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позволяет нам создавать формальные алгоритмы для обработки этих моделей.

Таким образом, транспортная сеть удобно представлена в виде графа.

Транспортная сеть способна организовать соответствующую транспортировку, то есть ограничения на состояние дороги, т.е. движение в одну сторону, ограничения на движение грузовых перевозок, общую массу транспортного средства, погрузку. Учитывать только количество. Таких как ось.

Транспортные сети могут быть представлены только связными графами. Моделирование транспортной сети начинается с размещения вершин. Вершина предназначена для пунктов формирования грузов и поглощения грузов, центра большого жилого района, изолированного населенного пункта. Вершины с транспортными связями между ними соединены ребрами или (в случае односторонних соединений) направленными дугами. Каждому ребру присваивается мера прибыльности, которая определяется не только затраченным временем, но и целями, которые должны быть достигнуты при решении задачи оптимального транспорта. В большинстве случаев за основу берется минимальное значение общего пробега. При одинаковых условиях вождения на всех участках пробега оптимальный план пробега является оптимальным с точки зрения времени и стоимости. Кроме того, вы можете использовать такие показатели, как платные дороги, многолюдные дороги и частоту пересечений населенных пунктов на этой дороге в качестве показателя прибыльности.

Таким образом, можно сделать вывод, что использование теории графов в пакетах программ будит выгодно для большинства предприятий.

Хотя выгоды являются косвенными, они, как правило, становятся заметными в средне- и долгосрочной перспективе из-за более низких производственных затрат. Все это определяет перспективность внедрения предложенной методологии в промышленности и сфере обслуживания населения владельцами всех форм Республики Башкортостана.

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CONSTRUCTION OF MATHEMATICAL PLANT GROWTH MODEL

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Abstract

A mathematical model of the plant growth dynamics of based on a system of differential equations is constructed. A separate differential equation which describes the development of the subsystem and its connection with other subsystems is developed for each plant subsystem. The system of differential equations is solved by a numerical method. From the set of solutions of the system of differential equations, only those are selected for which the sum of the squares of the deviations from the experimental values is the smallest.

The constructed mathematical model makes it possible to conduct simulation experiments and translate the results of field experiments into digital format.

Keywords: mathematical model, system of differential equations, Mathcad, subsystem, Brussels sprouts, dry matter, growth rate, Chanter equation.

Introduction. In the process of plant growth, plant subsystems undergo dynamic changes. In mathematical modelling of such processes there is a number of problems. Determination of plant parameters during growth is carried out at certain points of time. For fixed moments of time the regression equations are written down, trying to make generalizations for intermediate moments of time, and if possible, for the following, entering time into the regression equation. As it is known, the results obtained when using simple regression equations often do not coincide with the experimental data and such a semi-empirical description may have nothing to do with the real process of plant growth, which makes the constructed model inefficient.

Only a dynamic mathematical model that describes the interaction of plant subsystems, reveals the essence of the process of changing plant subsystems over time and the patterns of processes in them, is adequate in the mathematical description of individual characteristics of the real agrobiological system. As a rule, dynamic models are built on the basis of differential equations and their systems [1, 2, 3]. Therefore, the development of methods for obtaining mathematical models to describe multidimensional dynamical systems is relevant.

The purpose of this work. Construction of a mathematical model of the plant growth dynamics.

Analysis of recent research and publications. A significant contribution to the study of cabbage growth was made by V.I. Lykhatsky. [6], Cherednichenko V.M. [4, 5, 6, 7, 8], Chernensky V.M. [9, 8].

Cherednichenko V.M. during 2009-2013 in the research areas of Vinnytsia National Agrarian University conducted fundamental field experiments on growing cauliflower and broccoli [4, 5, 6, 7, 8]. The influence of water-retaining granules, mulching with film and black agrofiber on plant growth was studied. Phenological observations, biometric measurements and accounting were performed, the relationship between plant subsystems was studied, and a statistical analysis of plant growth indicators was performed.

Presentation of the main research material. The growth and development of plants can be described using growth functions that reflect the mathematical dependence of the amount of dry matter on time. Consider the most common equations of growth: logistics, Gompertz and Chanter's [1, 2].

Let's analyze Chanter's equation

$$M = \frac{M_0 \cdot B}{M_0 + (B - M_0) \cdot \exp\{-[\mu(1 - e^{-D \cdot t})/D]\}} \quad (1)$$

where, M, M_0, B, μ, D – parameters that have a biological meaning.

