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MODELING THE PRODUCTIVITY PROCESS OF PEAS IN UKRAINE

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ABSTRACT

The article considers the modeling of the agro-meteorological conditions influence on the pea photosynthetic productivity. The results of numerical experiments, the quantitative assessment of different sowing terms influence on the pea crop photosynthetic activity rate in the Ukraine are given. The influence of various agro-meteorological conditions on the pea photosynthesis rate considered.

The research is based on the mathematical modeling of the plant production process, in particular, the model of pea crop productivity formation developed on the basis of agro-ecosystems productivity model. The model parameters identification was made, the pea yield formation was conducted by an independent determination. Absolute and relative error of the yield calculation assessed. Using the numerical experiments the influence of different features of agro-meteorological conditions on the photosynthesis rate determined.

Keywords: *photosynthesis, temperature, growth, respiration.*

1. INTRODUCTION

Vegetation cover is the focus of agro-ecological system, the primary source of food resources of the mankind. Productivity of plants and their existence are due to the processes of energy and mass transfer which take place in it, the use of solar energy in a complex, multi-step and complex process of transforming atmospheric CO_2, water and minerals in the soil in a variety of organic compounds of green plants. Although green plant is the central link in these processes, they all belong to different scientific disciplines which develop relatively independently of each other.

The role of mathematical models (Bihele et al., 1980), which study regularities of formation the hydro-meteorological regime in phytocenosis and its impact on the production process of plants, is integrating. Development of mathematical models of functioning and productivity of agro-ecosystems provides opportunities to combine our knowledge of the physiology and ecology of plants, plant growing, biophysics, soil science, meteorology into a coherent whole, in order to study the functioning of the crop as a whole system.

The research based on mathematical modeling of the production process of plants, in particular, developed on the basis of agro-ecosystem productivity model (Polevoy, 2005), a model of pea crop productivity formation.

2. LITERATURE REVIEW

To evaluate the response of pea crop to changing agro-climatic conditions of cultivation due to climate change, we used model of pea yield (Polevoy, 1988). The basis of this model is the system of equations of radiation, heat and water balances and balance of biomass (carbohydrates and nitrogen) in the vegetation cover. The following are modeled: radiation, heat and water regimes of the "soil - plant - atmosphere" system, mineral nutrition regime of plants and the impact of these regimes on the plant photosynthesis and respiration processes, absorption of moisture and mineral nutrients by the root system of plants, plants growth and development, photosynthetic productivity of pea crop (Polevoy, 1988).

The basis of the biological part of the model is the simulation of *the plant biomass growth*. It is considered as a balance of carbohydrates (products of photosynthesis and decomposition of aging tissue, the cost of breathing) and proteins (nitrogen uptake from the soil, tissue decay products, renewal costs of vital tissue structures) at each time step:

$$\frac{dm}{dt} = \Phi + C_{hydr} - R + N_{abs} + N_{hydr} - N_{sen} , \qquad (1)$$

where $\frac{dm}{dt}$ is the plant biomass growth; Φ is the total plant photosynthesis; C_{hydr} is the weight carbohydrates produced by the decay of aging tissues; R is the cost of carbohydrates on respiration; N_{abs} is the amount of nitrogen absorbed from the ground; N_{hydr} is the amount of nitrogen produced by the decay of proteins; N_{sen} is the cost of proteins renewal.

The process of the leaf photosynthesis we describe with the formula (Bihele et al., 1980), in which in addition to environmental factors such as photosynthetically active radiation and the CO_2 concentration in the atmosphere is taken into account the impact on the photosynthesis level of mineral nutrition, stages of plant development, temperature regime and moisture supply of the plants (Polevoy, 1988):

$$\frac{d\Phi}{dt}=\frac{1}{1/\Phi_{pot}K_{\Phi}(N_{str}^{L})+1/a_C C_0+1/a_{\Phi}\Pi}min\left\{\alpha_{\Phi},\Psi_{\Phi},\frac{ET}{ET_{pot}}\right\},(2)$$

where Φ_{pot} is the intensity of potential photosynthesis; a_C is the slope of carbon-dioxide curve of photosynthesis; C_0 is the CO_2 concentration in the atmosphere; a_{Φ} is the slope of the photosynthesis light curve; Π is the photosynthetically active radiation absorbed by the vegetation cover; α_{Φ} is the ontogenetic curve of photosynthesis; Ψ_{Φ} is the temperature curve of photosynthesis; $K_{\Phi}(N^{L}_{str})$ is coefficient of the plant supply with mineral nutrients; ET is the total evaporation, ET_{pot} is the evaporability.

