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ROMUL — a model of forest soil organic matter dynamics as a substantial tool for forest ecosystem modeling

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Abstract

This paper discusses a model of forest soil organic matter based on the concept of succession stages of soil organic matter decomposition marked by different groups of soil fauna inherent to forest soils in contrast to well-mixed agricultural soils with microbiology kinetics. This model allows the calculation of the dynamics of soil organic matter and the corresponding dynamics of nitrogen, including the evaluation of the amount of mineral nitrogen which is available for plants. The input parameters are the amount and quality of litter input, climatic data and initial amounts of soil organic matter and corresponding nitrogen. The litter may be split into different cohorts which are characterised by different ash and nitrogen contents and location on/in a soil as above-ground and below-ground litter cohorts. A specially developed simulator of soil climate is also described. A comparison was made with a previous, more restricted version of this model. The origin of the differences is discussed in detail. Examples of simulation scenarios show a wide range of possible applications for the model as a separate unit of models for forest ecosystems dynamics. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Soil organic matter; Humus types; Succession; Soil nitrogen; Soil climate generator; Simulation scenarios

1. Introduction

The modeling of soil organic matter (SOM) dynamics plays a crucial role in terrestrial ecosystem simulation because of the great importance of the soil processes of organic matter accumulation and decomposition for the nutrient supply, ecosystem stability and carbon balance in terrestrial ecosystems. At the same time, this modeling is important to the study of theoretical soil science, which allows one to understand the main functional patterns of soil systems. The SOM modeling began last century, but it actually began with the seminal paper by Jenny et al. (1949), in which the negative exponential function of the decomposition of soil organic matter was pro-

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posed. Later, a similar simple model was developed by Olson (1963). Nowadays, the SOM modeling is developed through agroecosystem simulations and, additionally, through comparisons of the recent models (Powlson et al., 1996; Smith et al., 1997; Chertov et al., 1999).

It should be pointed out that the existing SOM models of agroecosystems are mostly based on field observations on the measured organic debris input (as crop residues and organic manure) and the corresponding SOM dynamics in fluctuating environmental conditions. These models, therefore, reflect the existing agropedological field data on the rate of soil processes, only. The models based on laboratory microcosm experiments on organic matter transformation in controlled conditions reflect the rate of the SOM transformation as 'rectified' processes without any deviations related to the environmental variations and possible weaknesses in the measured variables and parameters. Therefore, such models can help to point out some gaps in the authors' knowledge on soil and the functioning of the corresponding ecosystem, such as the role of fine root litter in the SOM dynamics, which can be important in the humus accumulation. The models constructed by data from the microcosm study of the SOM transformations are considered as more advantageous when exploring the soil system behavior from the points of view of carbon budget and turnover.

Another specific feature of the majority of recent SOM models is the consideration of the functional activity of soil microorganisms by determining their biomass as separate pools only, without making a division between fungi, actinomicetes and bacteria. However, the definition of biomass is based on indirect methods, which do not seem to be very precise. On the other hand, a microbiological concept of the SOM transformation is incomplete because of the great role of soil fauna in this process, as well as the existence of functional groups (communities) of destructors consisting of organisms of different taxonomic status. One feels certain that a definition of the integral rate of processes in the SOM mineralisation, with a quantification of the role of different groups of organisms-destructors, but without a consideration of the biomass of organisms (being less 1% of decomposing material), is a more reliable approach than a calculation of microbial biomass and its functional activity.

It should be stressed that a common approach to the simulation of the SOM dynamics is based on a generalisation of the SOM pool as a well-mixed substrate, the model dynamics of which may be described in terms of chemical kinetics. In the case of agro-ecosystems, this seems to be true because the most intensive processes of destruction are located in the upper, regularly destroyed, soil layer. One specific feature of forest soils is the natural succession dynamics of destructors on litter cohorts. In forest soils, the stages of decomposition of fresh litter can be distinguished, which is partially reflected in the morphological structure of the soil profile. It allows one to describe the general process of the forest SOM decomposition as a sequence of succession stages with specific tasks for different groups of soil biota in the destruction processes.

The previous model, SOMM (Chertov and Komarov, 1996, 1997), based on earlier simulation of forest floor mineralisation and humification (Chertov, 1985), has been developed using the classic pedological concept of the 'humus types'. This model has one pool of litter fall and three of SOM: undecomposed litter, partly humified organic material (forest floor and peat), and humus bonded with the mineral matrix of the top soil. There are three processes of SOM humification by three communities of organisms-destructors, and three processes of mineralisation. This model represents a system of ordinary differential equations with coefficients that depend on the soil temperature and moisture, litter nitrogen and ash content, and on the C/N ratio in the mineral topsoil. The dependencies of the coefficients on the above variables are taken from experimental data on litter decomposition in controlled conditions. This model also considers nitrogen transformation and release.

A comparison of the SOMM model with other models (Chertov et al., 1997; Smith et al., 1997) has shown that it simulates the SOM dynamics quite satisfactorily, but that it should be extended in relation to a more detailed consideration of the litter input (leaf and root litter) and the soil properties (clay and humus content) influencing the mineralisation and humification. These problems have been solved and a new version ROMUL (model of Raw humus, mOder and MULl) has been compiled. Additionally, a climate generator has been developed for the new model (Bykhovets and Komarov, in press) in order to convert standard meteorological data (air temperature and precipitation) to forest soil temperature and moisture. The generator also uses soil hydrological parameters affecting the soil moisture and, correspondingly, the rate of the SOM transformation. The objectives of this article are hence to describe this new model of the SOM dynamics, ROMUL, and to present the results obtained from testing it in comparison with the SOMM model, as well as to provide an example of its application in Forest Management operations.

2. A description of the model

2.1. The main assumptions and the general system of equations

Firstly, one would like to reiterate the main assumptions of the SOMM model (Chertov and Komarov, 1995, 1997), which take into consideration the new improvements concerned with a more detailed description of the main variables and parameters. The theoretical basis of this approach as a consequence of communities of organisms-destructors in the process of formation of various humus types (‘mor’, ‘moder’ and ‘mull’) has been described in detail in previous work (Chertov and Komarov, 1997).

A model of the formation and functioning of raw humus (Chertov, 1985, 1990) has been used as the basis of SOMM. This basic model takes into account: (i) the litter fall mineralisation and humification; (ii) the humified litter (forest floor) mineralisation; and (iii) nutrient release due to these processes.

The idea of a complex of humic substances with undecomposed plant debris (CHS) was proposed to make the model efficient. This complex is responsible for the ‘phase of slow decomposition’ in plant debris, which still contains a lot of easily mineralisable substances. It takes place because CHS, being impregnated with humic acids, is transforming with the rate of ‘true humus’. This idea gives new explanation to the ‘soil protective effect’ (VanVeen and Paul, 1981), which has previously been attributed to the lignin content in organic debris. It corresponds to a fraction of the humified organic layer in the forest floor and peat, and to ‘labile (active) SOM’ in the mineral topsoil.

The main features of the ROMUL model (Fig. 1) are as follows:

1. The main assumption is that there is a correlated successional change of complexes of organisms-destructors in the process of SOM decomposition corresponding to the concepts of ‘raw humus’, ‘moder’ and ‘mull’ existing in forest pedology (Wilde, 1958; Duchaufour, 1961).

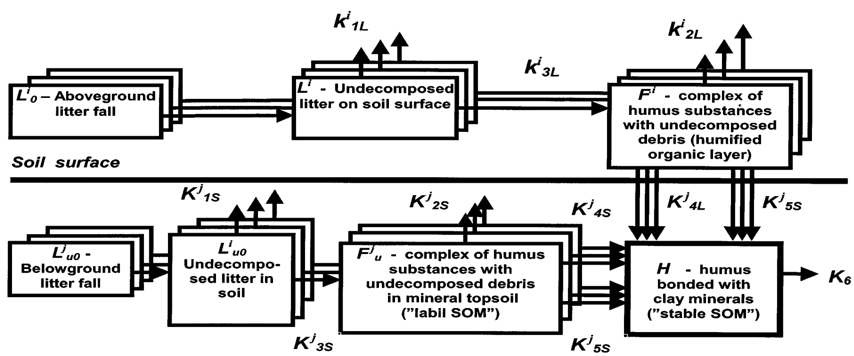

Fig. 1. Flow-chart of ROMUL model.

