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Control of Soil Acidity Using Remote Sensing Data

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***Abstract*— In the present paper an example of effective use of remote sensing data in agriculture is considered. To this end, management considered the problem of soil acidity on agricultural fields. To solve this problem using remote sensing placed on unmanned aerial vehicles. The starting point for solving the problem is a new methodology for estimating the state of the crops and the acid value based on remote sensing data. A feature of the methodology is to construct a quantitative estimate of crop biomass and soil acidity index. This approach differs significantly from the well-known method of determining the vegetation index NDVI (Normalized Difference Vegetation Index). New mathematical models and algorithms for the construction of quantitative estimates are proposed. Soil acidity is controlled by introducing ameliorant containing calcium. They act in the soil from 5 to 8 years. Therefore, the result of the formation of a management strategy for making dosage ameliorant data used crop rotation. To account for the spatial heterogeneity of soil based on the results of evaluation is isolated area with close indicator of acidity. These areas are considered to be homogeneous. Optimal strategies make ameliorant for each homogeneous area is formed. To generate jobs onboard regulators executive machinery of the entire strategy is only used optimal doses making improver for the first year crop rotation. In real time when driving through the field the machine to make ameliorant job-board regulator flow improver is formed as a weighted average value of optimum doses in homogeneous areas of the acid value.**

***Index Terms*— Remote Sensing, Ameliorant, Mathematical Model, Strategy of Ameliorant's Application**

I. INTRODUCTION

Agriculture is one of the most interesting and topical areas for using remote sensing (RS) data (Abhay S., 2014; Adamchuk V. at all, 2003; Zlinszky A. at all, 2015; Encyclopedia of Remote Sensing Series, 2014; Hatfield J. at all, 2008). The main objectives of using RS data are:

monitoring of agricultural land state on large areas where space RS data are being frequently used (Agapiou A. at all, 2012; Cilia C. at all, 2014; Ponzoni F.J. at all, 2014; Kowalik W. at all, 2014);

monitoring of crop and soil state on selected arable fields for the control of agricultural technologies, which mainly use aircraft and ground-sensing data recorded by systems placed on agricultural machinery (Lugassi R. at all, 2015; Waldner F. at all, 2015; Wang X.-G. at all, 2014).

In our paper we consider the second objective, when unmanned aerial vehicles are being used as the technical base for placement of remote sensor devices. At the present time these devices are just in the beginning of using in agriculture, but in the nearest future they will have become essential attributes of modern agricultural technologies and machinery. A successful development of this direction demands a solution of actual technological problem, which is considered in this paper.

Acidic soils are typical in climatic regions with high amount of precipitation. Rain and snow contribute to increasing soil moisture content and to decreasing concentration of calcium and magnesium cations in soil exchange complex. The calcium and magnesium cations can be leached by water from the soil exchange complex to soil solution downward moving out of soil profiles. Hydrogen cations substitute calcium and magnesium ones in the soil exchange complex and contribute to increasing soil acidification. If amount of precipitation exceeds 500 mm per year, the annual losses of leached calcium are approximately equal to 55 g/m^2. The almost same amounts of calcium can be removed from soils with crop yields. Extremely high (>9) and low (<4) soil pH values are toxic for plants. Within this range of values changes in pH affect behavior of nutrients, their adsorption and conversion into unavailable forms for plants. Optimal pH value is equal to 6.5 in slightly acidic soils.

Application of calcium or magnesium compounds into soils for reducing their acidity is called liming. Although the term "lime" refers to CaO (quicklime), the other calcium and magnesium compounds are also called lime. Liming is usually applied to increase soil pH values to 6.5. In contrast, if there is a need to increase the soil acidity, such nitrogen fertilizers as ammonium sulphate can be used, but application of elemental sulfur is the most effective way to increase the soil acidity. Liming solves two problems: reducing soil acidity and fertilization of soils with calcium and magnesium, for example, using dolomite powder (Nebolsin A.N., Nebolsina Z.P. , 2010; Yakushev V.P. at all, 2012).

