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MODELING

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# Dynamics of Microbial Population in the Framework of a Model of Nitrogen Transformation in Soil<sup>1</sup>

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**Abstract**—A model of the population dynamics of ammonifiers is proposed. It is shown that the rate of ammonification doesn't depend on the C:N ratio in the microbial biomass. It also follows from theoretical constructions that the biomass (or abundance) of ammonifying bacteria in soil should be proportional to the humus content.

**Keywords:** dynamic model, ammonification, microbial biomass.

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Dynamic models of the production process which include a description of the dynamics of nitrogen compounds in soil and plant, according to the terminology of de Witt and Penning de Vries [1], belong to models of the third level of productivity. The considerable interest in this subject is indicated by the large number of publications in the world agrochemical literature. For example, soil physicochemical processes with the participation of nitrogen-containing compounds are examined in detail in [2]; however, the author limited himself to a formal description of the problem, not having presented its algorithmic solution or even a computer realization of the model. The results of developing computer models of nitrogen dynamics given in [3–6] deserve special attention. These models are adapted to the soil and climatic conditions of West European countries and the United States, and substantial reprogramming of them or individual units is required for use under conditions of our country.

A computer model of nitrogen dynamics in the soil root zone was developed at the Agrophysical Institute (AFI) [7]. It was tested on experimental material of a seven-course crop rotation and a satisfactory correspondence of the calculated and practical indices was obtained. However, as experience of its operation showed, the structure of the model has a significant shortcoming. In it there is practically no module of the population dynamics of soil microorganisms, and the activity of soil microflora is taken into account indirectly by certain coefficients. This simplification disturbs the integrity of the model constructions. An improved version of the nitrogen cycle, in which a

module describing the dynamics of the microbial biomass is included as an equal-rights component, will be described below.

## METHOD

It is known that microbiological processes are important for transforming potential soil fertility into effective [8]. Many macro- and microelements participate in the humus transformation process, but the main role is played by carbon and nitrogen. The course of the ammonification process is related precisely with the ratio of carbon and nitrogen (C:N) both in humus and in cells of microorganisms.

We will examine this matter in greater detail. Ammonification requires the expenditure of energy. Therefore, only part of carbon is used for constructing the biomass of microorganisms, the other part is expended during respiration. This phenomenon is usually related to the "utilization coefficient." We will denote it by  $\rho$  ( $\rho \approx 0.5-0.6$ ) and the C : N ratio as  $R_{\Gamma}$  for humus and  $R_{mb}$  for microbial biomass (these quantities are substantially different). We will examine the following possible situations. Though this is unlikely, let the following equality be fulfilled:

$$\rho R_{\Gamma} = R_{mb}.$$

Then all nitrogen being produced during mineralization of humus is taken up into the tissue of microorganisms, and the output of mineral nitrogen is equal to zero.

Under the condition:

$$\rho R_{\Gamma} > R_{mb},$$

a part of nitrogen from the mineral pool is taken up into the microbial biomass, i.e., the process of immo-

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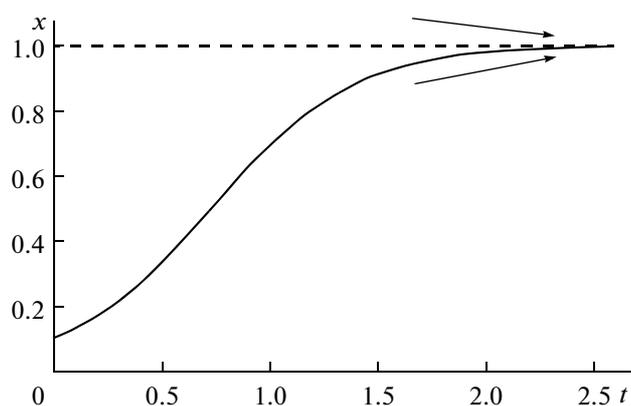


Fig. 1. Logistic curve.

bilization occurs. Thus, instead of an increase of the mineral nitrogen content in soil, its decrease occurs. This contradiction doesn't find an explanation in the agrochemical literature [8]. The present model was constructed precisely for its elimination.