2. The biomass of soil organisms represents a negligible part of all decomposed matter and has a high rate of decomposition; it is not taken it into consideration as a separate pool.
3. The number and species composition of decomposing organisms are dependent on the biochemical properties of the organic debris, hydrological and thermal conditions. It was postulated that there are no barriers for a rapid invasion of new organisms. Thus, it is possible to calculate the decomposition coefficients for the communities as a function of the biochemical properties of litter, temperature and moisture. The time of soil biota activation after stresses (drought, frost) is not taken into account. As a difference to SOMM the organic debris was divided into two main groups: above-ground litter coming on the soil surface in certain conditions of litter temperature and moisture, and below-ground litter consisting of root debris and decomposition depending on the soil temperature and moisture. ROMUL, unlike SOMM, has the possibility to take into consideration the above-ground and below-ground cohorts of litter differing by its chemical properties. The number of cohorts is not restricted.
4. The rate of the nutrients release due to mineralisation corresponds to the rate of the organic matter mineralisation. The only exception is the nitrogen kinetics in the organic layers (forest floor and peat), presumably. Because of its high rate of consumption by soil micro-organisms, the gross rate of nitrogen mineralisation is sufficiently lower than the same of carbon in the organic layers. In mineral horizons the rate of nitrogen release corresponds to the rate of carbon mineralisation when C/N ratio < 8 only (Alexandrova, 1970). The dynamics of nitrogen have been described by Chertov and Komarov (1995) and could be evaluated in ROMUL, including the evaluation of the nitrogen available for plants (Chertov et al., 1999a,b). The corresponding equations will be described in detail.
5. It was postulated that the community of *Bacteria* and *Arthtropoda* produces humus with a C/N ratio 15, and the community of *Lumbricidae* forms humus with a C/N ratio 8. These complexes of organisms spend 20% of the CHS nitrogen on their biomass, and 80% of nitrogen goes to humus formation. These considerations have been used for the calculations of the humification rate. The nutrients of the consuming matter are fully mineralised and available for plants for 1 year because of the short ontogenesis of *Arthtropoda* and *Lumbricidae*. To obtain the values for these parameters for soil *Arthropoda* and *Oligohaeta* activity, data on litter production was used in the temperate forests of the East European plain transforming by these groups annually (Goryshina, 1974), information on soil fauna biomass and their turnover (Chernova et al., 1975; Striganova et al., 1987; Dindal, 1990; Edwards and Bohlen, 1996) and the proportion of nitrogen assimilated by the soil fauna from the litter was calculated. For example, taking into account that earthworms consume all annual litter (3–4.7 ton ha^{-1} with C/N ratio 20) for the vegetation period and produce maximally 0.2 t of faunal biomass with a C/N ratio of about 7, a proportion of assimilated nitrogen of 15–23% was obtained.
6. It was assumed that nitrogen and elements being released due to mineralisation have been fully consumed by plants. If excessive nitrogen remains, then it is immobilised into the soil.
7. The leaching and diffusion of the soil organic matter and the input of nitrogen from the atmosphere, nitrogen fixation and denitrification are not taken into account in the ROMUL basic module, but the ways of accounting for these may be fully considered in the ecosystem model, when the nitrogen balance is calculated in the ecosystem.

Corresponding with these postulates, the kinetics of organic litter and humus transformation in the soil can be expressed by a system of linear differential equations of the first order with variable coefficients. The same system of equations has been written for nitrogen and other elements in the soil organic matter. The equations for phosphorus, potassium, calcium and magnesium are the same as for the total organic matter. The equations for nitrogen, being a principal limiting factor of plant nutrition in forest ecosystems, have some additional kinetic parameters, reflecting nitrogen retention in the soil system (Chertov, 1985, 1990). One distinguishes between above-ground (leaves/needles, branches etc.) and below-ground (the root system with its compartments) litter cohorts. The system of equations for the above mentioned two groups of the soil organic matter, nitrogen and their components is as follows:

$$
\begin{aligned}
\mathrm{d}L^i/\mathrm{d}t &= L_0^i - (k_{1\mathrm{L}}^i + k_{3\mathrm{L}}^i)L^i,\\
\mathrm{d}N_{\mathrm{L}}^i/\mathrm{d}t &= N_{\mathrm{L0}}^i - (k_{1\mathrm{L}}^i M_{\mathrm{L}}^i + k_{3\mathrm{L}}^i)N_{\mathrm{L}}^i,\\
\mathrm{d}L_{\mathrm{u}}^j/\mathrm{d}t &= L_{\mathrm{u0}}^j - (k_{1\mathrm{S}}^j + k_{3\mathrm{S}}^j)L_{\mathrm{u}}^j,\\
\mathrm{d}N_{\mathrm{Lu}}^j/\mathrm{d}t &= N_{\mathrm{Lu0}}^j - (k_{1\mathrm{S}}^j M_{\mathrm{L}}^j + k_{3\mathrm{S}}^j)N_{\mathrm{Lu}}^j,\\
\mathrm{d}F^i/\mathrm{d}t &= k_{3\mathrm{L}}^i L^i - (k_{2\mathrm{L}}^i + k_{4\mathrm{L}}^i + k_{5\mathrm{S}}^i)F^i,\\
\mathrm{d}N_{\mathrm{F}}^i/\mathrm{d}t &= k_{3\mathrm{L}}^i N_{\mathrm{L}}^i\\
&\quad - (k_{2\mathrm{L}}^i M_{\mathrm{F}}^i(F^i, N_{\mathrm{F}}^i) + k_{4\mathrm{L}}^i + k_{5\mathrm{S}}^i)N_{\mathrm{F}}^i,\\
\mathrm{d}F_{\mathrm{u}}^j/\mathrm{d}t &= k_{3\mathrm{S}}^j L_{\mathrm{u}}^j - (k_{2\mathrm{S}}^j(H) + k_{4\mathrm{S}}^j + k_{5\mathrm{S}}^j)F_{\mathrm{u}}^j,\\
\mathrm{d}N_{\mathrm{Fu}}^j/\mathrm{d}t &= k_{3\mathrm{S}}^j N_{\mathrm{Lu}}^j\\
&\quad - (k_{2\mathrm{S}}^j(H) M_{\mathrm{Fu}}^j(F_{\mathrm{u}}^j, N_{\mathrm{Fu}}^j) + k_{4\mathrm{S}}^j + k_{5\mathrm{S}}^j)\\
&\quad N_{\mathrm{Fu}}^j,\\
\mathrm{d}H/\mathrm{d}t &= \delta_{Bact}(\Sigma^m k_{4\mathrm{L}}^i N_{\mathrm{F}}^i + \Sigma^n k_{4\mathrm{S}}^j N_{\mathrm{Fu}}^j)\\
&\quad + \delta_{Lumb}(\Sigma^m k_{5\mathrm{S}}^i N_{\mathrm{F}}^i + \Sigma^n k_{5\mathrm{S}}^j N_{\mathrm{Fu}}^j) - k_6 H,\\
\mathrm{d}N_{\mathrm{H}}/\mathrm{d}t &= \gamma(\Sigma^m(k_{4\mathrm{L}}^i + k_{5\mathrm{S}}^i)N_{\mathrm{F}}^i + \Sigma^n(k_{4\mathrm{S}}^j + k_{5\mathrm{S}}^j)N_{\mathrm{Fu}}^j)\\
&\quad - k_6 M_{\mathrm{H}}(H, N_{\mathrm{H}})N_{\mathrm{H}}, \qquad (1)
\end{aligned}
$$

where superscript i denotes the i-th cohort of above-ground litter, j denotes the cohort of below-ground litter, n and m are the corresponding numbers of the cohorts, further on, superscript indexes are omitted in the text but in each case the description concerns a separate litter cohort; L_0 and N_{L0} are the inputs of L and N_{L} on soil; L_{u0} and N_{Lu0} are the inputs of below-ground litter and its nitrogen, L and N_{L} are undecomposed above-ground litter and the corresponding litter nitrogen contents; L_{u} and N_{Lu} are undecomposed below-ground litter cohorts and the corresponding litter nitrogen contents. F and N_{F} are CHS originating from above-ground litter cohorts and its corresponding nitrogen contents, F_{u} and N_{Fu} are CHS and its nitrogen contents of below-ground litter cohorts. H and N_{H} are fully humified material (humus) and its nitrogen content in soil. It should be noted that there are different and independent forms of decomposition for above- and below-ground litter cohorts for the first two stages of litter transformation and one united pool of humus bonded with the mineral topsoil. Coefficients δ_{Bact}, δ_{Lumb} and γ reflect the relations between the spending of nitrogen to the destructors' biomass and humus formation. The dimensions of L, L_{u}, F, F_{u}, H, N_{L}, N_{Lu}, N_{F}, N_{Fu} and N_{H} are (kg m^{-2}), k_i, (day^{-1}).