A rate of ameliorants is induced by the following conditions:

degree of soil acidity - more acidic soils demand higher rates of ameliorants to change pH values to required levels;

soil texture class - salty and clay soils with high cation exchange capacity require higher rates of ameliorants than sandy soils;

level of soil organic matter content - soils enriched with organic matter have high absorption capacity to calcium and magnesium compounds,

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amount of precipitation - rain and melt water leach calcium and magnesium cations from soil exchange complex;
ameliorant type and its particle size.

Furthermore, it should be kept in mind that extreme rates of ameliorants may prevent a favorable growth of plants whereas an excess of lime prevents consumption of other essential nutrients by plant roots.

Hence, the problem of quantification of optimal rates of ameliorants is actual and still complex. Moreover, the process of soil acidity change occurs slower than plant growth and key metabolic processes in soils. Therefore, liming effects of ameliorants on soil acidity can last for several years and influence on the state of crops during several growing seasons. Another feature of this process is a presence of large spatial heterogeneity of soil physical properties that results in the spatial heterogeneity of soil acidity. The problem of rational control of soil acidity can be successfully solved on the basis of modern technologies and systems of precision agriculture using RS data as main source of information for decision-making.

The purpose of this paper is to solve soil acidity management tasks through the use of optimal control theory of stochastic dynamical systems in conjunction with the methodology of optimal estimation according to ERS.

II. MATERIALS AND METHODS

Materials and methods in the article are new and are published for the first time is presented.

There is no direct relation between soil hydrolytic acidity and spectral reflectance data, which are used in the RS methodology. Therefore the problem of estimating state of control object is complicated. An agricultural plot as the control object includes soils and crops. If among all soil limiting factors the soil acidity is dominant factor for crops, changes in that can lead to a significant decrease in crop yields even if other soil limiting factors are favorable.

Therefore there is an opportunity to apply two-step scheme of optimal estimation of soil acidity on the basis of RS data as shown in Figure 1. These steps are numbered. The two-step scheme is based on a combination of results of mathematical modeling and direct measurements of the dynamics of crop and soil state.

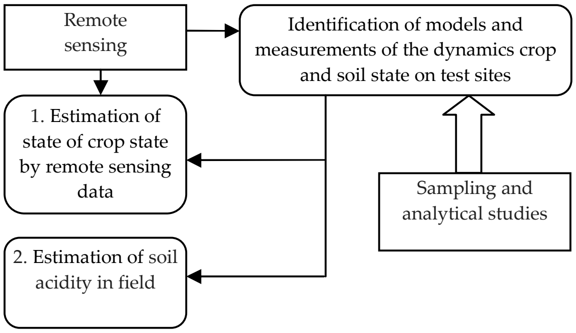

Fig.1 Block-diagram of estimation of crop state and soil acidity

Taking into account that the soil acidity is the dominant factor of decreasing crop yield under site-specific conditions, it is reasonable to predict the decrease in crop yield compared to its potential level for given conditions and *j*-th arable culture by:

$$\Delta u_j(k,T) = (U_j(F) - u_j(k,T)) = p_{1j}(k^* - k(T)) + p_{2j}(k^* - k(T))^2 + \xi_j(t),$$
$$U_j(F) = \mathrm{B}^{\mathrm{T}}\mathrm{F},$$
(1)

$\Delta u_j(k,T)$ – the value of reduction in crop yield in the *T*-th year as compared to its potential level *U(F)* for vector of existing conditions *F*, and optimal level of soil acidity k^*; B – the vector of model parameters of potential crop; *k(T)* – the soil acidity in the T-th year; $u(k,T)$ – the predicted crop yield in the T-th year; p_1, p_2 – the model parameters; $\xi_j(T)$ – the error of prediction, which is a random variable with mean zero and variance d_u; T – the index of the transposition of vectors and matrices.

Polynomial model of decrease in crop yield induced by increasing soil acidity (1) is being used for the given culture and the selected unit area, m^2 or hectares.

