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The estimation of energetically self-sufficient agroecosystem's model

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ABSTRACT

The article deals with the study of a balanced agroecosystem on the production of crop products, livestock products and biofuel with respect to its energy autonomy with ensuring its environmental safety. The structure of straw use in agroecosystem and its influence on humus balance and level of electric and thermal energy supply is investigated. The balance of humus in crop rotation was chosen as the criterion of ecological safety. The criterion of energy autonomy is the level of providing the agroecosystem with electric energy and thermal energy through the use of biofuels of its own production. The coordination of environmental safety, energy autonomy and economic efficiency was taken as the basis for the functioning of the agroecosystem. In a balanced agroecosystem on the production of crop products, livestock products and biofuel up to 41% of straw should be used to maintain the balance of humus in the soil. Up to 22% of straw can be used to produce heat and electricity for own needs. Up to 37% of straw can be used to produce electricity for sale according to the green tariff.

Keywords: energy, straw pellets, biodiesel, biogas, straw gas, model

INTRODUCTION

A modern agricultural enterprise is an agroecosystem (Golub et al., 2017), which presupposes the crop rotation which provides the production of crop and animal products. The classical determination of an agroecosystem is the following: agroecologicalsystem is a natural complex which is transformed by the agricultural activity of a man (Conway, 1987; Moonen and Bàrberi, 2008). The sustainability of agroecosystems depends on the maintenance of the economic, biological and physical components that make up the system. The high level of integration of these components implies that any evaluation of agroecosystem sustainability must consider the dynamics of multiple components (Belcher et al., 2004; Sami et al., 2013). The main task of the agroecosystem is to ensure stable food production (Mockshell and Villarino, 2019). The effect of machinery and equipment parameters, as well as the technical and economic indicators of technologies applied within the agroecosystem, on the performance of the agroecosystem was also investigated and studied (Golub et al., 2017). The agroecosystems simulation should be done with reference to the crop rotation area.

However, energy security also plays an important role in the sustainable development of individual regions and countries (Prodanuks and Blumberga, 2015). Balanced and efficient use of renewable energy sources can significantly increase the level of energy security in the world and in the countries of the European Union (Križan et al., 2017). Studies by scientists (Golub et al., 2017; Ryabchenko et al., 2017) argue that the agroecosystem has a known potential for biofuel production.

Agricultural enterprises can effectively produce several types of biofuels, namely biogas, diesel biofuels, bioethanol, straw in bales, fuel pellets and briquettes (Melece and Krieviņa, 2016; Golub et al., 2017; Rzeznik and Mielcarek, 2018, Matin et al., 2019). The main agricultural raw material for biofuel production is plant biomass (Verdade et al., 2015). The use of biomass for biofuel production is a concern of scientists regarding the reduction of food production and the negative impact on the soil environment (Verdade et al., 2015). In addition, there is an opinion that biofuels obtained in agricultural production have low energy efficiency (Gomiero, 2018). To reduce the negative impact from the biofuel production calls for an increase in the biological diversity of agroecosystems (Kazemi et al., 2018) and a clear monitoring of the ecological sustainability of the agroecosystem (Peterson et al, 2018). Besides, the sustainability and safety criteria of agroecosystems are necessary for the safe and efficient biofuel production (Di Vita at al., 2018).

Considering concerns about the deterioration of soil conditions in the cultivation of energy crops (Hunt et al., 2016) was propose as criterion of ecological safety of agro- ecosystems, the balance of humus. In the study (Ryabchenko et al., 2017) the energy security of the agroecosystem is proposed to be assessed by the energy intensity of the unit of output. However, this assessment does not allow characterizing the agroecosystem in which biofuels are produced. Was proposing to assess the energy security of agroecosystems by the level of energy autonomy at the expense of own production of biofuels. Many scientists believe, for example (Ohotina et al., 2018), that the economic efficiency of production processes is the key to their financial security. Therefore, another task of the agricultural enterprise is to obtain economic profit as a criterion of economic efficiency. The basis for the functioning of the agroecosystem is the coordination of three criteria: environmental safety, energy autonomy and economic efficiency.