The coefficient $k_{1\mathrm{L}}$ is the rate of above-ground litter mineralisation by a complex of soil destructors consisting of *Fungi* and *Acarina*; $k_{1\mathrm{S}}$ is the corresponding rate of below-ground litter mineralisation by this complex; $k_{2\mathrm{L}}$ and $k_{2\mathrm{S}}$ are the rates of mineralisation of above- and below-ground CHS, correspondingly; $k_{3\mathrm{L}}$ and $k_{3\mathrm{S}}$ are the rates of litter transformation to CHS as a process of organic debris humification; $k_{4\mathrm{L}}$ and $k_{4\mathrm{S}}$ are the rates of CHS (originated from above- and below-ground cohorts correspondingly) consumption by a community of *Bacteria* + *Arthropoda*; $k_{5\mathrm{S}}$ is a rate of CHS consumption by earthworms; k_6 is a rate of true humus mineralisation; M_{L}, M_{F}, M_{Fu}, M_{H} are relative rates of nitrogen mineralisation in L, L_{u}, F, F_{u} and H pools. It should be noted that the coefficients $k_{i\mathrm{L}}$ and $k_{i\mathrm{S}}$ are calculated by the same formulae using different temperature data as an input parameters. The coefficients with index L use litter temperature, with an index S they use soil temperature. All coefficients $k_{i\mathrm{L}}$ are dependent on litter moisture, $k_{i\mathrm{S}}$ use soil moisture.

2.2. Evaluation of the rates of the SOM transformation

In further calculations the coefficients index is omitted, which is responsible for the usage of different temperatures and the constants in the expressions for the coefficients are described. The values of $k_{i\mathrm{L}}$ or $k_{i\mathrm{S}}$ coefficients change depending on the litter cohort properties (ash and nitrogen content), temperature and moisture.

The coefficients k_{1L}, k_{2L}, k_{3L}, k_{1S}, k_{2S}, and k_{3S} describing the functioning of a fungi and micro fauna complex have been calculated on the basis of a synthesis of well-known literature data on laboratory experiments on the rate of organic debris decomposition. This method represents piece-wise linear regression equations for the coefficients in dependence of: (i) nitrogen and ash content in decomposing litter cohort; (ii) soil or litter temperature; and (iii) soil or litter moisture (mass percents). The material and the methods of calculation for the coefficients have been published earlier (Chertov, 1985, 1990; Chertov and Komarov, 1995, 1997). Some additional laboratory experiments were carried out to specify the differences between decomposition of the above ground and underground cohorts. They are described below.

The variable coefficients k_{4L}, k_{4S} and k_{5S} in dependence on the factors were found on the basis of experimental data referenced in literature (Chertov and Komarov, 1995, 1997) for soil arthropods and earthworm activity. The coefficient k_6 for 'true' humus mineralisation has been investigated in the work of Ionenko et al. (1986, 1987). The maximal values of the coefficients have been quoted by Chertov and Komarov (1995, 1997).

The corresponding equations for the values of the earlier mentioned coefficients with some improvements to the SOMM model and some extensions reflecting the new model's structure are presented below. The calculation may be narrowed down into the following steps: (i) dependencies on ash and nitrogen contents (yearly step); (ii) dependencies on soil/litter temperature and soil/litter moisture (monthly step); (iii) corrections of the coefficients for below-ground litter.

2.2.1. Dependencies of kinetic parameters on ash and nitrogen contents

Piece-wise linear dependencies for the coefficients k_{iL} in relation to ash and nitrogen contents may be expressed by equations:

$$k_{1L} = 0.002 + 0.0009x_1 + 0.003x_2, \tag{2}$$

$$k_{2L} = \begin{cases} 0.002x_2 & x_2 \leq 0.5\% \\ 0.00114 - 0.00028x_2 & x_2 > 0.5\% \end{cases} \tag{3}$$

$$k_{3L} = \begin{cases} 0.005x_1 & x_1 \leq 0.5\%, \\ 0.04 - 0.003x_1 & 5\% \leq x_1 < 12\%, \end{cases} \tag{4}$$

$$k_{4L} = \begin{cases} 0.005x_2 & x_2 \leq 2\%, \\ 0.001 & x_2 > 2\%, \end{cases} \tag{5}$$

$$k_{5S} = \begin{cases} 0.2x_1 & x_1 \leq 5\%, \\ k'_5 & x_1 > 5\%, \end{cases} \tag{6}$$

and

$$k'_5 = \begin{cases} 0 & x_2 \leq 0.5\%, \\ 0.00462x_2 - 0.00231 & 0.5\% < x_2 < 2\% \\ 0.007 & 2\% < x_2, \end{cases} \tag{7}$$

$$k_6 = 0.00006, \tag{8}$$

where x_1 is the ash concentration, g 100 g^{-1} ($0 < x_1 < 12$); x_2 is the nitrogen concentration, g 100 g^{-1} ($0 < x_2 < 3$). It should be noted that Eqs. (2)–(8) are equitable for any litter cohort with the corresponding ash and nitrogen contents including those mentioned in the system (1) coefficients k_{1S}, k_{2S}, k_{3S} for the below-ground cohorts.

2.2.2. Dependencies of the kinetic parameters on soil (litter) temperature and soil (litter) moisture

The dependencies on temperature and moisture are represented as a correction to k_i ($I = 1, \ldots, 6$), which is a product of two functions: $a_i = f_i(T)g_i(W)$, where T is temperature, and W is moisture of the decomposing materials. It should be noted that T is the litter temperature for the above-ground litter cohorts but T is the soil temperature for below-ground cohorts. W means litter moisture (mass percent) for above-ground cohorts and soil moisture (mass percent) for the below-ground cohorts of litter.

$$f_1(T) = \begin{cases} 0 & T \leq °\text{C} \\ 0.35 + 0.325T & 0°\text{C} < T \leq 20°\text{C} \\ 0.20T & T > 20°\text{C}, \end{cases} \tag{9}$$

$$g_1(W) = g_3(W) = \begin{cases} 0 & W \leq 7\% \\ 0.0435W - 0.304 & 7\% < W \leq 30\% \\ 1 & 30\% < W \leq 300\% \\ 2 - 0.0033W & 300\% < W \leq 600\% \\ 0 & 600\% < W, \end{cases} \tag{10}$$

$$f_2(T) = \begin{cases} 0 & T \leq 0°C \\ 0.05T & T > 0°C, \end{cases} \tag{11}$$

$$g_2(W) = \begin{cases} 0 & W \leq 7\% \\ 0.0233W - 0.163 & 7\% < W \leq 50\% \\ 1.3125 - 0.00625W & 50\% < W \leq 90\% \\ 0.811 - 0.00068W & 90\% < W \leq 1200\% \\ 0 & 1200\% < W, \end{cases} \tag{12}$$

$$f_3(T) = \begin{cases} 0 & T \leq -3°C \\ 1.3 & -3°C < T \leq 7°C \\ 1.472T - 0.0245 & 7°C < T \leq 60°C, \end{cases} \tag{13}$$

$$f_4(T) = \begin{cases} 0 & T \leq 0°C \\ 0.01T & 0°C < T \leq 10°C \\ 0.09T - 0.8 & 10°C < T \leq 20°C \\ 1 & 20°C < T \leq 40°C \\ 2.0 - 0.025T & 40°C < T \leq 80°C, \end{cases} \tag{14}$$