The value of crop yield, as an element of the structure of total plant biomass of a particular culture, is presented in the spectral reflectance pattern that is specified by model of measurements in two working optical bands, i.e. visible and near infrared spectrums.

$$\mathrm{W(P,X)} = \begin{bmatrix} p_{01} & p_{11}x_1 & p_{12}x_2 & p_{13}x_1^2 & p_{14}x_2^2 & p_{15}x_1^3 & p_{16}x_2^3 \\ p_{02} & p_{21}x_1 & p_{22}x_2 & p_{23}x_1^2 & p_{24}x_2^2 & p_{25}x_1^3 & p_{26}x_2^3 \end{bmatrix},$$
(2)

W(P,X) – the vector-valued function of spectral reflectance of crop; X – the crop state's vector which components are: x_1 – the average value of total plant biomass on an arable plot within a given area, x_2 – the average value of harvest yield on an arable plot within a given area, p_{01}–p_{26} – the model parameters.

A high inertia of the process of change in soil acidity demands from us to consider this process on annual time scale in order to distinguish it from many other dynamic yield-limiting soil factors, which are being studied on daily time scale. We can predict the losses of crop yield by model (1) on annual time scale and only in the case if we use a dynamic model of changes in soil acidity parameters:

$$k(T+1) = ak(T) + bd(T) + cw(T) + \zeta(T), \qquad (3)$$

$d(T)$ – the rate of ameliorant per unit area in *T*-th year; $w(T)$ – the mean monthly rainfall in *T*-th year; a, b, c – the parameters of model; $\zeta(T)$ – the error of modeling, which is a random variable with zero mean and variance d_k.

Estimation of model parameters (1), (2), (3) is being carried out on 8–10 test sites of 25–50 m^2 of area, which is used for growing the same crops and for application of the same management technology of crop planting as on main agricultural plot. The test sites differ in levels of technological impacts including different rates of ameliorants to reach different levels of soil acidity and different levels of total biomass and crop yield losses. Measurements of biomass weight and soil properties were carried out on the test sites twice a week. On the basis of these measurements and predicted values of soil and crop state by (1), (2), (3) models we quantified the required parameters of models. The algorithm of application of the model is shown on the diagram (Figure 1).

The procedure of identification of models on the test sites is performed once a year, at the end of the relevant *T*-th growing period. The unmanned aerial vehicle fulfils optical sensing of surface of the studied plots immediately before harvesting.

Based on the results of optical sensing, an electronic double layer map is formed. The map shows parameters of reflection of crop surface in selected optical bands, which are represented in the vector form:

$$\mathbf{Y}(z,h) \quad \begin{matrix} y_1(z,h) \\ y_2(z,h) \end{matrix} , \qquad (4)$$

z, *h* – the dimensional coordinates of surface of plot.

The first stage of evaluation is to solve the inverse information objective when the electronic map is built on RS data. The solution of the inverse information objective is applied to minimize the quadratic functional for the entire area vector electronic map. Formally this objective is written as follows:

$$I_1 \quad \overset{Z,H}{\underset{0}{}} \quad [\mathrm{Y}(z,h) \quad \mathrm{W}(\mathrm{P},\mathrm{X}(z,h))] \quad [\mathrm{Y}(z,h) \quad \mathrm{W}(\mathrm{P},\mathrm{X}(z,h))]dzdh \quad {}_{\mathrm{X}(z,h)} \quad \min$$

(5)

The solution of objective (5) leads to the development of a two-layer (vector) map of crop state $\mathrm{X}(z,h)$. We are mainly interested in a second component of the map – the estimate of crop yield for the whole area of plot $x_2(z,h)$.

The assessment of crop yield $x_2(z,h)$ serves as the basis for quantifying the soil acidity on a second stage of evaluation. Formally, this objective is to minimize the quadratic functional for the entire area of monolayer electronic map of *j*-harvest assessment of *j*-th culture. The objective is written as follows:

$$I_2 \quad \overset{Z,H}{\underset{0}{}} \quad [x_2(z,h) \quad (p_{1k}(k_j \quad k_j(z,h)) \quad p_{2k}(k_j \quad k_j(z,h))^2]^2 dzdh \quad {}_{k_j(z,h)} \quad \min$$

, (6)

The solution of objective (6) results in the development of soil acidity map $k_j(z,h)$, which is being used for developing the strategy of application of ameliorants.