Let $M = 100\ g$ – the mass of dry matter for the period of harvest;

$M_0 = 1\ g$– the mass of dry matter of the plant at the time $t = 0$;

B – availability of nutrient medium;

$$B = \frac{M \cdot M_0 \cdot (e^{\mu/D} - 1)}{M_0 \cdot e^{\mu/D} - M}, \quad (2)$$

$\mu = 0{,}5$ – specific growth rate;

D – an indicator of complication, which characterizes μ the change with plant development.

When deriving the logistic equation, it is assumed that the growth rate of the plant is regulated by the resource of the nutrient medium. In the Gompertz equation it is assumed that the resource of the nutrient medium is unlimited, i.e. the growth energy is not affected and is proportional to the dry mass, and the specific growth rate is constant [1].

By selecting the value D for from the interval $0 \le D \le \mu/[\ln(M/M_0)]$, you can build a family of curves, which is bounded on the left by the logistic curve, and on the right – the Gompertz curve. When $D \to 0$ (for example, $D = 0{,}00086$), and B determined by formula (2), equation (1) becomes logistical. When $D \to \mu/[\ln(M/M_0)] = 0{,}1086$ – in the Gompertz curve, when $D = 0{,}05$ the curve is between the logistic curve and the Gompertz curve. All curves have the same values of initial and final dry weight of the plant and the initial specific growth rate. The inflection point shifts towards D larger values of time as increases. The Gompertz curve shows faster growth in the initial phase, slower approach to the asymptote and a longer linear section at the ends of the inflection point (Fig. 1).

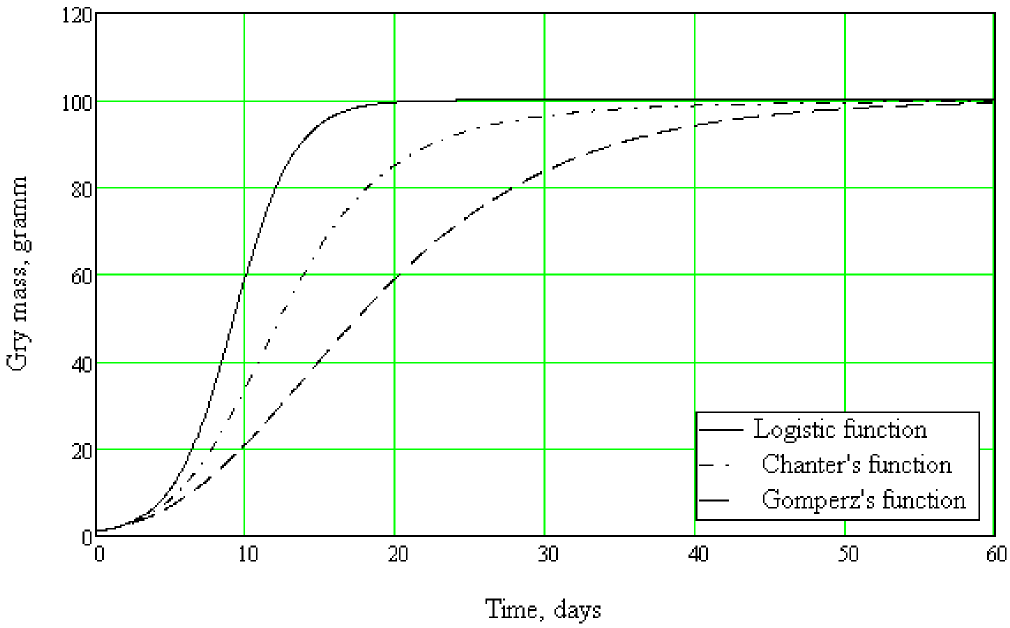

Fig.1 Chanter's growth function

Thus, the growth curves of Chanter, Gompertz and the logistic curve can be used in the development of dynamic models of plant growth as its components.

Combining the growth curves of Chanter, Gompertz and the logistic curve, we can build a perfect mathematical model of plant growth dynamics, which is described by a system of differential equations.

Most differential equations and their systems that describe the dynamics of agrobiological systems do not have analytical solutions or their solutions are too cumbersome [1, 2, 3, 12]. Therefore, it is important to be able to solve the corresponding differential equations and their systems by numerical methods. This possibility is provided by the Mathcad system [13, 14].