$$g_4(W) = \begin{cases} 0.025W & W \leq 40\% \\ 1 & 40\% < W \leq 400\% \\ 2.333 - 0.0033W & 400\% < W \leq 700\% \\ 0 & 700\% < W, \end{cases} \tag{15}$$

$$f_5(T) = \begin{cases} 0 & T \leq 0°C \\ 0.0333T & 0°C < T \leq 3°C \\ 0.1T - 0.3 & 3°C < T \leq 13°C \\ 1 & 13°C < T \leq 25°C \\ 2.0 - 0.04T & 25°C < T \leq 50°C, \end{cases} \tag{16}$$

$$g_5(W) = \begin{cases} 0 & W \leq 2\% \\ 0.0769W - 0.1538 & 2\% < W \leq 15\% \\ 1 & 15\% < W \leq 70\% \\ 2.4 - 0.02W & 70\% < W \leq 120\% \\ 0 & 120\% < W, \end{cases} \tag{17}$$

$$f_6(T) = \begin{cases} 0 & T \leq 0°C \\ 0.05T & T > 0°C, \end{cases} \tag{18}$$

$$g_6(W) = \begin{cases} 0.025W & W \leq 40\% \\ 1 & W > 40\%. \end{cases} \tag{19}$$

To specify the differences in the rates of decomposition of the above and below-ground cohorts, two long-term laboratory experiments in controlled conditions (in dark, under constant temperature, $18 \pm 2°C$, and moisture 60 mass% for mineral composts and 300 mass% for plant litter) were conducted using a complex study scheme by Chertov et al. (1994). This scheme had the following set of variants: (1) single plant debris composting — the simulation of litter decomposition; (2) composting of plant debris incorporated in humus accumulative loam horizon (mixed 1:10) — the simulation of soil organic matter transformation; (3) composting of plant debris incorporated in non-carbonate humus-free moraine loam and sand (mixed 1:10) — the simulation of soil organic matter accumulation at primary succession.

Five types of plant debris were used in each experiment. Oak bark (C/N 45, ash content, 5.0%; lignin, 41.0%) and spruce needles (C/N 38, ash content, 5.7%; lignin, 41.0%) were used as slowly decomposed material. Shoots and leaves of clover (C/N 16, ash content, 7.6%; lignin, 30.2%) were used as easily decomposed material. Oak leaves (C/N 21, ash content, 5.4%; lignin, 39%) and green mosses (C/N 24, ash content, 4.2%; lignin, 31.3%) were additionally used for the first experiment, only. The biochemical composition of the initial samples was also determined. The composting process was controlled by the chemical analysis of the dried samples (pH_{H_2O}, organic carbon, organic nitrogen and also weight loss) at 0, 1, 3, 6, 8 and 12 months. Finally, 29 curves of loss of organic matter weight due to mineralisation were obtained.

The curves were analysed to evaluate the values of the kinetic coefficients (k_i) separately for pure organic material and for plant debris incorporated in various mineral horizons using a graphical analysis by Chertov (1985), which is widely used in physical chemistry (Kudriashov, 1986). A tangent from the initial point of weight loss curve characterises the initial rate of fast mineralisation of fresh organic debris (k_1) for a time determined in the point of intersection of the tangent with horizontal axis on the graph (time of the experiment). A tangent at final point of the experimental curve can be used to evaluate the rate of mineralisation of humified organic material (k_2). The rate of humification (k_3) of decomposing material can be determined by a line from a point with a co-ordinate ($x = y = 0$) to the intersection of two tangents. The curves were calculated using these graphically obtained coefficients, which were fully coincided with.

Using the obtained results, a comparison of the numerical values of the kinetic parameters for pure litter and litter incorporated in mineral horizons was done to compile the correction factors to the basic values as described above (Nadporozhskaya et al., 2000). These correction factors are as follows:

$$k_{1S} = 1.6k_{1L},$$
$$k_{2S}(H) = k_{2L}(1.22 + 0.488H_m),$$
$$k_{3S} = 1.35k_{3L},$$
$$k_{4S} = k_{4L}, \qquad (20)$$

where H_m is the humus content (%) in the mineral horizon. The correction factors are represented as coefficients to the k_{iL} parameters. It is interesting to point out two aspects: (1) there is clear influence of mineral topsoil on the SOM decomposition but the effect of variation in soil texture on the rate of below ground litter decomposition was not detected; (2) the effect of soil humus content was significant for k_{2S} only.

2.3. Correction coefficients

Some correction coefficients are included in the system of Eq. (1): M_L, M_H, M_F, M_{Fu}, as well as some of their modifications for different litter cohorts.

It is well known that nitrogen mineralisation falls behind that of organic matter at the first stage, after which it markedly increases. Previous data (Mikola, 1954; Staaf and Berg, 1977; Berg and Staaf, 1980a,b, 1981) show that there are two critical levels of nitrogen mineralisation: below the first level, nitrogen mineralisation is about 0.1 of the organic matter decomposition rate; between the first and the second it is close to 0.5; and above the second level the rates of nitrogen and organic carbon mineralisation are equal. Taking into account the previous results (Chertov, 1985, 1990), the relative rates of nitrogen mineralisation can be defined as:

$$M_N = \begin{cases} 0.1M_{OV} & y - 1.16x_1 \le 0.44; \\ 0.5M_{OV} & 0.44 < x_2 - 1.16x_1 \le 1.50; \\ 1.0M_{OV} & 1.50 < x_2 - 1.16x_1. \end{cases} \qquad (21)$$

where M_{OV} is the mineralisation of organic matter (%); M_N is the mineralisation of nitrogen; x_1 is the initial content of nitrogen in nondecomposed litter; x_2 is the current nitrogen contents of the decomposing organic layer. These conditions may be applied to the relative rates of nitrogen mineralisation of organic compartments. In the model one set $M_L = 0.1$; M_F and M_{Fu} satisfy the unequality above, and M_H depends on the C/N ratio in the soil. If C/N ≤ 8 then $M_H = 1$ else $M_H = 0.8$.

The values of coefficients $\delta_{Bact,}$, δ_{Lumb} and γ in the equations for H and the corresponding nitrogen H_N are based on item 4 of the main model assumptions. As was mentioned above, the community of *Bacteria* and *Arthtropoda* produces humus with a C/N ratio 15, and the community of *Lumbricidae* forms humus with a C/N ratio 8. These complexes of organisms spend 20% of the CHS nitrogen on their biomass, and 80% of nitrogen goes to humus formation. Therefore, it can be said that $\gamma = 0.8$. This assumption allows one to calculate the amount of humus by simple operations. If there is a complex with output C/N equal to 15 then the relation between soil organic matter and the corresponding nitrogen is SOM = 30N. Taking into account the above-mentioned 80% coming to humus formation, one has the final relation that for the fraction going from CHS to humus SOM =

24N. It can said that $\delta_{Bact} = 24$ and for *Lumbricidae* complex it can be accordingly said that SOM = 12.8N. In this case $\delta_{Lumb} = 12.8$.

2.4. Additional procedures as an interface with ecosystem models

The amounts of mineralised humus and nitrogen available for plants are important outputs from ROMUL. At every time step, the mineralised amount of humus is calculated as

$$H_{miner} = k_{1L}L + k_{1S}L_u + (k_{2L} + k_{4L} + k_{5S})F + (k_{2S} + k_{4S} + k_{5S})F_u - \delta_{Bact}(k_{4L}N_F + k_{4S}N_{Fu}) - \delta_{Lumb}(k_{5S}N_F + k_{5S}N_{Fu}) + k_6H, \quad (22)$$

H_{miner} may be used for evaluation of the gross production of carbon dioxide as

$$CO_2 = 1.83H_{miner}. \quad (23)$$

This expression allows the application of the model for an evaluation of carbon flow from soil to the atmosphere due to the SOM mineralisation.

The nitrogen available for plants is defined as:

$$N_{avail} = k_{1L}M_LN_L + k_{1S}M_LN_{Lu} + k_{2L}M_FN_F + k_{2S}M_{Fu}N_{Fu} + \gamma((k_{4L} + k_{5S})N_F + (k_{4S} + k_{5S})N_{Fu}) + k_6M_HN_H, \quad (24)$$

These values are summarised for 1 year. The other output values of variables and coefficients were taken at the end of a year.