We assumed that a crop rotation includes a sequence of crop denoted as indices *j* = 1,2,...N. In this case the objective of soil acidity control will be to minimize the yield losses of all crops in all rotations taking into account the lowest expenses for application of ameliorants. This objective is supported by the following criterion of optimality for average values of soil acidity and crop losses on the selected area of arable plots:

$$I \quad M\{\overset{N}{\underset{T \ 1}{}}[\frac{g}{N}(k \ (T) \quad k(t))^2 \quad c_u \quad u(k,T) \quad c_d d(T)]\} \quad {}_{D_1 \ d \ D_2} \quad \min$$

(7)

M – the mathematical expectation in the time domain; c_u, c_d – price per unit of crop yield and unit mass ameliorant; D_1, D_2 – the limits on the maximum and minimum value of application rates of ameliorants in the same year; g – the weighting factor, which is an optional internal (algorithmic) factor of optimization and is automatically selected in program of control in accordance with maximization of net income from liming.

In accordance with the generally accepted theory of optimal control (Kazakov I.E., 1987) we will take into consideration Hamiltonian for the model (4) and the criterion (7):

$$H = M[c_u \Delta u_j(k,T) - c_d d(T)] + \lambda(T+1)[ak(T-1) + bd(T) + cw(T)]$$

(8)

$\lambda(T) = \dfrac{\partial H}{\partial k(t)}$, $\lambda(N) = 2(k^* - k(N))$ – the conjugate variable of system and its end values for the last N-th culture of crop rotation.

Then the optimal strategy for annual application of ameliorant rates is being performed by the following sequence of operations:

$$d^*(T)_n = d^*(T)_{n-1} - \delta \frac{\partial H}{\partial d}(T)_n, \text{if } \ D_1 \quad d^*(T)_n \quad D_2;$$

$$\text{if } \ d^*(T)_n \le D_1, \ \text{ then } \ d^*(T)_n = 0;$$

$$\text{if } \ d^*(T)_n \le D_2, \ \text{ then } \ d^*(T)_n = D_2,$$

(9)

where n - is the index of sequence of operations.

Given the expressions for the models (1), (3), (4) the gradient of the Hamiltonian (8) and a model for the conjugate variable are as follows:

$$\lambda(T) = \frac{\partial H(T)}{\partial k} = [2g(k^*(T+1) - k(T+1)) + c_m(p_2(k^*(T+1) - k(T+1)) - p_1) + a\lambda(T+1)],$$

(11)

$l\,(N) \quad 0, \ T \quad (N,1).$

In accordance with the strategy $d^*(T)$ optimum rates of ameliorant being induced by type of crops and rate of rise of soil acidity may be maximally allowable or zero. Optimal strategies are specified on the basis of results of crop year to ensure their adaptation to actual conditions and to decrease the errors in calculation of optimal rates of ameliorant.

Thus, we have presented our general proof for calculation of annual rates of ameliorant in crop rotations. Annual rates of ameliorant are elements of the optimal strategy, which ensures the minimum of criterion of optimality. We have not yet answered an important question: how to take into account a spatial heterogeneity of soil acidity within a field? The technology and technique of precision agriculture can help us to answer the question.

Electronic cards of soil acidity allow to distinguish large homogeneous zones, *i* = 1,2,...I, significantly differing in the soil acidity (Yakushev V.P. at all, 2007). In accordance with the methodology of precision agriculture we need to develop the strategy of ameliorant application for each of the homogeneous areas that provides an initial basis for the calculation of application rates of ameliorant in the homogeneous areas, while maintaining the overall balance of application of ameliorant:

$$S \cdot d^*(T) = \sum_{1}^{I} S_{\Omega_i} \cdot d_{\Omega_i}(T), \qquad (12)$$

S, *Si* – the total area of agricultural plot and the area of homogeneous zones.