The goal of the paper is to show the feasibility of providing the agroecosystem's energetic self-sufficiency in satisfying the needs for electric and heat energy when preserving the humus balance. Herewith, the humus balance in crop rotation is taken as a criteria of an agroecosystem's ecological safety. This criterion is a basic one for its functioning, because keeping the balance of an organic matter is of great importance for fertile soils. The capability to cover the cost of heat and electric

energy by means of agroecosystem's feasibility is taken as a criteria of energetic self- sufficiency.

MATERIALS AND METHODS

Humus balance in soils of agroecosystems is a determining factor in assessing its environmental safety. Therefore, it is necessary to set thresholds for the volume of raw materials for the production of biofuels on the basis of maintaining the balance of humus. Concerning the studies (Shikula, 2003; Golub and Kukharets, 2014), it was established that humus state modelling can be carried out on the basis of humus carbon flows and stocks in soil and organic carbon of non-humus nature (organic residues and organic fertilizers). With this in mind, the system of equations of humus carbon dynamics in the soil has the form:

$$\begin{cases} V\dfrac{dY}{dt} = PV - k_y YV - k_{yx} YV = PV - k_T YV; \\ V\dfrac{dX}{dt} = k_{yx} YV - k_x XV, \end{cases} \quad (1)$$

where Y – content of non-humus carbon in soil, kg/m^3; X – content of humus carbon in soil, kg/m^3; t – the period of humus mineralization, years; V – volume of fertile soil layer, m^3/ha; P – annual input of non-humus carbon into the soil, kg/m^3 year; $k_y YV$ – annual mineralization of non-humus carbon in soil, kg/ha year; $k_{yx}YV$ – the annual humification of non-humus carbon in the soil, kg/ha year; k_xXV – the annual mineralization of humus carbon in soil, kg/ha year; k_y – the coefficient of annual mineralization of non-humus carbon in the soil, rel. un./year; k_{yx} – the coefficient of annual humification of non-humus carbon in the soil, rel. un./year; k_x – the coefficient of annual mineralization of humus carbon in soil, rel. un./year; $k_T = k_y + k_{yx}$ – the ratio of the annual transformation of non-humus carbon in the soil, rel. un./year.

Under initial conditions: $t=_0 \rightarrow X=X_0 \rightarrow dX/dt=(dX/dt)_0$ where X_0 – carbon content in the soil at a time $t=0$, kg/m^3; $(dX/dt)_0$ – rate of change of humus content in the soil at a time $t=0$, kg/m^3 year, it is obtained the general solution of the system of differential equations (1), which has the following form:

$$X = \frac{1}{k_T - k_x}\left(-X_0 k_x + \frac{k_{yx}}{k_x k_T}\Pi - \left(\frac{dX}{dt}\right)_0\right)\exp(-k_T t) + \\ + \frac{1}{k_T - k_x}\left(\left(\frac{dX}{dt}\right)_0 + X_0 k_x - \frac{k_{yx}}{k_x k_T}\Pi\right)\exp(-k_x t) + \frac{k_{yx}}{k_x k_T}\Pi. \quad (2)$$

On the basis of equation (2), it is established the necessary level of annual introduction of non-humus carbon into the soil in an amount of $P = (k_x k_T X_0) / k_{yx}$, in order to prevent dehumification and keep the humus content at the initial level.

The level of production of electricity and heat in the agroecosystem can be found by the expression:

$$Q_e = k_{le}\sum_{i=1}^{n} N_i q_i k_{ie}; \quad Q_h = k_{lh}\sum_{i=1}^{n} N_i q_i k_{ih}, \quad (3)$$

where Q_e – production of electric energy, J; Q_h – production of thermal energy, J; N_i – potential of i- type of biomass, t or m^3; q_i – specific energy intensity of the i- type of biomass, J/t or J/m^3; n – the number of biomass types, un.; k_{ie}– efficiency coefficient of energy potential of the i- type biomass for power generation; k_{ih} – efficiency coefficient of energy potential of the i-type biomass for the production of thermal energy; k_{le} – coefficient of losses in the production, transportation and use of electric energy; k_{lh} – coefficient of losses in the production, transportation and use of thermal energy.