Under stressful conditions and *plant aging* the tissue decay processes occur. We describe these processes with the enzyme catalysis kinetic equations (Frans and Tornli, 1990). At sufficiently high concentrations of hydrolyzed substrate the decay rate may be described by the reaction equation of zero order and at a sufficiently low one – with the first order reaction equation:

$$\frac{dC_{hydr}}{dt}=K_{hydr}^{0}K_{hydr}(T_a)K_{hydr}(W)\ \text{ at } C\geq C_{crit} \quad (3)$$

and

$$\frac{dC_{hydr}}{dt}=K_{hydr}^{1}K_{hydr}(T_a)CK_{hydr}(W)\ \text{ at } C<C_{crit} \quad (4)$$

where K_{hydr}^{0} is reaction rate constant of zero order; K_{hydr}^{1} is the reaction rate constant of the first order; $K_{hydr}(T_a),K_{hydr}(W)$ is the influence functions of temperature T_a and soil moisture W on the decay rate of aging tissues; C_{crit} is a critical amount of carbohydrates that defines the beginning of the decay reaction as a first-order reaction; C is the carbohydrates amount of aging tissues.

The cost of growth respiration and maintenance respiration are modeled using the concept of (Polevoy, 2005) taking into account the changes in the respiration rate in ontogenesis (Polevoy, 1988) and under the air temperature influence

$$\frac{dR}{dt}=\alpha_R\left[C_G\frac{dm}{dt}+C_m m\varphi_R\right], \quad (5)$$

where α_R is the ontogenetic curve of respiration; C_G is the coefficient of cost on the growth respiration; C_m is the coefficient of cost on the maintenance respiration; m is the weight of plants; φ_R is the temperature curve of respiration.

The process of plant *nitrogen absorption* from the soil goes actively or passively (the removal of the nitrogen with the transpiration stream)

$$\frac{dN_{abs}}{dt}=\frac{N_{abs}^{max}\overline{N}_{s.r.}m_r}{K_{abs}^{N}+\overline{N}_{s.r.}}K^{N}(T_s)+T_r\overline{N}_{s.w.}, \quad (6)$$

where N_{abs}^{max} is the maximum rate of nitrogen absorption by the root system of plants; $\overline{N}_{s.r.},\overline{N}_{s.w.}$ are the nitrogen concentration at the roots surface and in the soil solution respectively; m_r is the weight of roots; K_{abs}^{N} is the Michaelis-Menten constant; $K^{N}(T_s)$ is the influence function of soil temperature on the nitrogen absorption rate by the root system; T_r is the plant transpiration.

The *proteins decay* in the plant organs is described by equations similar to the equations (3) and (4).

It is assumed that the *protein renewal rate* of each *i*-th plant organ is proportional to the nitrogen content in the tissues of this organ

$$\frac{dN_{isen}}{dt}=\alpha_{sen}N_i\ , \quad (7)$$
$$i\in l,s,r,p,$$

where α_{sen} is the relative velocity of proteins renewal; N_i is the nitrogen content in the tissues of the i-th organ, l is the leaves; s is the stems; r is the roots; p is the beans.

In the simulation of plant growth considered that the plant consists of two functionally related parts: aboveground and belowground. Aboveground part in its turn is divided into separate organs. The distribution of carbohydrates and nitrogen between individual organs of the aboveground plant part (leaves, stems, pods) is performed using the concept of their distribution over the need for the growth period by dividing and for the growth period by stretching of plant organs (Polevoy, 1988).

The abovementioned system of equations (1) - (7) describes the influence of environmental factors on the basic vital processes of plants and the formation of their photosynthetic productivity.