In the Mathcad system, you can solve differential equations and their systems in symbolic and numerical forms. Symbolic methods for solving equations are unfortunately limited, but instead of them numerical methods have been developed for solving differential equations and their systems, such as the Caushy problem. Numerical methods for solving problems such as the Caushy problem for GDE (general differential equations) is a long and detailed technology. The simplicity of the form of presenting the results and the analysis of the solutions depending on the values of the system parameters play a significant role here.

Most computational problems do not usually have any computational problems (they are solved using a simple Runge - Kuta algorithm), and special methods, so-called «hard» ones, require special methods. All these algorithms are embedded in the Mathcad system, and the user has the opportunity to choose a specific one based on the type of equation.

In modelling biological processes, biological systems or ecosystems are considered as those for which the basic laws of physics, chemistry and biology are valid. All the basic principles and laws, in accordance with which various processes take place in inanimate nature, retain their patterns for living nature. Therefore, any mathematical model should be based on the laws of conservation of matter, electric charge, energy, impulse and momentum, on the laws of mass interaction, radioactive and chemical transformations.

Let's consider the method of constructing a dynamic model of plant growth based on the obtained experimental data. Such mathematical model requires a significant array of experimental data. Potatoes [3], tomatoes [12], sugar beets and cabbage are convenient for the development of mathematical models of growth.

For example, let's build a model that describes the growth dynamics of Brussels sprouts. As a basis we will take the model of Zagorodny Y. V. [3]. In plants, we distinguish separate subsystems: W_1 – root, W_2 – stem, W_3 – leaves, W_4 – heads. The total dry weight of the plant is:

$$W = \sum_{i=1}^{4} W_i \quad , \tag{3}$$

The growth of subsystems (stem roots, leaves) for Brussels sprouts is described by the growth equation:

$$W_i = \frac{A_i \cdot B_i}{A_i + (B_i - A_i) \cdot e^{-\kappa_i t}} , \tag{4}$$

where A_i is the dry weight of the corresponding subsystem for seedlings;

B_i – dry mass of the relevant subsystem for the period of completion of harvesting.

The model is built according to the following algorithm:

1. In plants, we distinguish separate subsystems: W_1 – root, W_2 – stem, W_3 – leaves, W_4 – head.

2. We determine the dry weight of plant subsystems with a period of 5-7 days throughout the growing season.

3. Based on experimental data, we determine the unknown parameters of growth functions for each subsystem of the plant.

4. We write the differential equations for the dynamics of each subsystem.

We combine differential equations into a system:

$$\begin{cases} \dfrac{dW_1(t)}{dt} = a_{1,1} W_1(t) \cdot \rho(t) \cdot f(t) \cdot \dfrac{k_1 e^{-k_1 t}(B_1 - A_1)}{A_1 - e^{-k_1 t}(A_1 - B_1)} + a_{1,2} w W_2(t) - a_{1,3} W_3(t) - a_{1,4} W_4(t) \\ \dfrac{dW_2(t)}{dt} = a_{2,1} W_1(t) + a_{2,2} W_2(t) \cdot \dfrac{k_2 e^{-k_2 t}(B_2 - A_2)}{A_2 - e^{-k_2 t}(A_2 - B_2)} + a_{2,3} W_3(t) - a_{2,4} W_4(t) \\ \dfrac{dW_3(t)}{dt} = a_{3,1} W_1(t) \cdot a_{3,2} W_2(t) + a_{3,3} W_3(t) \cdot f(t) \cdot \dfrac{k_3 e^{-k_3 t}(B_3 - A_3)}{A_3 - e^{-k_3 t}(A_3 - B_3)} - a_{3,4} W_4(t) \\ \dfrac{dW_4(t)}{dt} = \left[a_{4,1} W_1(t) + a_{4,2} W_2(t) + a_{4,3} W_3(t) \cdot f(t)\right] s(t) - a_{4,4} W_4(t) \end{cases} \tag{5}$$

where $\begin{bmatrix} a_{1,1} & a_{1,2} & a_{1,3} & a_{1,4} \\ a_{2,1} & a_{2,2} & a_{2,3} & a_{2,4} \\ a_{3,1} & a_{3,2} & a_{3,3} & a_{3,4} \\ a_{4,1} & a_{4,2} & a_{4,3} & a_{4,4} \end{bmatrix}$ – matrix of coefficients of the system of equations, which characterizes the interaction of elements of plant subsystems;

$a_{1,1}$ – coefficient characterizing the strength of root growth;

$a_{1,2}$ – coefficient that characterizes the rate of exchange between the subsystem «root – stem»;