The potential of raw materials for the production of biofuels in the agroecosystem can be determined by the example of straw:

$$N_S = \sum_{i=1}^{n} s_i u_i \left[k_{bp} - \left(k_{ibp} + k_{kbp}\right)\right] - \sum_{j=1}^{m} n_j m_{abp} \quad (4)$$

where N_S – yield of straw, which can be used to increase the level of energy autonomy, t; k_{bp} – coefficient of the yield of i- crop straw; k_{ibp} – coefficient taking into account straw losses while harvesting and storage; k_{kbp} – coefficient taking into account the supply of straw to restore the balance of humus; s_i – area of growing i- crop; u_i – yield of i-crop, t/ha m – number of species of animals and birds; n_j – population of animals and birds of the j- species; m_{abp} – need for straw for bedding of the corresponding animal or bird species, t/head per year.

Knowing the amount of raw materials needed for biofuel production and energy consumption in the agroecosystem, it is possible to find the level of energy supply. In turn, the amount of biomass for humus restoring, taking into account the costs of humus in the cultivation of crops, determines the humus supply to the fields.

The purpose of this study is to establish the possibility of full provision of the agroecosystem with electricity and heat of its own production, while maintaining the balance of humus and the impact of these conditions on the economic efficiency of the agroecosystem. The simulation model of functioning of the balanced agroecosystem (Figure 1) with organic production, the structure of which is substantiated in scientific works (Golub et al., 2017, Ryabchenko et al., 2017), considering the dependencies (1-4). The agronomers have conducted a lot of research as to the impact of many factors on the agroecosystem. These factors can be: crops yielding, the level of grain realisation, fertiliser's distribution according to branches of animal industry, the cost of petrol and diesel fuel, the amount of biomass which remains in the fields after harvesting and many other factors.

The structural model of agroecosystem includes crop rotation with cultivation of the main crops. On this basis, the production of pork, beef, fish and chicken, milk,

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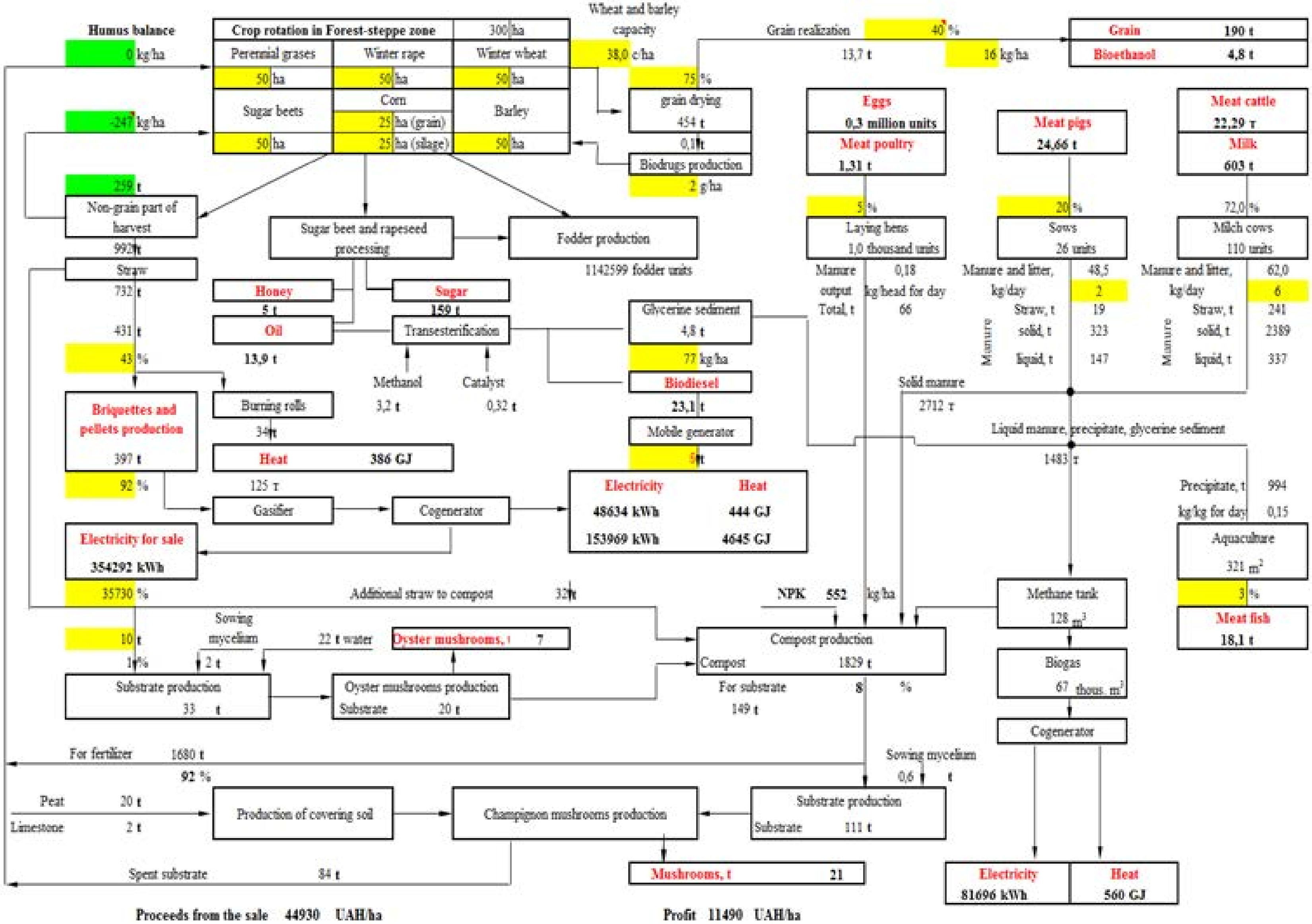