To describe the dynamics of dry biomass growth of individual organs A.N.Polevoy suggested the following system of equations (8):

$$\left.\begin{aligned}
&\frac{\Delta m_i^j}{\Delta t} = \frac{\beta_i^j \Phi^j}{1+c_{G_i}} - \frac{(\alpha_{R_i}^j c_{m_i} \varphi_R^j + \vartheta_i^j)\tilde{m}_i^j}{1+c_{G_i}},\\
&\frac{\Delta m_p^j}{\Delta t} = \frac{\beta_p^j \Phi^j}{1+c_{G_i}} - \frac{\left(\alpha_{R_p}^j c_{m_p} \varphi_R^j \tilde{m}_p - \sum\limits_i^{l,s,r} \vartheta_i^j \tilde{m}_i^j\right)}{1+c_{G_i}},\\
&\frac{\Delta m_g^j}{\Delta t} = \frac{\Delta m_{g_{max}}^j}{\Delta t} \cdot \frac{\Delta \tilde{m}_p^j / \Delta t}{k_g + \Delta \tilde{m}_p^j / \Delta t},
\end{aligned}\right\} \quad (8)$$

where $\frac{\Delta m_{i(p)}}{\Delta t}$ is the growth of biomass of i-th vegetative (reproductive) organ; $\tilde{m}_{i(p)}$ is the functioning biomass of i-th vegetative (reproductive) organ;

$\Delta m_g / \Delta t$ is the growth of the beans dry biomass;

$\Delta m_{g_{max}} / \Delta t$ is the maximum possible growth rate of the beans dry biomass under the real conditions;

β_i is the growth function of the vegetative period; ϑ_i is the growth function of the reproductive period; C_G is the coefficient of cost on the growth respiration; α_R is the ontogenetic curve of respiration; C_m is the coefficient of cost on the maintenance respiration; φ_R is the temperature curve of respiration; k_g is the Michaelis-Menten constant; i is the organs, l is the leaves; s is the stems; r is the roots; p is the beans.

3. MAIN RESULTS

This numerical experiment was conducted based on the average long-term data of agro-meteorological observations for the period from 1986 to 2005. Using a modified model the main indicators of the photosynthesis rate and pea crop yield were calculated for the main climatic zones of the Ukraine: Polesye, Forest-steppe, Northern Steppe and Southern Steppe.

As a result of the performed work is given a quantitative assessment of the impact of sowing time on the rate of photosynthetic activity of plants in crops and pea beans yield for the major climatic zones of the Ukraine. As such assessment for pea the growth value of vegetative mass per was decade adopted.

Analysis of agro-meteorological conditions shows that intensive growth related with improvements in water and heat regimes (Gulyaev et al., 1988). The average air temperature per decade at the time of pea sowing in Polesye (second decade of April) was in the same range 9.5 ^{0}C; in the Forest-steppe (the second decade of April) was 10.4 ^{0}C; in Southern and Northern Steppe (first and second decade of April) was 11.4 ^{0}C and 14.2 ^{0}C, respectively. Precipitation in the same period fell unevenly: in Polesye (second decade of April) precipitation was 20 mm; in the forest steppe (the second decade of April) was 14mm; in Southern and Northern Steppe (first and second decade of April) was 14mm.

Reported features of agro-meteorological conditions appropriately reflected in the formation of leaf surface area and the level of net photosynthetic productivity of pea (Sinitsyna and Le Thi Kim Zung, 1984).

Analysis of agro-meteorological conditions shows that intensive growth related with improvements in water and heat regimes. Thus, the maximum leaf area index in Polesye accounted for sowing terms in the third decade of April and makes 3 m^2/m^2, the relative moisture supply during this period is 0.64 relative units, the air temperature is 16.6^{0}C; in the Forest-steppe maximum leaf area accounted in the second decade of April and makes 2.9 m^2/m^2, the air temperature was 17 ^{0}C, relative moisture supply is 0.57 relative units. In Southern and Northern Steppe maximum values of leaf area accounted for sowing terms in the first and second decade of April and amounted to: in South Steppe is 2.5 m^2/m^2, the relative moisture supply during this period is 0.57 relative units, air temperature 16 ^{0}C, and Northern Steppe - 2.8 m^2/m^2, the relative moisture supply during this period is 0.56 relative units, air temperature is 17.1 ^{0}C. Results are presented in Table 1.