Based on the balance (12), setting of agricultural machinery for incorporation of ameliorant in a process of its moving across the field is being performed:

$$g(y,T) = \sum_{i=1}^{M} \frac{l_i}{L} d_{\Omega_i}(T), \qquad (13)$$

g(*y*,*T*) – the specific discharge, per unit of length of machinery running; *M* – the number of homogeneous zones with different application rates in a width of capture of machinery; l_i – the width of homogeneous zone in the width of capture of machinery; *L* – the total width of machinery.

To calculate the application rates ameliorant for homogeneous areas, the same algorithm (8)–(11) is being used, with the only difference that the values of soil acidity are put into the criterions of optimality separately for each area.

III. RESULTS

Interval of control is chosen one crop rotations. In this model of soil acidity's dynamics (2) precipitation is assumed to be equal to mean annual values.

Figure2 shows the results of identification of mathematical model for predicting the losses of perennial grass yield caused by increasing soil acidity. The minimum point on this graph corresponds to the optimum pH value for the parameter of the culture (pH = 5,4).

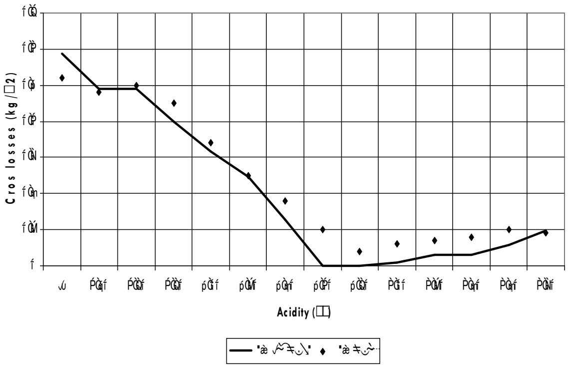

Fig. 2. Results of identification of the model harvest losses on the index of acidity salt for perennial grasses.

Similar models are developed for other crops of rotation. The models differ in their parameters and optimal values of soil acidity, which maintain minimum losses of crop yield. Figure3 shows the results of identification of mathematical model for predicting soil acidity dynamics. The model is developed on the basis of data on retrospective monitoring of soil conditions. Here rises the acid value in years making improver. Identification error (simulation) does not exceed 10%, which meets the requirements of the soil acidity management tasks.

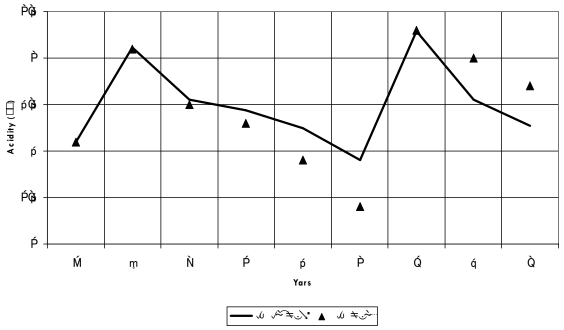

Fig. 3. The results of the identification of models of dynamics of saline soil acidity by year crop rotation.

Figure4 shows the optimal strategy for application of ameliorant taking into account the following initial data: price of ameliorant 8000 rubles/t, the price of production of crop rotation: potato – 20 rubles/kg; perennial grasses – 4.0 rubles/kg, vegetables (beet) – 21 rubles/kg winter rye – 8.5 rubles/kg; spring wheat – 12 rubles/kg.

Besides, we developed optimal strategies for incorporation of ameliorant at lower and higher values of initial soil acidity. At the lower values of soil acidity the rates of ameliorants were decreased for the first two years and were passed for the fourth year. In contrast, at the higher values of soil acidity, we increased application rates of ameliorant for the first two years and fourth year, with little change in application rates of ameliorant during other 6 years of whole control interval.

We also studied the effect of changes in the extent of limitation of ameliorant's application rate to calculate its minimum value. An increase in the extent of the limitation caused a formation of additional gaps in timing of ameliorant application that led to large deviations of soil acidity values from their optimum level for some crops (see Figure 5). A decrease in the extent of the limitation of ameliorant's application rate resulted in splitting applications of ameliorant and reducing the deviations of soil acid values from their optimal values for crops.