$a_{1,3}$ – coefficient that characterizes the rate of exchange between the subsystem «root – leaf» through the stem;

$a_{1,4}$ – coefficient that takes into account the decrease in the rate of root growth due to the growth of the head;

$a_{2,1}$ – rate of exchange between subsystems «stem – root»;

$a_{2,2}$ – characterizes the growth rate of the stem;

$a_{2,3}$ – rate of exchange between subsystems «stem – leaf»;

$a_{2,4}$ – takes into account the decrease in the growth rate of the stem due to the growth of the heads;

$a_{3,1}$ – rate of exchange «leaf – root» through the stem;

$a_{3,2}$ – rate of exchange «leaf – stem»;

$a_{3,3}$ – characterizes the growth rate of leaves;

$a_{3,4}$ – takes into account the decrease in leaf growth due to the growth of heads;

$a_{4,1}$ – characterizes the influence of roots on the growth rate of dry weight of heads;

$a_{4,2}$ – characterizes the influence of the stem on the growth rate of dry weight of the heads;

$a_{4,3}$ – characterizes the influence of leaves on the growth rate of dry weight of heads;

$a_{4,4}$ – takes into account the decrease in the intensity of the growth rate of the heads due to the aging of the plant organism;

$\rho(t)$ – soil moisture function;

$f(t)$ – soil temperature function;

$F(t)$ – air temperature function;

A_1 – dry mass of seedling roots;

B_1 – dry mass of roots for the period of completion of harvesting;

K_1 – coefficient of the logistic equation of root growth;

A_2 – dry mass of seedling stem;

B_2 – dry weight of the stem for the period of completion of harvesting;

K_2 – coefficient of the logistic equation of stem growth;

A_3 – dry mass of seedling leaves;

B_3 – dry weight of leaves for the period of completion of harvesting;

K_3 – coefficient of logistic level of leaf growth;

S(t) –a function that characterizes the growth rate of heads.

4. We set the initial conditions – values $W_{i,0}$ for the moment of time $t = 0$.

5. We give the initial approximations of the unknown coefficients $a_{i,j}$ of the system of differential equations.

6. We solve the system of differential equations in Mathcad by the Runge-Kutta method with a constant step. We use the built-in function:

$$rkfixed(y, x1, x2, n, D).$$

7. We find the weighted sum of the squares of the deviations of the experimental values from the calculated ones $\sum_{i=1}^{n}\sum_{j=0}^{m}\left(\frac{W_{i,j}-WP_{i,j}}{WP_{i,j}}\right)^2$.

8. By the method of coordinate descent we change the values of the coefficients $a_{i,j}$.

9. We solve the system of equations and calculate the sum of squares of deviations.

10. The computational procedure is completed at

$$\sum_{i=1}^{n}\sum_{j=0}^{m}\left(\frac{W_{i,j}-WP_{i,j}}{WP_{i,j}}\right)^2 = min. \quad (6)$$

11. We fix the optimal values of the coefficients $a_{i,j}$.

12. We substitute the obtained optimal values of the coefficients into the system of differential equations (3) and solve it.

13. We analyze the solution of the system of equations and investigate the interaction between the individual elements of plant subsystems. We build graphs.

To determine the dry weight of plant subsystems, field experiments were performed (table 1). The plants were cleaned from the soil, their components were isolated: root, stem, leaves, heads, placed in a thermostat with a temperature of 50-60ºC and dried for 4-5 hours. After that, at a temperature of 103-110 ºC the plants were dried (brought to constant weight) for 3-5 hours. The average value was determined by averaging the masses of 5-7 plants.

Table 1

Dry mass of plant subsystems

t	0	10	30	37	46	55	60	67	75	91	98	112
W_1, g	0.53	2.2	3.7	6	12.8	12.4	14.1	16.1	16.2	18.5	17.3	18.9
W_2, g	0.34	1.1	6.7	7	15.2	20.1	23.8	26.0	26.1	28.7	28.8	28.5
W_3, g	2.61	5.8	18.5	28	57.3	65.2	66.0	69.6	75.9	77	75.3	78.1
W_4, g	0	0	0	0	0.9	6.8	22.1	30	36	38	39.6	41.7

The function that characterizes the growth rate of Brussels sprouts has the form:

$$S(t) = \begin{cases} 0, & if\ t < 50 \\ e^{-\eta_1 t}, & if\ 75 < t \geq 50, \\ e^{-\eta_2 t}, & if\ t \geq 75 \end{cases} \quad (7)$$

where: $\tau -$ the period of time from planting seedlings to the beginning of tying the head,

$\eta_i -$ exponent coefficients ($\eta_1 = 0.09704, \quad \eta_1 = 0.09623$).