We make the natural assumption that the relative growth rate of the microbial population  $V_g$  in a certain volume of soil is proportional to the humus content in this volume:

$$V_g = \frac{1}{M_b} \frac{dM_b}{dt} = \alpha \Gamma, \quad (1)$$

where  $M_b$  is the biomass of the microbial population, carbon units;  $\Gamma$  is the humus content;  $\alpha$  is a growth parameter;  $t$  is time. Then for the dynamics of the change in biomass of microorganisms we can write a relation—the balance between the accumulation and mortality of microorganisms:

$$\frac{dM_b}{dt} = \alpha \Gamma M_b \left( 1 - \beta \frac{M_b}{\Gamma} \right), \quad (2)$$

where the coefficient  $\beta$  characterizes the mortality of microorganisms caused by competition for food.

Equation (2) with an accuracy to the notations coincides with the Verhulst logistic equation [8]:

$$\frac{dx}{dt} = rx \left( 1 - \frac{x}{k} \right).$$

If we treat it as an equation describing the dynamics of the abundance or biomass of the biological population under conditions of limited resources, then coefficient  $r$  should be taken as the relative (or logarithmic) population growth rate:

$$\frac{1}{x} \frac{dx}{dt} = \frac{d \ln x}{dt} = r,$$

and  $k$  as the capacity of the environment (i.e., the maximum possible population size). The solution of the logistic equation has the form (Fig. 1):

$$x(t) = \frac{kx_0 \exp(rt)}{k + x_0(\exp(rt) - 1)},$$

where  $x_0$  is the initial condition ( $x_0 > 0$ ).

The Verhulst equation has two singular points—equilibrium positions:

$$x = 0 \quad \text{and} \quad x = k,$$

the first of them being unstable and the second, stable. This means that, with any deviations of the path of the system from the value  $x = k$ , it approaches this value asymptotically (Fig. 1).

Thus, with the course of time the path of the system approaches a stable position proportional to the humus content:

$$M_b(t \rightarrow \infty) = \Gamma/\beta, \quad (3)$$

and with a change in soil conditions fluctuates near this equilibrium position (Fig. 1).

We'll examine five soil nitrogen sources: mineral nitrogen enters soil as a result of decomposition of humus and organic residues, nitrogen fixation, death of microbial biomass, from fertilizers and the atmosphere. All these sources are taken into account in the nitrogen cycle model including in the AGROTOOL modeling system [7]. We'll characterize such source as ammonification. The rate of intake of mineral nitrogen (ammonia)  $N_a$  into soil can be described as

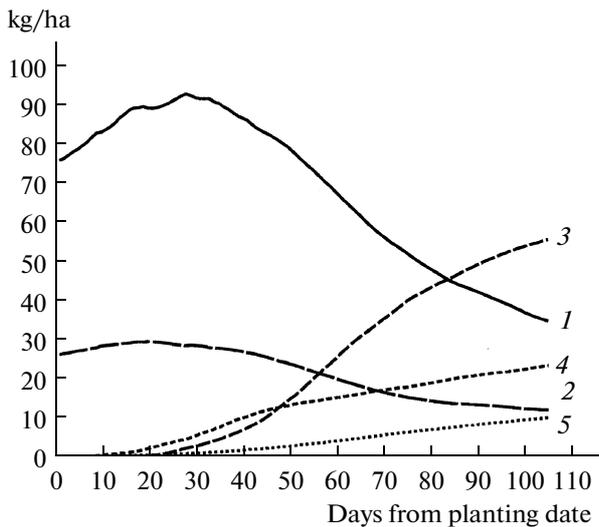
$$\frac{dN_a}{dt} = \frac{1}{R_\Gamma} V_g M_b - \frac{1}{R_{mb}} \frac{dM_b}{dt}. \quad (4)$$

Precisely this equation with the inclusion of certain additional terms in it is used for program realization of the new version of the model.

## RESULTS AND DISCUSSION

In Eq. (4) the first term on the right in accordance with (1) is always positive. The second term (subtrahend) will be positive during growth of the microbial population and negative during its dying off. In this case, the result in the right side as a whole can become negative. This is immobilization, when the mineral component of nitrogen decreases as soil organics decompose. But this process can only be brief because due to dying of the microbial biomass the subtrahend becomes negative and all immobilized nitrogen again enters the soil. The mechanism operates so that immobilized nitrogen is temporarily removed from the mineral pool, but is then returned to it in the same amount. And under quasi-equilibrium conditions, the second term in relation (4) is practically equal to zero.