Some additional parameters may be included into the ROMUL dynamics procedure as part of the ecosystem model. They are: a humus leached down H_{leach}, an annual input of atmospheric nitrogen N_{atm} (4 kg ha^{-1} in unpolluted conditions); nitrogen leaching $N_{leach.}$ The values of leaching for developed soils has been calculated on the basis of the Kazimirov and Morozova (1973) data and the previous model of Chertov et al. (1978):

$$H_{leach} = 0.0024H_s;$$

$$N_{leach} = 0.0017N_s, \quad (25)$$

where H_s is the total SOM mass in a soil (H_s = L + F + H), N_s is the total nitrogen mass in L and F soil compartments. $H_{leach.}$is added to the equation for H in the main system of equations for the ROMUL dynamics, N_{atm} is appended to the litter nitrogen input, and N_{leach} is aggregated with forest floor nitrogen.

An important compartment of the nitrogen pool in the soil is nitrogen appended by nitrogen-fixing microorganisms. It was calculated and added to the soil nitrogen using a previous formula (Chertov, 1981, p. 154).

$$N_{FIX} = 0.004/(N_L + N_F + N_H) - 0.0003 \text{ (kg m}^{-2}\text{ year}^{-1}), \quad (26)$$

where N_L, N_F and N_H are nitrogen contents in L, F and H soil compartments, correspondingly.

The iteration step in the ROMUL sub-model is one day, but in the ecosystem model input data is used as monthly average values.

The inputs are the litter input (amount and time), nitrogen and ash content of the different cohorts of litter fall (%) and the same of woody parts, the initial amounts of soil organic matter and nitrogen in litter on/in soil (L), CHS (F) and humus (H), the temperature of the organic layers and mineral topsoil (monthly means), the moisture (mass%) of the organic layers (L and F) and the mineral topsoil (monthly means).

The model outputs include the simulated annual amounts of L, F, H (organic matter and nitrogen), the C/N ratio of humus, gross production of carbon dioxide and the available nitrogen due to organic matter mineralisation.

3. Description of the soil climate generator

A soil climate generator is used in the model for two purposes:

- as a method of evaluation of soil temperature and moisture using measured standard meteorological long-term data;
- statistical simulation (generation) of realisations of long-term series of necessary input climate data with known statistical properties.

The model uses monthly average data on air, litter and soil temperature, precipitation, litter and mineral soil moisture. Air temperature and precipitation are usually measured at numerous meteorological stations, soil and litter data are seldom measured and, moreover, these data are mostly a result of scientific forest studies. Therefore, the procedure of simulating the necessary monthly meteorological input data is an important sub-model of the whole ecosystem model and should be linked with the soil organic matter model. One tried to develop a simple statistical model for the simulations of these data. A detailed description of soil climate generator and its verification is described by Bykhovets and Komarov (in press).

3.1.1. Air temperature and precipitation

The main assumptions of the statistical version of the soil climate generator are based on climatological investigations (Belchenko, 1989), and verified by the analysis of measured long-term monthly series from several stations in Russia. They are as follows:

- air temperature is normally distributed with a monthly average $\overline{T_{a,m}}$ and the standard deviation $\sigma_{T_{a,m}}$;
- monthly precipitation is distributed normally logarithmically;
- autocorrelation in the monthly average temperature series is significant as opposed to the precipitation series;
- crosscorrelation between air temperature and precipitation is significant, moreover, in the boreal zone it is positive in winter and negative in summer.

The air temperature simulation takes into account the autocorrelation with a monthly lag and the crosscorrelation of air temperature and precipitation. Thus the monthly average air temperature (denoted as $T_{a,m}$) is simulated as

$$T_{a,m} = \overline{T_{a,m}} + B_{aa,m} \cdot (T_{a,m-1} - \overline{T_{a,m-1}}) + B_{ar,m} \cdot (\ln r_m - \ln \overline{r_m}) + n_1 \cdot S_{T_{a,m}} \quad (27)$$

where $\overline{T_{a,m}}$ is the long-term monthly average air temperature of m-th month, which has usually been published in regional reference books; $B_{aa,m}$ and $B_{ar,m}$, the corresponding regression coefficients obtained separately on the basis of long-term climatic investigations, and $S_{T_{a,m}}$, residual deviation, n_1 is the normally distributed random variable $N(0, 1)$.

3.1.2. Soil temperature

The soil temperature (denoted as $T_{s,m}$) may be simulated on the basis of the Gauss distribution accounting both for autocorrelation and correlation with air temperature. The corresponding statistical model is

$$T_{s,m} = \overline{T_{s,m}} + B_{ss,m} \cdot (T_{s,m-1} - \overline{T_{s,m-1}}) + B_{sa,m} \cdot (T_{a,m} - \overline{T_{a,m}}) + n_1 \cdot S_{T_{s,m}} \quad (28)$$

where $\overline{T_{s,m}}$ is the long-term monthly average soil temperature; $B_{ss,m}$ and $B_{sa,m}$, the corresponding regression coefficients and $S_{T_{s,m}}$, the residual deviation.

There are usually no forest data available for this statistical model of soil temperature. One has enough data measured at standard conditions under grass at meteorological stations in Russia. Conversely, one has data on evaluating the difference between the soil temperature under grass at standard meteorological stations and under the forest (Elagin and Izotov, 1968; Pavlov, 1975). It may be seen in Fig. 2 that the differences between soil temperature under grass and forest are significant and relatively stable for a large geographical region. It allows one to assume as the first approximation that this difference does not depend on other factors.

Consequently, the main scheme of evaluation of soil temperature using a statistical model includes: (1) the evaluation of soil temperature under standard meteorological conditions (under grass); and (2) an account of the corresponding differences between standard conditions and forest conditions.

3.1.3. Soil moisture

The construction of a strictly statistical model for the evaluation of soil moisture is dependent on precipitation, air and soil temperatures, air humidity, etc. This is, in principle, possible, but there is not enough measured data. Some quite

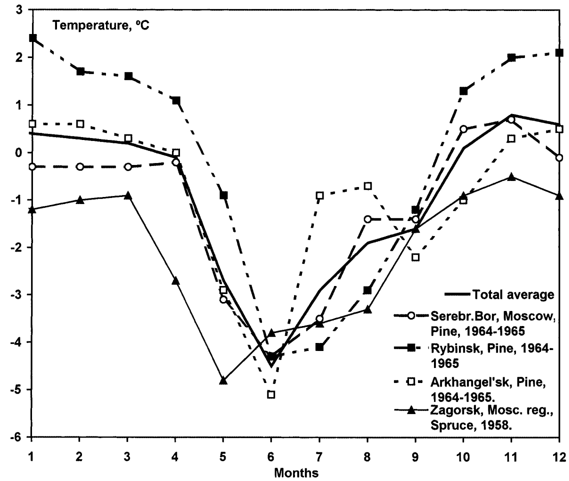

Fig. 2. The annual course of the difference between soil temperatures at the depth of 0.20 m under a forest and under a grass cover. Data used from (Elagin and Izotov, 1968) for pine forests and from (Pavlov, 1975) for spruce forest.

simple balance equations can be used. It is clear that a change in the water content of the active soil layer $\Delta W = W_2 - W_1$ may be defined as

$$\Delta W = W_2 - W_1 = r - E - f \tag{29}$$

where r is the precipitation, E is the evapotranspiration, f is the total runoff, W_1 and W_2 are soil water contents at the beginning and at the end of the month, respectively.

The method of evaluation of evapotranspiration based on accounting of the components of water balance and their dependencies on soil moisture was used (Budyko, 1974; Zubenok, 1976).

Evapotranspiration E is defined as

$$E = \begin{cases} E_0 & \text{at } W > W_0 \text{ (or } W^{(P)} > W_0^{(P)}) \\ E_0 \dfrac{W^{(P)}}{W_0^{(P)}} = E_0 \dfrac{W - W_{WP}}{W_0 - W_{WP}} & \text{at } W < W_0 \text{ (or } W^{(P)} < W_0^{(P)}) \end{cases} \tag{30}$$

where W is the water content in the root zone, W_0 is the critical value of W, $W^{(P)} = W - W_{WP}$; W_{WP} is the value of W at the permanent wilting point.