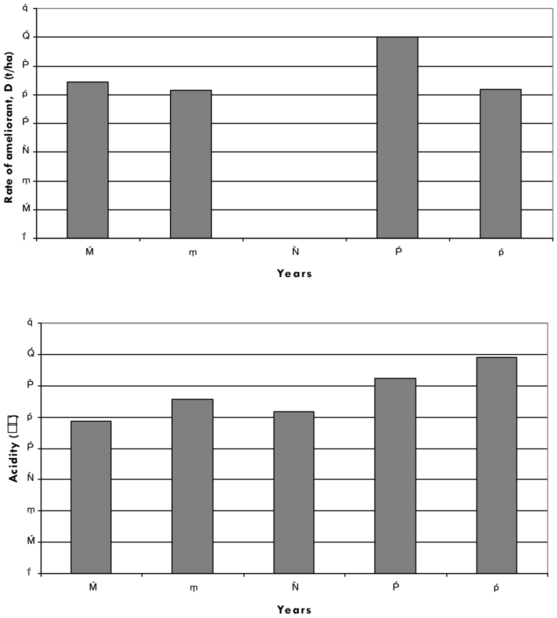

Fig.4. The optimal strategy aameliorant making by year crop rotation and forecast the dynamics of saline soil acidity for the strategy for limiting the minimum dose of 3 t / ha, and the initial value of soil acidity 4.0. The value of the optimality criterion I = 0,08, profit from liming P = 23,2 rub. / m^2 per year.

Our study of role of ameliorant's prices showed that they: (i) had a little influence on the parameters of the strategy of ameliorant application, but (ii) were more clearly reflected in the net income from the effect of reducing soil acidity.

As it is stated above, in real time the only first year of current crop rotation is implemented in the optimal strategy of soil acidity control. During the other years of crop rotation the remaining data is purely forward-looking information, which we can use for buying harvesting-relevant amounts of ameliorants and for preparation of machinery for their incorporation.

Figure 6 shows the homogeneous parts of agricultural plots with initial values of soil acidity. The initial values of soil acidity are derived from electronic cards of distribution of yield's perennial grasses using solution of inverse information objective (6). Here on crop loss estimates were determined values of the index of acidity, which corresponded to the greatness of these losses.

For these initial values of soil acidity we developed optimal strategies of ameliorant application for each zone. Figure7 shows the rates of ameliorant application for the first year of crop rotation to be implemented in real time. Such an implementation is presented in Figures 8 and 9. The width of capture of machinery is equal to a half of width of the plot (two passes of machinery) and a quarter of width of the plot (four passes of machinery). The Figures 8 and 9 show the discharge of ameliorant while machinery is moving on the plot. The discharge of ameliorant occurs through a dispenser controlled by on-board computer.

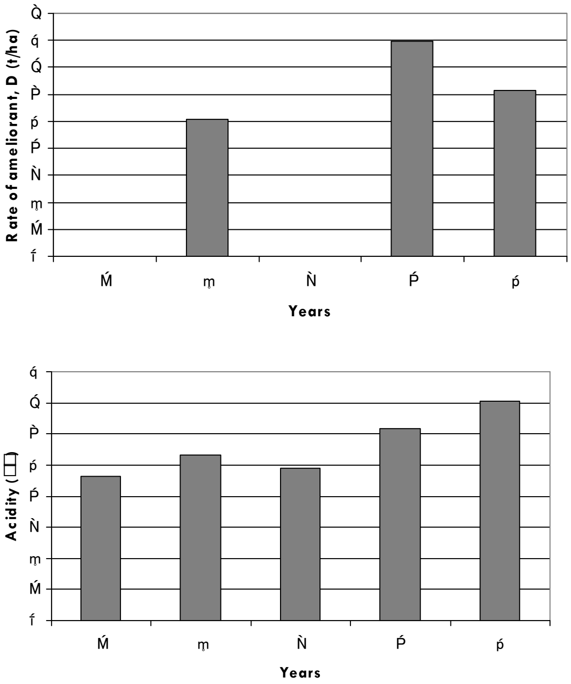

Fig.5. The optimal strategy making improver by year crop rotation and forecast the dynamics of saline soil acidity for the strategy for limiting the minimum dose of 5 t / ha, and the initial value of soil acidity 5.0. The value of the optimality criterion I = 0,11, profit from liming P = 23.0 rubles. / m^2 per year.