The described model of the dynamics of a microbial population with certain improvements (consideration of soil moisture and temperature stress effects) was included in the comprehensive model of the nitrogen cycle in the soil root zone [7]. This latest model was identified on the basis of data of a multiyear field

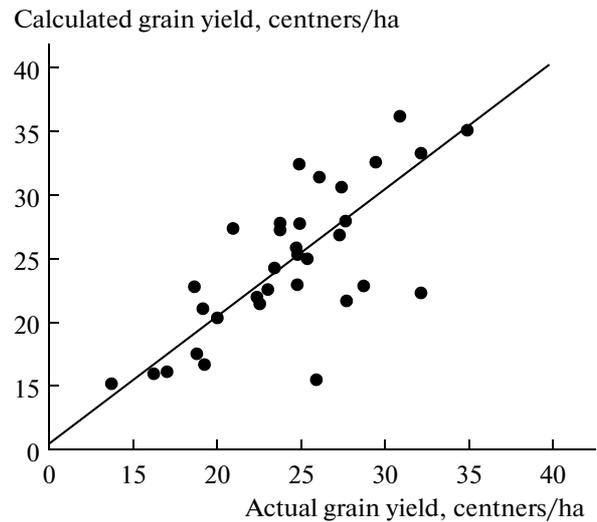


**Fig. 2.** Dynamics of nitrogen compounds (kg/ha) in 0–100 m soil layer: (1) mineral, (2) ammonium, (3) absorbed by plant root system, (4) losses due to denitrification, (5) washed out beyond the meter layer.

experiment at AFI's Men'kovo Experiment Station (50°25'22"N, 30°01'55"E) carried out according to a seven-course crop rotation design of the cereal–row crop type (first-year perennial grasses, second-year perennial grasses, potato, spring barley, occupied fallow, winter rye, annual grasses with undersowing of perennial grasses). Spring barley, spring rye, and potato were selected for parametric identification of the model. As an example, Fig. 2 shows calculated curves of the dynamics of various nitrogen forms in soil under a spring barley crop during the 2004 growing season at a nitrogen fertilizer level of 45 kg primary nutrients/ha. Figure 3 gives the results of a comparative analysis of calculated and experimental data on barley yield during 1983–1989 and 2006–2010 with three doses of nitrogen fertilizers,  $N_0$ ,  $N_{45}$ , and  $N_{90}$ .

Thus, it follows from relationship (4) that the value of C:N in the microbial biomass has almost no effect on the ammonification process rate, and in old arable lands the content of microbial biomass (or abundance of microorganisms) in soil is proportional to the organic carbon (humus) content with a certain constant factor of proportionality. It need be noted that immobilization in a pure form is found only in transient processes, when organic fertilizers with a broad C:N ratio, for example, straw, are added to the soil. However, on reaching an equilibrium regime, immobilization is compensated by the mineralization process. All this pertains not only to humus but also to any organic substrate ending up in soil: plant residues, organic fertilizers.

SPELL: 1. Witt, 2. Vries, 3. agrochemical



**Fig. 3.** Comparative data on calculated (modeled) and experimental values of barley yield.

## REFERENCES

1. Penning de Vries, F.W.T., Jensen, D.M., ten Berge, H.F.M., and Baketa, A.H., *Simulation of Ecophysiological Processes of Growth of Several Annual Crops*, Wageningen: Pudoc, 1989.
2. Nikolaenko, A.N., Mathematical Description of Physicochemical Processes of the Nitrogen Complex of Soils, *Dokl. Rossel'khozakademii*, 2002, no. 2, pp. 38–41.
3. Franko, U., Oelschlagel, B., Schenk, S., Simulation of temperature-, water- and nitrogen dynamics using the model CANDY, *Ecol. Modelling*, 1995, vol. 81, pp. 213–222.
4. Johnsson, H., Bergstrum, L., and Jansson, P.-E., Simulated Nitrogen Dynamics and Losses in Layered Agricultural Soil, *Agr. Ecosyst. Environ.*, 1987, vol. 18, pp. 333–356.
5. Ma, L., Malone, R.W., Jaynes, D.B., and Ahuja, L.R., Simulated Effects of Nitrogen Management and Soil Microbes on Soil Nitrogen Balance and Crop Production, *Soil Sci. Soc. am. J.*, 2007, vol. 72, pp. 1394–1603.
6. Poluektov, R.A. and Terleev, V.V., Computer Model of Nitrogen Dynamics in the Soil Root Zone, *Agrokimiya*, 2101, no. 10, pp. 68–74.
7. Tuv, N.A., *Mikrobiologicheskie protsessy gumusobrazovaniya* (Microbiological Processes of Humification), Moscow: Agropromizdat, 1989.
8. Verhulst, P.F., Notice sur la loi que la population suit dans son accroissement, *Corr. Math. Phys.*, 1838, vol. 10, pp. 113–121.