Figure 1. Model of the agroecosystem with biofuel production

eggs, oil, sugar, honey and mushrooms was modelled. The structural model provided for the production of diesel biofuels and bioethanol in the agroecosystem in the amount necessary to ensure the operation of mobile equipment, biogas, generator gas, and solid biofuels from straw (rolls, pellets, briquettes).

In the agroecosystem model, biogas is used to generate electricity and heat. Part of the plant biomass in the form of rolls or straw chaff is used to produce heat. Part of the plant biomass (straw) is used for the production of pellets from which the generator gas is produced. Generator gas is proposed to be used for the production of electric energy. The structural model of agroecosystem assumes performance of all agrotechnical processes at the expense of own power resources. The agroecosystem model ensures environmental sustainability by maintaining the humus balance and economic efficiency by maximizing profits.

RESULTS

It is well known that any agroecosystem should seek to ensure the balance of humus in soils or its expanded reproduction. After all, the soil is the main component of the agroecosystem, or the basis on which it is based. By ensuring the balance of humus, it is possible to vary other components of the system to ensure energy autonomy. By increasing the production of heat and electricity, it is possible to increase profits by selling the energy produced at the green tariff. Figure 1 presents a structural model of the agroecosystem in which they are agreed the needs in thermal and electrical energy with balance of humus in the soil.

An important condition for the functioning of the agroecosystem is the structure of the forage base (Figure 2). The structure of the feed base influences the energy costs of obtaining livestock products.