Unknown coefficients k_i of growth functions of plant subsystems were determined by a statistical method based on the results of field experiments, the value was obtained: $k_1 = 0{,}0880;\ 0{,}0825;\ 0{,}0995.$

The average daily values of soil temperature, air and soil moisture were approximated by nonlinear equations.

Let's build a mathematical model of Brussels sprouts growth based on experimental ones according to the described algorithm (Table 1). Let's estimate values of parameters of model for an array of experimental data (table 1) under initial conditions (values of dry weight of subsystems of plants at the time of landing of seedling):

$$W_1(0) = 0{,}53$$
$$W_2(0) = 0{,}34$$
$$W_3(0) = 2{,}6$$
$$W_4(0) = 0$$

The optimal solution of the system of differential equations (5) will be at the values of the coefficients $a_{i,j}$ (table 2):

Table 2

Values of model coefficients

i \ j		1	2	2	4
		Root	Stem	Leaf	Heads
1	Root	0,047	0,0041	0,0038	0,0083
2	Stem	0,015	0,675	0,0031	0,0134
3	Leaf	0,069	0,0078	0,064	0,036
4	Heads	0,35	0,27	0,43	0,00068

The simulation results are shown in Fig.2.

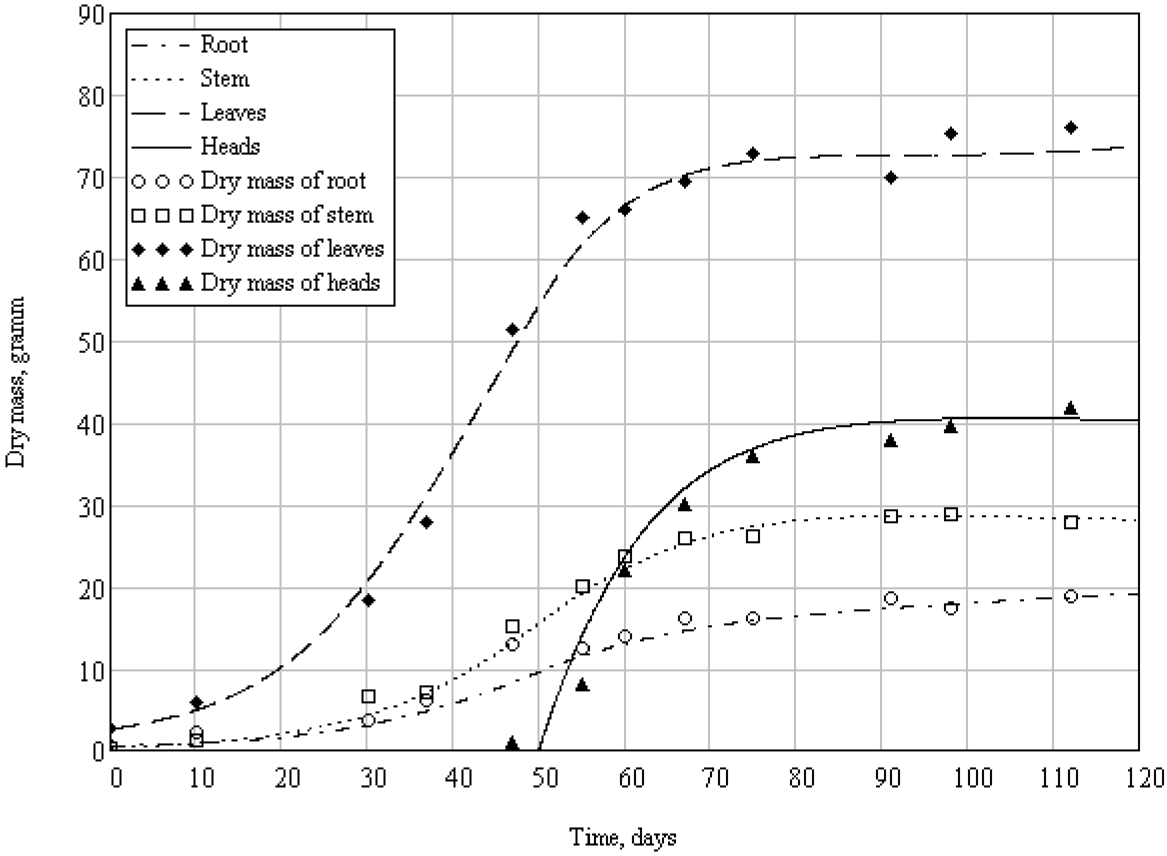

Fig.2. Dynamics of dry mass of Brussels sprouts

The constructed model is very sensitive to changes in parameters, it allows to simulate plant growth, for example, changing the value of the coefficient a_{31}, which characterizes the rate of exchange «leaf – root» through the stem from 0,069 to 0,076, leads to an increase in head weight and a significant increase in leaf weight (Fig. 3). A series of experiments is needed to determine the real effect of the coefficients on plant growth.