Runoff is defined as

$$f = \mu \cdot r \cdot \frac{W^{(P)}}{W_k^{(P)}} = \mu \cdot r \cdot \frac{W - W_{WP}}{W_k - W_{WP}} \tag{31}$$

where

$$\mu = \begin{cases} \alpha & \text{at } r < E_0 \\ \dfrac{\alpha}{\sqrt{\alpha^2\left[1 - \left(1 - \dfrac{E_0}{r}\right)^2\right] + \left(1 - \dfrac{E_0}{r}\right)^2}} & \text{at } r > E_0 \end{cases}$$

$\alpha \approx 0.2$ (for latitudes larger than 45°), empirical coefficient;

$$W_k = \begin{cases} W_{FC} & \text{(field capacity) for well-drained soils,} \\ W_S & \text{(full capacity) if ground water is close to surface,} \end{cases}$$

For the boreal zone, usually $W_K = W_S$.

The soil water balance accounts for large areas (without a detailed soil description), $W_S^{(P)} = 350$ mm and $W_{FC}^{(P)} = 200$ mm. Values of $W_0^{(P)}$ changed from 200 mm during cold seasons to 170 mm at midsummer. For concrete sites with known soil conditions, $W_0^{(P)}$ changed proportionally to $W_S^{(P)}$ or $W_{FC}^{(P)}$.

The evaluation of potential evapotranspiration by this method requires additional input data: air humidity, net radiation, etc. Therefore, the authors have restricted themselves in this version to the simple well-known model of Blaney and Criddle (1950), which allows one to evaluate potential evapotranspiration using air temperature only:

$$E_0 = 25.4 \cdot k_m \cdot p_m \cdot (1.8 \cdot T_{a,m} + 32), \tag{32}$$

where p_m is the percentage sum of light duration per month in relation to its yearly sum, which is a function of latitude and may easily be computed; k_m is a coefficient reflecting seasons and the vegetation type. It was found that $k_m = 0.5$ during the vegetation period and $k_m = 0.2$ during winter. These values correspond well with the Budyko-Zubenok method for the Central European part of Russia.

After substituting the Eqs. (30) and (31) into Eq. (29) and setting $W = (W_1 + W_2)/2$ the final equation for W_2 was solved. Calculations were done for the period using positive air temperature. During winter, with negative temperatures, soil moisture is set as constant. Precipitation (without evaporation), are added and entered into the soil in the first month with positive air temperatures (including this month's precipitation). For transition to moisture (mass%) w_{weight}, the following expression was used:

$$w_{\text{weight}} = 0.1W/d_{\text{b}} = 0.1(W^{(P)} + W_{WP})/d_{\text{b}} \quad (33)$$

where d_{b} is soil bulk density (g cm^{-3}).

3.1.4. Litter temperature and moisture

The calculation of the temperature and moisture of litter is conducted in this version rather conventionally. Litter moisture is equal to w_{weight} multiplied by 5. This is close to the measured experimental data and reflects the difference in corresponding bulk densities.

The litter temperature is defined as:

$$T_{\text{litter}} = \begin{cases} T_{\text{air}}, & \text{if } T_{\text{air}} > 0 \text{ and } T_{\text{soil}} > 0; \\ T_{\text{soil}}, & \text{if } T_{\text{air}} < 0 \text{ and } T_{\text{soil}} < 0; \\ 0 & \text{in all other cases.} \end{cases} \quad (34)$$

Testing of these conventional rules using a soil sub-model shows realistic results and may be deemed as satisfactory at this stage. But further extension of the soil climate generator (using additional experimental data), in particular the simulation of litter conditions, is necessary. The results of simulation using the described simulator were compared with the measurements from the Valday Laboratory of the State Hydrological Institute (Materials of Observations of Valday Branch of State Hydrological Institute, 1986). The soil parameters of Fedorov (1977) were used. An example of the comparison of soil temperature and moisture at the forest site is shown in Table 1. Actual data in the first two rows of Table 1 represent monthly mean values for 30 years observation. Next two rows show results of simulation of soil moisture using measured actual data of air temperature and precipitations for the same period. Last two rows demonstrate the results of simulation if air temperature and precipitation are simulated by a generator also. It should be noted that simulated results almost coincide with measured data.

4. Program implementation

To implement the model, a pilot research version of the ROMUL software was developed. This was achieved with Object Oriented Design technology as well as Microsoft Visual C++ software with MFC (Microsoft Foundation Classes) (Operating Systems, 1996) under MS Windows NT. In addition, Open Data Base Connectivity (ODBC) technology was applied to implement the input-output data processes (Microsoft ODBC, 1997).

5. Comparison of ROMUL and SOMM

Because the new model is based on previous versions (Chertov, 1985; Chertov and Komarov, 1997) a comparison of ROMUL and SOMM was carried out. A scenario for the comparison was compiled on the basis of experimental data on the biological productivity of Scots pine, Norway spruce and Silver birch ecosystems in the central boreal zone (Kazimirov and Morozova, 1973; Kazimirov et al., 1977, 1978; Morozova, 1991). The other set of data were materials on the biological productivity of meadows and soil carbon in the boreal zone (Poniatovskaya, 1978; Bazilevich, 1993). The input data for the comparisons are shown in Table 2, where the parameters for ROMUL and SOMM are fully identical in relation to the total amount of SOM and nitrogen in soil and litter.

Hundred-year Monte-Carlo simulations with a St. Petersburg climate scenario simulated by a climate generator were run in a course of model tests which calculated the mean values and the corresponding standard deviations of SOM pools. The results of the comparison of ROMUL and SOMM are represented in Table 3.

The results of the comparison of the models for forest soils show quite an interesting picture. Simulated SOM pools were practically identical in dry, poor sandy podsolic soils of the Scots pine stand of the *Cladina* type. Simulated data for poor and medium fertility podsolic soils with normal drainage under Scots pine and Silver

Table 1
Thirty years averages and S.D. of actual (from Materials of Observations of Valday Branch of State Hydrological Institute, 1986) and predicted by climate generator soil moisture and temperature under Norway spruce forest, Valday, Novgorod region, Russia

Data and results	Values	Month											
		1	2	3	4	5	6	7	8	9	10	11	12
Soil moisture at the end of month, average within 0–1 m layer (wt.%)													
Actual data 1957–1986	Average	18.3	17.9	18.8	19.7	16.7	15.2	14.3	13.7	14.8	16.1	17.3	17.9
	S.D.	1.9	1.7	1.6	2.0	1.8	1.8	2.2	3.2	2.9	1.7	1.8	1.2
Predicted (with actual weather)	Average	17.6	17.6	17.7	21.1	18.3	15.8	14.6	14.2	14.9	17.2	17.7	17.7
	S.D.	1.8	1.8	1.9	1.1	1.6	2.1	1.9	1.7	1.7	1.6	1.9	1.9
Predicted (with simulated weather)	Average	17.8	17.8	18.1	20.9	18.2	15.6	14.2	14.5	15.4	17.5	17.8	17.9
	S.D.	2.1	2.1	2.1	1.3	2.4	2.1	1.6	1.7	1.9	1.8	2.1	2.1
Monthly average soil temperature at 0.20 m depth (°C)													
Actual data 1957–1986	Average	–	–	–	–	6.2[a]	10.0	12.4	12.6	9.7	6.0[a]	–	–
	S.D.	–	–	–	–	2.4[a]	1.1	0.9	0.7	0.7	1.3[a]	–	–
Predicted (with actual weather)	Average	0.1	0.0	0.1	2.3	7.3	10.0	13.7	13.6	9.6	6.2	2.7	0.9
	S.D.	0.6	0.3	0.3	1.0	1.2	1.1	1.3	1.0	1.0	1.4	0.7	0.5
Predicted (with simulated weather)	Average	0.2	0.1	0.1	2.5	7.3	9.9	13.7	13.7	9.5	6.5	2.8	0.9
	S.D.	1.2	0.8	0.6	0.9	1.1	1.4	1.0	1.0	1.0	1.4	0.9	0.6

[a] Values were calculated from a few years data only.