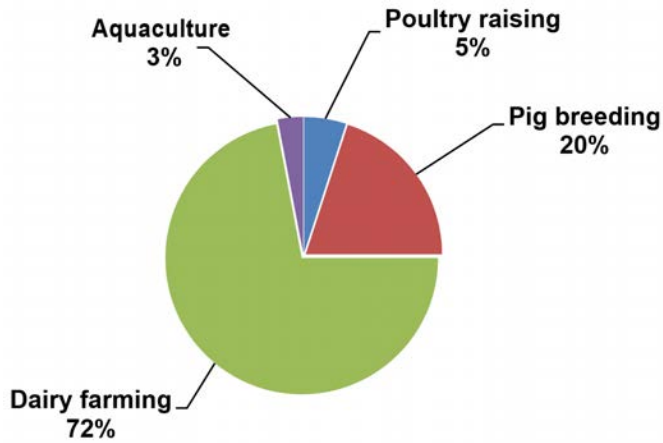

Figure 2. The structure of fodder use

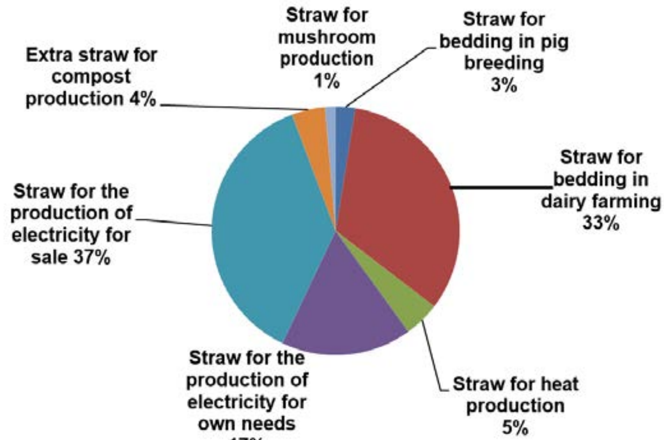

Figure 3. The structure of the straw use

The structure of the use of straw is shown in Figure 3. According to the structural scheme, in a balanced agroecosystem with organic production, up to 41% of straw should be used to maintain the balance of humus in the soil (with subsequent return to the soil). For the production of heat and electricity to meet their own needs need up to 22% of straw. For the production of electric energy for sale on a green tariff it can be used up to 37% of straw.

As Figure 4 shows, the achievement of humus balance is ensured by the biomass of siderates, weeds and other plant residues, as well as compost, which is produced from manure, litter manure and waste substrate from biogas plant.

The analysis of indicators of agroecosystem functioning testifies that observance of thermal and electric energy balance is possible with preservation of positive balance of humus. The total amount of electricity consumed by the agroecosystem is 284.3 thousand kW h/year (Figure 5). The greatest costs of electric energy (up to 68%) are required in the production of milk. Up to 23% of electric energy is spent for biofuel production, including 15% for production of fuel pellets and briquettes.

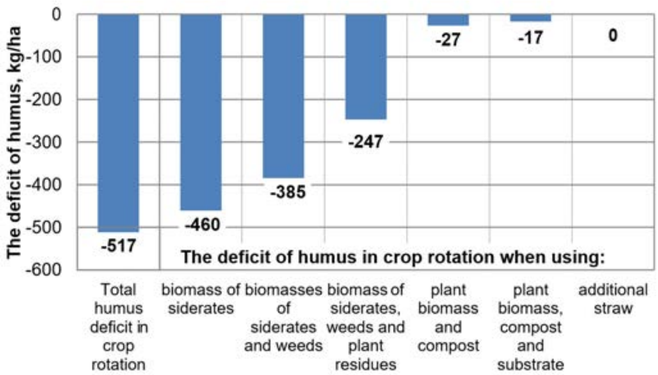

Figure 4. The structure of elimination of humus deficit in crop rotation

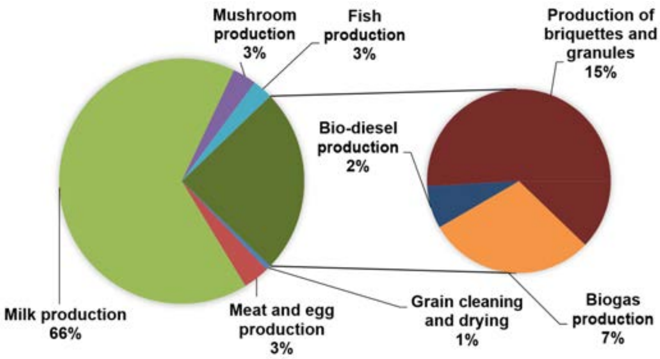

Figure 5. The structure of electric energy consumption

Analysis of electricity production in the agroecosystem (Figure 6) shows that to meet its own needs it is necessary 45% of the produced electricity, including 24% of the electricity produced from straw, 13% of electricity produced from biogas and 8% – from biodiesel. Up to 55% of the electricity produced from straw is available for sale at the green tariff.