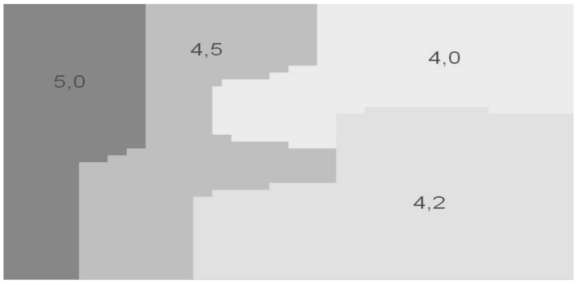

Fig.6. The initial value of the indicator estimates the urinary acidity (pH) in homogeneous areas of the field.

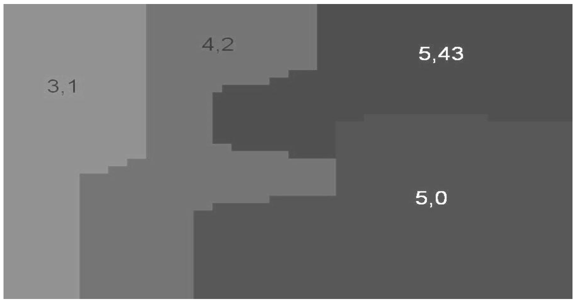

Fig.7. Optimal application rates ameliorant in homogeneous areas of the field, t ha-

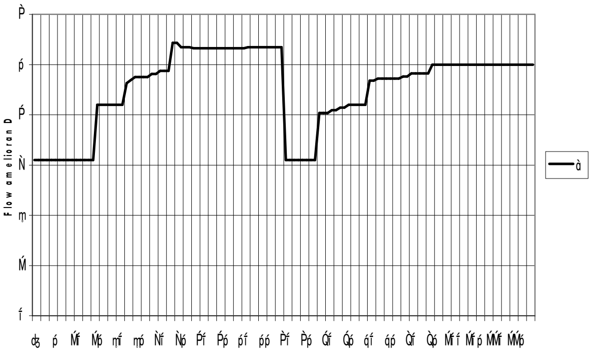

Fig.8. Schedule changes in consumption when driving on the car to make the field ameliorant with two aisles, t/ha.

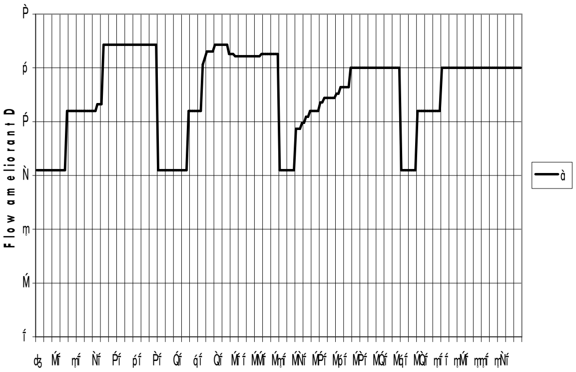

Fig.9. Schedule changes in consumption when driving on the car to make the field ameliorant with four aisles, t/ha.

CONCLUSIONS

This paper presented the theory of soil acidity control, which includes mathematical model of the optical quantification of crop state from remote sensing data.

To solve the objective of soil acidity control, we used (1) the model for predicting crop yield losses caused by deviations of soil acidity from its optimum pH values for individual crops, and (2) the dynamic model for predicting soil acidity. The objective is solved by the optimality criterion which is considered as average risk of losses of crop yield and expenses on liming. On the basis of this theory the software and hardware complex was developed to create (i) optimal strategies of ameliorant application for several years of crop rotations, and (ii) algorithm of ameliorant application for the first year of crop rotation in homogeneous areas of agricultural plots. Parameters of optimal strategies of ameliorant application mainly depended on: initial values of soil acidity in homogeneous areas and selected limitations on minimum and maximum rates of ameliorant. The parameters of optimal strategies of ameliorant application showed a weak dependence on ameliorant price.

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