unit in order to produce additional energy and materials (in this case, in the form of organo-mineral fertilizers).

To conduct the sample agroecosystems analysis, nine districts with a sufficiently developed transport infrastructure were chosen. The study was based on statistical data taken from the annual agricultural bulletins for the period from 2005 to 2010.

It was revealed that Tomsky, Kozhevnikovsky, and Zyryansky districts bear the highest burden of energy consumption, having, respectively, the following consumption values in the energy-based equivalent: 61.7-69.8*10^{13}J; 54.5-66.9*10^{13}J; 21.1-28.8*10^{13}J. Maximum indicators for the amount of basic (natural) sources of energy used in the form of organic fertilizers and forages were noted in Tomsky, Chainsky, Pervomaysky and Asinovsky districts (44.5-62.3*10^{13}J, 7.7-9.3*10^{13}J, 10.1-16.4*10^{13}J, and 7.4-16.5*10^{13}J, respectively).

3.2. Energy assessment of agroecosystems in the steppe zone of Kazakhstan

The physical-geographical conditions of the steppe zone (Karaganda Oblast) are characterized by sharply continental climate with insufficient moisture – the amount of precipitation not exceeding 350 mm per year. The territory is covered with thin black soils and dark-chestnut soils, vegetation consists of steppe herbs. The considered agroecosystem, with an area of more than 2000 hectares, annually receives solar energy in the amount of 52323 GJ/ha, or 1250 tons/year in oil equivalent. The received solar energy is transformed into the energy accumulated by vegetation, soil and other components of the geosystem.

The study has taken into account the transformed solar energy, which was accumulated by plants and then converted into natural fertility of the soil cover and stored in natural fossil fuels. So, 1 hectare of land sowed by grain crops accumulates 21GJ/year of energy on average, thus total accumulated energy on the farm territory comprising 42,000 GJ/year. During one season, the farm collects an average of 4 tons/ha of straw (with the energy value of 57.6 GJ/ha); harvests more than 1000 tons of hay (with the energy value of 14.6*10^{12}J); over 250-350 tons of forage (3.65*10^{12}-5.1*10^{12}J) is directly used for feeding and litter for animals, the remaining part of the forage is sold or exchanged for additional materials [5]. A significant amount of nutrients stored in soils is taken away when harvesting the crop, and they must be returned into the soil by applying fertilizers containing these substances (otherwise humus will degrade as the most fertile layer). With this purpose, using the method of Mindrin A.S. [6], the amount of organic fertilizer required to maintain the fertility of dark-chestnut soils was calculated; it comprises 3.7 GJ/ha in energy terms, including the costs of fertilizer transportation and introduction into the soil. We have also calculated the amount of nutrients energy in organic fertilizer that would compensate for the losses associated with the crop harvesting.

Precipitation is caused by the influence of solar energy on the Earth’s atmosphere, leading to intensified cloud formation. As it is known, the dissipated thermal energy serves as water vapor carrier and participates in the circulation of water on the Earth. Part of the dissipated thermal energy returns to the system as precipitations – thermal energy raises the water vapor forming the clouds, which, when accumulated, create precipitations, thus being converted back into energy.

Natural moistening of agricultural lands saves, first of all, non-renewable natural resources and anthropogenic energy, since the irrigation of land in arid regions is a matter of energy and labor.
In the course of study, energy savings conditioned by precipitation in the steppe zone of Central Kazakhstan were determined, according to the method of [1]. The energy savings comprise 16.4 GJ/ha. When creating artificial irrigation systems in arid regions, energy costs for their development, construction and operation are 20-30 times higher than the production costs in the areas with natural precipitation, and require huge amounts of additional energy sources.

The ecological capacity of the entire agroecosystem is $10.47 \times 10^{16}$ J/year in energy units. This huge amount of energy represents, in fact, the natural rent, which allows for considerable energy savings during economic activity, but is not often considered at all during the cost estimate [7].

The study takes into account the total energy costs (direct and indirect): physical labor, electricity, energy of solid and liquid fuels, forage resources, as well as the costs of maintaining the main means of production. The calculations have shown that 59,185 GJ/year was spent on the production process; the maintenance of equipment and premises took at least 5163 GJ/year (an average of 30% of the cost of creating fixed assets); the total energy consumption for the year comprised 64,348 GJ/year. While, after all these huge energy spendings, the total energy yield in animal husbandry produce made up only 5600 GJ/year.

It is believed that energy losses in agroecosystems are determined by the difference between the energy used during production and the energy contained in the produced goods. In the studied case, 64,348 GJ was used in animal husbandry, while the produced energy comprised only 5600 GJ (9% of total energy consumption). Thus, transformational losses amounted to 58,748 GJ (91%) of energy.

In animal husbandry and in other types of agriculture, the major role belongs to the cost of forage resources, which amount directly depends on the productivity of ecosystems. The rest of the costs account for 36.6% of the total energy investments. The costs of human labor are indeed very small in comparison with the other investments of natural-anthropogenic energy.

Considering all of the above, it follows that the production of 1 unit of agricultural goods requires 11.4 units of production costs. We have identified the following structure of costs: labor resources – 0.3% of the costs; electricity costs – 1.1%; acquisition of additional materials – 5.2% of costs; energy costs for the maintenance of fixed assets – 8%; consumption of liquid and solid fuel – 21.9%; forage resources – 63.4% [5].

In order to reduce the energy costs in the production, the latest biogas technologies were tested on the farm, as part of the agroecosystem. According to the data received, 950-1000 tons of agricultural waste is generated on the farm annually, which corresponds to 4249 GJ/year of produced biogas energy. At this, operating costs and production losses of the biogas plant comprise at least 30% of all energy produced. Calculations have shown that the use of a biogas plant for simultaneous production of electric and thermal energy (cogeneration) will allow the farm to convert 40-50% of energy into thermal energy, and 30-40% – into electrical energy. The total energy needs spent on heating administrative premises, heating water for household needs and electricity comprise 5845 GJ per year (data for 2005).

Considering the own needs of the biogas plant in electric power and its production losses of at least 30%, the above calculations show the use of biogas will allow the farm to cover the costs of premises heating, water heating and electricity to more than half, depending on the operating costs of the plant.

Thus, the introduction of biogas plants into the farms structure will allow them to solve five major problems:

- ecological (full disposal of manure);
- energetic (production and usage of biogas);
- agrochemical (production of fertilizers);
- social (improvement of labor conditions and creation of new jobs);
- economic (reduction of payments and generation of profit from the sale of fertilizers).
4. Conclusion
Based on the conducted studies, we found that in some years selected agro-farms in Tomsk Oblast could provide for almost 75% of their energy needs through the use of by-products from own production, by simultaneously producing easily digested organomineral fertilizers.

In the steppe zone of Kazakhstan, the energy needs of the farms could be satisfied for over 50%, through the use of biogas, obtained from the production waste.

Therefore, the most environmentally safe and economically viable solution to the problem is anaerobic processing of waste with the production of biogas and high quality disinfected fertilizers.

According to the methodology used, overall efficiency of production is determined by the energy contribution of the ecosystem – the greater it is, the more efficient is the farm as a whole. This principle is a promising strategic reference point for further economic activities. When producing the goods, in the first place, agricultural goods, it is necessary to give priority to the tasks that result in maximized energy contribution of Nature: improving the potential productivity of soils, producing energy in a closed production cycle, using production waste, more efficient usage of solar energy (increased energy density), and so on.

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