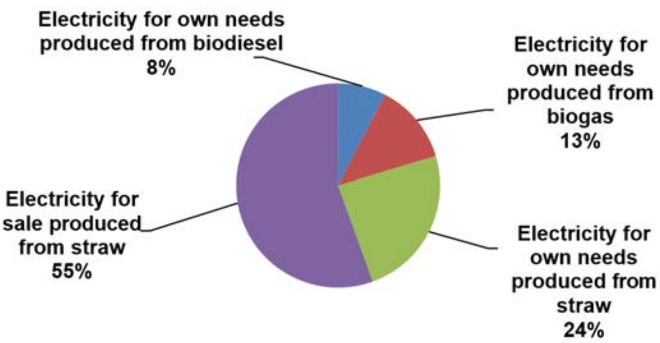

Figure 6. The structure of electricity production

The amount of the consumed thermal energy is 2789 GJ/year. Most of the thermal energy is spent for the production of milk – up to 60%; for the production of biofuels it is consumed up to 14% of the heat energy including 13% for biogas production (Figure 7).

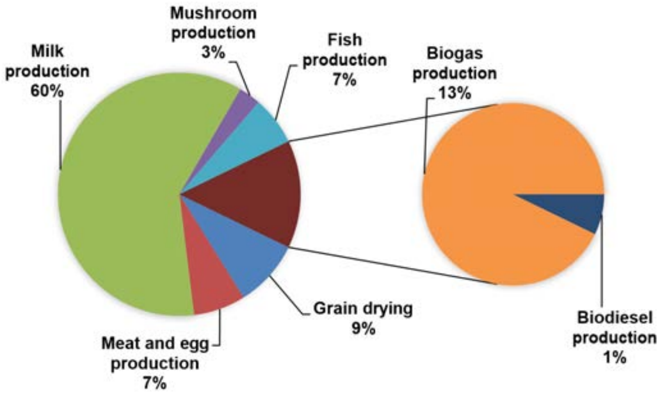

Figure 7. The structure of thermal energy consumption

The agroecosystem supplies the needs for thermal energy by: the operation of the gas generator - up to 77%, the use of biogas - up to 9%, the use of biodiesel - 7%, burning of baled straw - 7% (Figure 8).

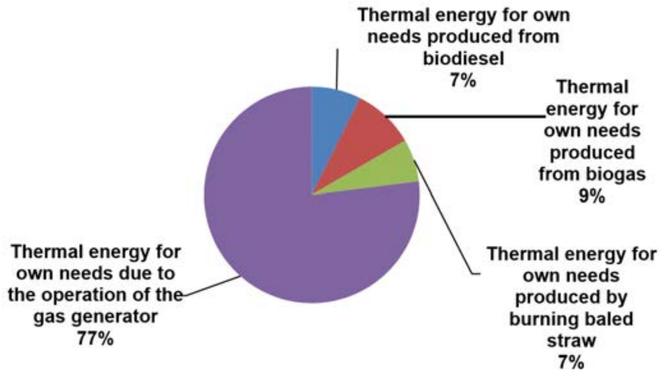

Figure 8. The structure of thermal energy production

The agroecosystem can be fully supplied with electric energy and thermal energy due to biofuel, which is produced from the agroecosystem resources. This will ensure the balance of humus. The part of the electricity can be sold to improve the agroecosystem efficiency (Figure 9).