An important role in formation of pea yield plays the leaves work productivity. We consider net photosynthetic productivity (NPP) in the period corresponding to the maximum leaf area. In the Polesye at the third decade of April NPP was 15.9 g/m^2 per day; in the Forest-steppe in the second decade of April was 17.4 g/m^2 per day. In Southern and Northern Steppe in the first and second decade of April NPP was 20.1 g/m^2 and 21.8 g/m^2 per day respectively.

Table 1. Effect of different sowing dates on the basic parameters of the plant photosynthetic activity in crops and yield of the pea beans

Natural climatic zones	Sowing terms	Maximal leaf area, m^2/m^2	Relative moisture supply, relative units	Air temperature per decade, ^0C	NPP in the period with max. leaf area, g/m^2 per day	K_{HOZ}	FSP, m^2/m^2	Yield, c/ha at 14% beans moisture
Polesye	18.04	2.9	0.67	15.9	15.3	0.21	148	21.5
	28.04	3	0.64	16.6	15.9	0.23	159	21.7
	8.05	2.9	0.63	17.4	14.8	0.23	123	19.5
Forest-steppe	6.04	2.8	0.59	16.1	17.5	0.17	130	19.1
	16.04	2.9	0.57	17.0	17.4	0.21	134	22.8
	26.04	2.8	0.55	17.8	18.2	0.21	115	21.3
Northern Steppe	2.04	2.8	0.56	17.1	17.5	0.23	136	19.2
	12.04	2.8	0.55	17.1	17.2	0.23	130	19.4
	22.04	2.7	0.5	18.2	17.8	0.23	110	17.9
Southern Steppe	11.04	2.5	0.57	16.0	20.1	0.22	141	16.2
	21.04	2.4	0.54	17.4	19.9	0.21	165	13.9
	1.05	1.9	0.51	17.8	17.7	0.23	112	12.2

The rate of photosynthesis (NPP) determines the pea production process (Gulyaev et al., 1989). NPP progress curves show that the fall and rise of pea plants in its different variants were observed in the same periods. Since the plants were in various stages of development, we can assume that the productivity of photosynthesis is largely determined by agro-meteorological conditions.

Analyzing the indicators of the photosynthetic potential (FSP) in each natural climatic zone (Gulyaev et al., 1989) at different sowing terms, we see that the maximum values in Polesye occur in the second decade of April are 159 m^2/m^2. In the Forest-steppe the maximum values of FSP occurs in the second decade of April and are as follows: 134 m^2/m^2. In North and South Steppe maximum FSP observed in Southern Steppe at the third decade of April and is 165 m^2/m^2; Northern Steppe in the second decade of April is 136 m^2/m^2.

Maximum indicators of the pea yield (at 14% moisture of beans) in Polesye as well as the maximum values of FSP and leaf area occurred in the third decade of April and made 21.7 c/ha. In the Forest steppe maximum values of peas yield as well as the maximum values of leaf area occurred in the second decade of April and made 22.8 c/ha. In Southern and Northern Steppe maximum observed values of the yield in the first and the second decade of April: South Steppe - the second decade of April 16.2 c/ha; North Steppe - in the second decade of April 19.4 c/ha.

The main processes forming the plant biomass as a result are photosynthesis and respiration. The productivity of photosynthesis is determined by agro-meteorological factors that are constantly changing during the whole vegetation period. At a certain stage of the plant development the photosynthetic productivity per unit leaves area under the given light conditions depends on agro-meteorological conditions, namely, the air temperature and humidity conditions.