Table 2
Simulation scenario for comparison SOMM and ROMUL

Vegetation	Soil	Initial soil organic matter pools (kg m^{-2})					Litter parameters		
		Cohort	Organic layer	Nitrogen of organic layer	Mineral topsoil	Nitrogen of mineral topsoil	Amount (kg m^{-2} year)	Ash concentration (g 100 g^{-1})	Nitrogen concentration (g 100 g^{-1})
Dry Scots pine forest of Calluna type	Crust mor sandy surface-podzolic	Above[a]	1.30	0.017			0.175	2.5	0.55
		Below[a]	0.20	0.002			0.048	1.3	0.40
		Total	1.50	0.019	7.50	0.150	0.223	2.3[b]	0.52[b]
Scots pine forest of Myrtillus type	Mor (raw humus) sandy podzol	Above	5.00	0.050			0.350	1.7	0.72
		Below	0.60	0.008			0.095	1.3	0.45
		Total	5.60	0.058	9.80	0.245	0.445	1.6	0.66
Pendula birch forest of Oxalis type	Moder loamy podzolic	Above	1.60	0.027			0.370	3.5	1.00
		Below	0.20	0.003			0.100	1.1	0.60
		Total	1.80	0.030	10.0	0.280	0.470	3.0	0.90
Norway spruce forest of Myrtillus type	Mor loamy gley-podzolic	Above	1.66	0.024			0.385	3.0	0.66
		Below	0.20	0.003			0.095	1.3	0.50
		Total	1.86	0.027	10.50	0.262	0.480	2.8	0.63
High productivity grassland	Loamy sod-podzolic	Above	0.69	0.030			0.300	6.0	1.30
		Below	1.00	0.040			0.700	4.0	0.70
		Total	1.69	0.070	16.30	0.670	1.000	4.6	0.88
Mean productivity grassland	Sandy loam sod-podzolic	Above	0.30	0.003			0.160	6.0	1.30
		Below	0.70	0.007			0.470	3.0	0.60
		Total	1.00	0.010	9.70	0.300	0.630	3.7	0.78
Low productivity grassland	Loamy sand sod-podzolic	Above	1.00	0.060			0.060	3.0	1.30
		Below	2.00	0.130			0.140	2.0	0.60
		Total	3.00	0.190	7.50	0.450	0.200	2.3	0.81

[a] Here and below: above, above-ground fraction of forest floor or grass litter; below, below-ground fraction of organic material being not bonded with soil minerals ('labile, active fraction of soil organic matter') to run ROMUL model.
[b] Here and below: weighted mean values calculated by fractions' concentration to run SOMM model.

Table 3
Soil organic matter pools, kg m^{-2} after 100 year simulation with two models

Vegetation	Soil	ROMUL				SOMM	
		Above-ground[a] (L+F)	Below-ground[a] (L_u+F_u)	Organic layer total	Mineral topsoil (H)	Organic layer total (L+F)	Mineral topsoil (H)
Dry Scots pine forest of *Cladina* type	Crust mor (raw humus) sandy surface-podzolic	5.048 ± 0.154	1.238 ± 0.044	6.286 ± 0.160	7.794 ± 0.007	6.577 ± 0.297	7.806 ± 0.008
Scots pine forest of *Myrtillus* type	Mor sandy podzol	2.882 ± 0.037	0.342 ± 0.084	3.224 ± 0.092	11.243 ± 0.024	4.026 ± 0.178	10.931 ± 0.023
				t = 12.6	*t* = 29.7		
Pendula birch forest of *Oxalis* type	Moder loamy podzolic	1.495 ± 0.073	0.089 ± 0.006	1.584 ± 0.074	12.789 ± 0.018	2.187 ± 0.097	13.082 ± 0.018
				t = 15.6	*t* = 36.4		
Norway spruce forest of *Myrtillus* type	Mor loamy gley-podzolic	3.155 ± 0.153	0.304 ± 0.076	3.459 ± 0.171	11.662 ± 0.021	4.080 ± 0.190	11.855 ± 0.021
				t = 7.7		*t* = 20.5	
High productivity grassland	Loamy sod-podzolic	0.630 ± 0.040	0.677 ± 0.113	1.307 ± 0.120	19.476 ± 0.055	3.356 ± 0.173	22.831 ± 0.033
				t = 30.7	*t* = 165.3		
Mean productivity grassland	Sandy loam sod-podzolic	0.336 ± 0.021	0.551 ± 0.086	0.887 ± 0.088	10.960 ± 0.029	2.648 ± 0.112	12.901 ± 0.020
				t = 39.1	*t* = 88.2		
Low productivity grassland	Loamy sand sod-podzolic	0.168 ± 0.009	0.172 ± 0.027	0.340 ± 0.028	8.031 ± 0.027	0.922 ± 0.034	9.229 ± 0.022
				t = 16.6	*t* = 108.9		

[a] See notes to Table 1.

birch stands demonstrate a 19–28% lower accumulation of organic layers for ROMUL simulations, with 2–3% difference only in the SOM pool in the mineral topsoil. In poor drained gley-podsolic soils of the Norway spruce stands there was 15% lower accumulation of forest floor and practically identical amounts of humus in the mineral topsoil.

One clear difference in the results of the comparison of the models for grassland soils entailed a 2–3 times lower accumulation of SOM in pools of ‘pure’ organic material: grass floor and active humus. However, in relation to SOM accumulation in mineral topsoil, the simulation shows an irregular difference of 13–20% between ROMUL and SOMM.

The comparison of the models shows that there is one regular difference between ROMUL and SOMM. The amount of available nitrogen released in a process of full mineralisation of soil organic matter (Norway spruce forest of *Myrtillus* type) is significantly higher in ROMUL (Fig. 3). In grassland soils, where root fall is dominant, the pool of available nitrogen, calculated as the mean value for a period of 80–100 years of simulation in a relatively steady state, is shown in Table 4. The difference between ROMUL and SOMM in this case is 39% in rich soil and 34% in poor soil.

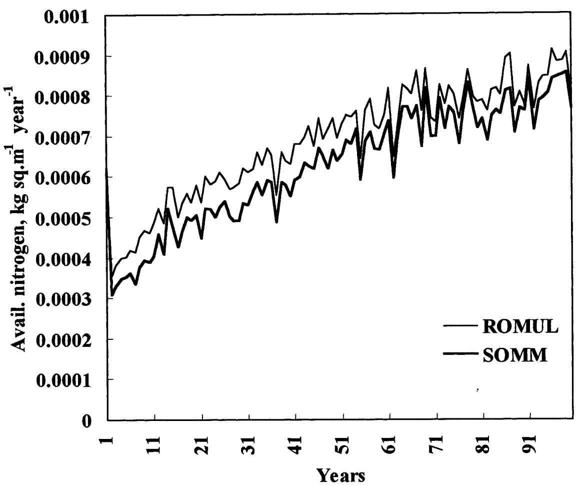

Fig. 3. Comparison of amounts of available nitrogen as outputs of ROMUL and SOMM models.

Table 4
A pool of simulated available nitrogen kg m^{-2} $year^{-1}$ (averages of ten Monte Carlo runs and S.D.s)[a]

Model	Rich grassland sod-podsolic soil	Poor grassland sod-podsolic soil
SOMM	0.0050 ± 0.00015	0.0017 ± 0.000047
ROMUL	0.0070 ± 0.00046	0.0022 ± 0.000146

[a] Averages of organic matter for different models are distinguishing with significance level 0.001 for each soil.

6. Example of the response of soil organic matter dynamics at forest clear cutting

An experimental simulation of the response of forest soil to forest clear cutting was conducted using the ROMUL model. The scenario was as follows: a stationary system ‘spruce forest/soil’ (Norway spruce forest of *Myrtillus* type) with the initial data of soil corresponding with Table 2 and a constant litter flow of 0.4 kg m^{-2} $year^{-1}$, with clear cut at 16 simulation steps. Soil characteristics varied around certain steady states in correspondence with the amount and quality of litter (spruce needles with ash content 1.7%, nitrogen content 0.6%; branches with ash content 1.5%, nitrogen content 0.24%; fine roots with ash content 2.0%, nitrogen content 0.6%; coarse roots with ash content 1.5% and nitrogen content 0.2%). This litter flow corresponded to the soil characteristics in Table 2. The climate scenario was based on Petrozavodsk (Russian Karelia) meteorological data.