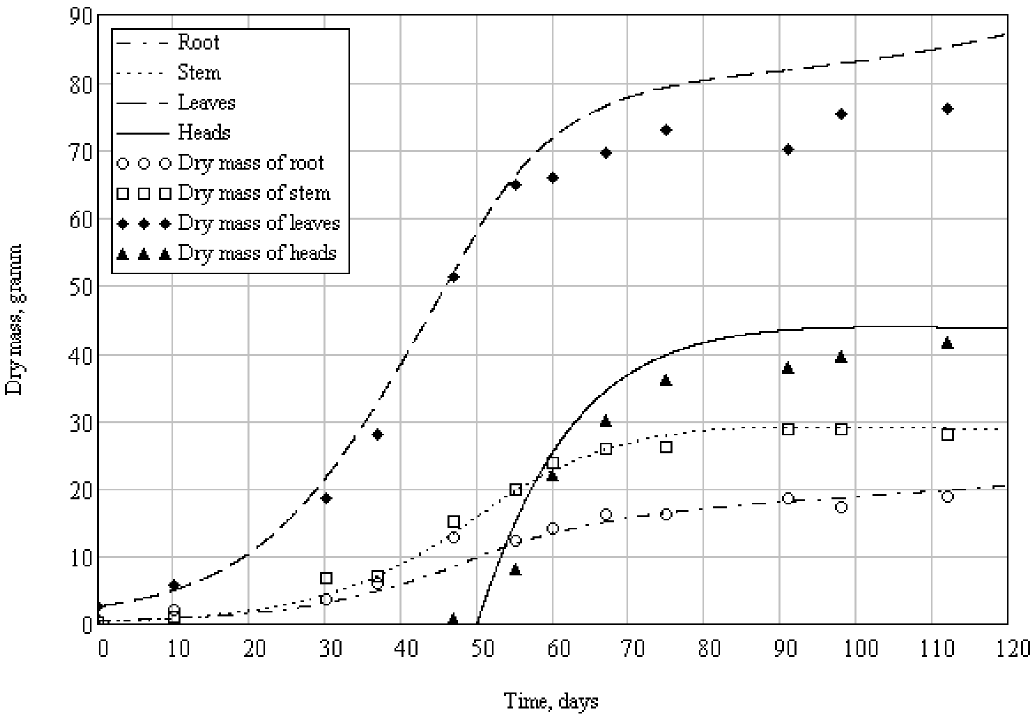

Fig. 3.
The effect of changing parameters (the value of the coefficient of the model a_{31} changed from 0,069 to 0,076)

Conclusions.

Development of mathematical models of dynamic processes in agro-industrial complex will contribute to a detailed description of processes in dynamic systems, simulation of computer processes, which will accelerate the introduction of new technologies, reduce the time for development of new machines and mechanisms, adjust plant development and thus reduce the cost of agro-industrial products. Its main advantage is that it allows the scientist to translate the results of field experiments into digital format.

The proposed mathematical model accurately describes the process of plant development. It gives the opportunity to study the impact on the growth process of various factors: irrigation, mulching, soil moisture, temperature, light, climate, fertilizers and plant growth regulators.

Disadvantages of the mathematical model:

- the model is closed on itself;
- it requires a significant array of field experimental data;
- it is accompanied by cumbersome mathematical calculations.

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ТЕРМОДИНАМИЧЕСКИ СОГЛАСОВАННАЯ МОДЕЛЬ ТЕОРИИ ПОРОУПРУГОСТИ ХИМИЧЕСКИ АКТИВНОГО ГЛИНСТОГО СЛАНЦА

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A THERMODYNAMICALLY CONSISTENT MODEL OF THE POROELASTICITY THEORY OF CHEMICALLY ACTIVE SHALE

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