Figure 1 shows a graph of the photosynthesis rate of pea leaves Φ dependence on photosynthetically active radiation (PAR) at optimal moisture supply at different temperature levels ($t = 22^0C$, $t = 13^0$ C). Comparing the light curves of photosynthesis, it can be seen that the increase in the flux density of incident photo synthetically active radiation results in an increase of the photosynthesis rate. The shape of curves does not change depending on the air temperature. Maximum photosynthesis observed at the flux density of the incident PAR more than 0.7-0.9 cal/(cm2 • min) and air temperature of 22^0C and 23.5 mg $CO_2/(dm^2$ • hour). With decreasing the air temperature decreases the photosynthesis rate. When the air temperature is 13.2^0 C, the maximum photosynthesis is 14.2 mg $CO_2/(dm^2$ • hour).

Figure 2 shows a graph of leaf photosynthesis Ф dependence on the air temperature at different soil moisture levels: 1 - optimal moisture content, 2 - lack of moisture. Comparison of the photosynthesis light curves obtained at optimal moisture content (condition 1) and lack of moisture (condition 2) shows that the increase in the flux density of the incident PAR results in an increase of the photosynthesis rate. Maximum photosynthesis observed at a flux density of the incident PAR greater than 0.7-0.9 cal/(cm^2 • min) and air temperature 22^{0}C.

At optimum moisture and temperature 22^{0}C maximum photosynthesis is 22.3 mg CO$_2$/(dm^2 • hour), while at the lack of moisture it is 6.6 mg CO$_2$/(dm^2 • hour). With decreasing the air temperature the photosynthesis rate decreases too.

Identification of the parameters of the pea crop formation model was conducted by an independent determination. The identification was based on the materials of agro-meteorological observation network of the agro-meteorological stations of the Ukraine on the agro-meteorological conditions of the pea cultivation for the period 1986-2005 as well as on the literature sources, which cover the problem of the study.

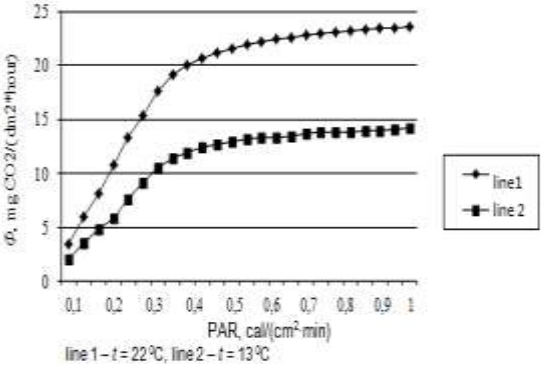

Figure 1 - The dependence of photosynthesis rate of pea leaves (Φ) on photosynthetically active radiation (PAR) at different temperature levels

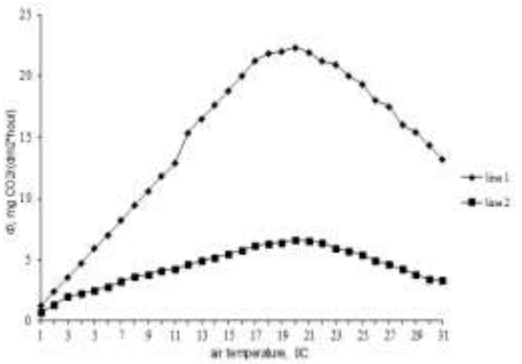

Figure 2 - The dependence of the photosynthesis rate (Φ) on the air temperature at different levels of soil moisture

The verification was conducted on the vegetation seasons data of 2011-2015. Absolute and relative error of the yield calculation assessed. Relative error of the calculation varies from 0.5 to 19%.

4. CONCLUSION

As the result of the work the influence of different sowing terms on the photosynthetic activity rate of the pea crop plants was studied. A comparative quantitative assessment of the pea productivity in different climatic zones at different sowing terms was give. The obtained results showed that at later sowing terms the pea productivity formation takes place under less favorable agro-meteorological conditions that leads to a significant reduction in leaf area, which in turn results in a decrease in FSP and as a consequence to the decrease of yield.

Using the numerical experiments determined the features of the different agro-meteorological conditions influence on the photosynthesis rate. The quantitative assessment of the impact of solar radiation, air temperature and moisture supply at which the pea photosynthesis rate reaches maximum was obtained.

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