Clear cutting was simulated when litter flow sharply increased and at the same time the litter amount increased by a factor of 6 for all litter cohorts. Further litter flow simulated the growth of spruce forest up to the previous steady state (Fig. 4A). The corresponding dynamics of soil organic matter in the forest floor and in mineral topsoil is shown in Fig. 4B.

The dynamics of organic matter reflects the changes in litter input. The CHS complex demonstrates a rather complicated response to the large amount of litter in one year. A decrease in the amount of CHS occurs due to a decrease in the litter input and the amount of CHS returns to its

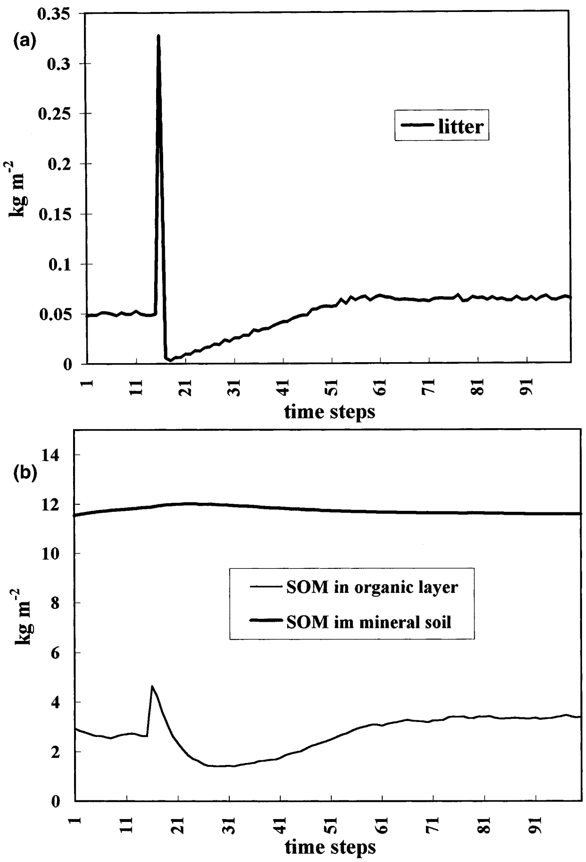

Fig. 4. Simulation of response of forest soil system to clear cutting. (A) Dynamics of litter, (B) dynamics of soil organic matter in different soil layers.

steady state only after 50 years. It should be noted that in this scenario the recovery of litter input is faster than in real forest. Humus in mineral topsoil demonstrates more smoothing dynamics but its response may also be easily seen.

This simple simulation experiment shows the possibilities of ROMUL for simulating real operations of Forest Management for a wide range of forest, soil and climate conditions.

7. Discussion and conclusion

Both the SOMM and the ROMUL versions have two common principal features.

1. They realise the idea of succession changes for communities of organisms-destructors of various taxonomic status, which are consequently decomposing fresh litter. It should be noted that these successive changes are inherent to undisturbed forest and grassland soils. Usually the fauna complex in agricultural soils is significantly reduced and in these conditions the microbial community is dominant. Thus, almost all existing models of SOM dynamics utilise only the microbiological concept of SOM mineralisation and transformation due to the fact that they originated from agricultural applications (Powlson et al., 1996). In undisturbed forest soils, the stages of SOM decomposition can be marked by fauna indicators and, correspondingly, evaluate rates of decomposition which are concomitant to visually marked fauna changes.
2. They yield experimental data in laboratory experiments on organic matter decomposition in controlled conditions, unlike the models using microbiological concepts, which are mostly based on the results of long-term field observations of SOM dynamics (Powlson et al., 1996; Smith et al., 1997; Chertov et al., 1999).

A compilation of the model displayed sufficient gaps in available experimental data, in particular, for the decomposition of below-ground litter. New experimental data were obtained which specified numerical values of kinetic coefficients for decomposition of below-ground fractions of soil organic matter. These data show quite specific shifts in the rates of some below-ground processes. Nevertheless, there is a necessity for additional efforts to check the coefficients and correction factors in a wider range of environmental conditions and soil parameters.

The disputable feature of the model is the postulate on the assimilation of 20% of nitrogen from organic material by soil mesofauna. The classic trophic pyramid shows about 10% of organic matter produced by the upper level from the matter of the lower one. The proportion differs in relation to elements. For nitrogen, being a limiting factor in the majority of terrestrial ecosystems, this increase of nitrogen concentration at other trophic levels is well documented (Odum, 1959). To understand the role of this proportion some calibration runs of ROMUL have been conducted using another value for assimilation of nitrogen by mesofauna. The result was a 3% increase in the SOM pool in the mineral topsoil only for a 100-year simulation, when the part of nitrogen assimilated by the soil fauna from organic material was set at 10%. From the model structure (Eq. (1)), it can be easily seen that this variation does not influence the rates of decomposition in organic horizons. Moreover, the more important model output for the forest ecosystem models, the available nitrogen, mostly comes from the organic layer (forest floor). Thus, this poorly defined proportion from the experiments does not significantly influence the SOM and nitrogen dynamics. Note, when calculating carbon pools this proportion may be more significant, hence one is planning to calibrate ROMUL more precisely for this purpose.

The main cause for the development of this new version of a soil organic matter model, ROMUL, resulted from earlier model evaluations using experimental datasets (Chertov et al., 1997). The previous version, SOMM, demonstrated satisfactory results in relation to forest soils with dominant leaf litter fall, and overly high accumulation of organic layers in grassland soils. The structure of ROMUL was improved with the addition of pools of below-ground litter and humified organic material corresponding to fractions of 'labile' or 'active' humus in mineral horizons.

The evaluation of the SOMM model met difficulties in relation to input data for soil temperature and moisture. Now, in ROMUL, the soil climate generator with monthly steps was especially compiled for the correct calculation of input data for soil temperature and moisture, which are the driving variables in the model. It provides the possibility to simulate weather parameters for a wide range of climatic conditions.

The comparison of the ROMUL model with the previous version, SOMM, has shown that the simulation results are practically identical for raw humus forest soils with a domination of surface litter fall. A significant difference in the fraction of the total organic layer was detected in soils with a high proportion of below-ground litter. A small accumulation of the fraction of below-ground pure organic material (F_u) in ROMUL runs was found because of higher mineralisation of root litter fall when it was considered as a separate pool. A higher rate of available nitrogen formation in ROMUL was also observed here. This is a very significant feature from an ecological point of view when the crucial role of the soil nitrogen supply in the majority of forest ecosystems is considered.

Existing dynamic models of SOM transformation, as a rule, have no pool of organic layer (Smith et al., 1997). Therefore, it seems that the application of these models, when quantifying forest soil dynamics, will meet difficulties in relation to the adequacy of simulation. The expansion of grasslands SOM models has been attempted to simulation of forest soils by including a pool of organic layer, as was done by Friend et al. (1997) in relation to the CENTURY model (Paustian et al., 1992).

The ROMUL model demonstrates quite complicated dynamics of soil systems. The decomposition dynamics in organic and mineral topsoil is driven by different complexes of organisms destructors, and ROMUL reflects these circumstances as gross carbon dioxide and available nitrogen outputs. This is a very important aspect for the calculation of the carbon balance and productivity of an ecosystem.

ROMUL has been developed as a compartment of a forest ecosystem model (Chertov et al., 1999a). The advantage of ROMUL is the possibility to calculate a quite comprehensive balance of organic matter, nitrogen and, potentially, the dynamics of other elements in forest soils as driven by the input of various cohorts of litter. It allows a simultaneous calculation of the dynamics of leaves fall, big wood litter due to forest disturbances (gap formation due to storm activity with tree windfall) and different litter cohorts from ground vegetation.

It is thought that these specific features of the ROMUL model are promising. It now allows the simulation of SOM dynamics in undisturbed forest and grassland ecosystems. Moreover, ROMUL linked with a soil climate generator can be applied to a wide range of climatic conditions.

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