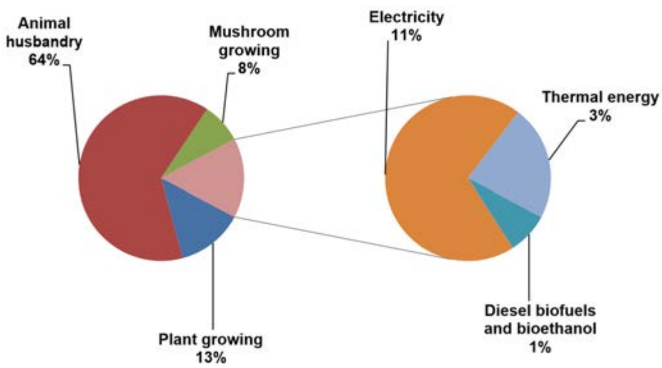

Figure 9. The structure of the obtained profits in the agro-ecosystem

Analysis of the economic results of the functioning of the agroecosystem to ensure the balance of humus indicates that due to the production of energy produced from biofuels it is possible to obtain up to 15% of the additional profit, of which 11% is due to the production of electricity

DISCUSSION

The presented model of the agroecosystem is an improvement of the model linking the production of biofuels with the capabilities of the agroecosystem (Golub et al., 2017). The developed model of the agroecosystem is based on the results of experimental studies previously conducted by the authors. In particular, those are the production and use of diesel biofuels for the replacement of fossil fuels (Golub et al., 2018b), of biogas (Kukharets et al., 2019) and of generator gas (Golub et al., 2018a) for generate electricity. Experimental studies have shown that there is a possibility to create a model of agroecosystem that can provide full energy autonomy of agricultural production. When changing the structure of the feed base, the possibility of ensuring environmental safety, energy autonomy and economic efficiency of a balanced agroecosystem with organic production can vary, but achieving a balance of humus using the existing feed base is always possible. The use of gas generator sets also provides energy autonomy for electricity when using other options for the structure of the forage base. As for economic efficiency, it almost always increases with an increase in livestock production and an increase in the amount of straw for the production of electricity, which can be sold according to the green tariff. In order to implement various crop rotation options, structures of the use of feed base and the possibility of changing other parameters of the structural model of a balanced agroecosystem with organic production, it was developed a corresponding computer simulation model allowing the implementation of various calculation options, taking into account the needs of agricultural production.

At present, there is no data available in open publications on the possibility of providing energy autonomy of agroecosystems in the aspect the complete electric autonomy of agricultural enterprises with providing of humus balance in the soil (Belcher et al., 2004; Mockshell and Villarino, 2019). Scientific discussions on the feasibility of using biofuels in agricultural production are being conducted (Verdade et al., 2015; Gomiero, 2018; Kazemi et al., 2018). The basis of these discussions is that maintaining the balance of humus when using plant biomass as biofuels is impossible. However, the models of agroecosystems presented demonstrate the possibility of achieving energy autonomy while preserving the humus balance in agroecosystems. Presented of agroecosystem models can be applied to agrarian enterprises, regardless of their size, and can also be used to modelling the agricultural production of individual countries.

CONCLUSIONS

The agroecosystem model which is demonstrated in this study shows how to achieve energetic self-sufficiency when keeping the humus balance in agroecosystem. This model can be used by any-size enterprise as well as for the agrarian production of certain countries.

In a balanced agroecosystem on the production of plants products, animal products and biofuel, up to 41% of straw should be used to maintain the balance of humus in the soil. Up to 22% of straw can be used to produce heat and electricity for own needs. Up to 37% of straw can be used to produce electricity for sale according to the green tariff. Straw can be used to produce pellets and the further production of the wood gas. The wood gas is advisable to use for the production of electricity and heat.

To meet the own needs, it is necessary 45% of the produced electricity, of which 24% are produced from straw, 13% are produced from biogas and 8% – from biodiesel.

Up to 55% of the electricity produced from straw are available for sale according to the green tariff.

The needs in thermal energy in agroecosystem can be supplied by: the operation of the gas generator – up to 77%, the use of biogas – up to 9%, the use of biodiesel

– 7%, and 7% of the heat are provided by the burning of baled straw. Due to the production and use of biofuels, it is possible to obtain up to 15% of additional profits, 11% of them due to the production and sale of electric energy.

The further research will be directed on developing the analogic indices for the agroecosystem with an intensive production of plant produce without animal farming.

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