

# **Model Components for Evaluating Climate Change Impact on Wetlands**

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**Abstract:** Reaction of terrestrial ecosystems to climate change and human perturbations can be complex and uncertain. It is reflected in changes of ecosystem biogeochemical cycles of carbon and nitrogen. For wetland and spruce forest ecosystems of boreal forest area in European territory of Russia and Western Siberia the series of compartment models for combined carbon-nitrogen cycle dynamics is developed and analyzed. The models are realized in several software modules allowing make estimates of stability boundaries for equilibria, trajectories of ecosystem dynamics under climate change and perturbations initiated by human activities.

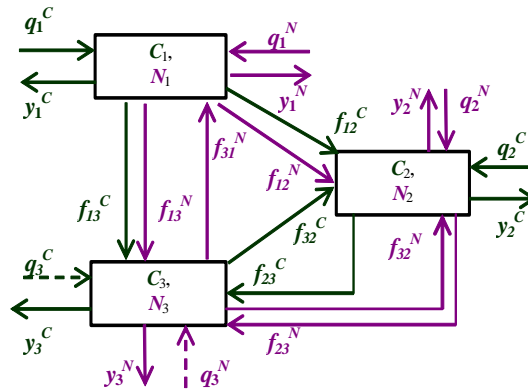
**Keywords:** carbon and nitrogen cycle, wetland, spruce forest, dynamic system, equilibrium, stability, bifurcation, climate change impact.

## **Introduction**

Transformations of terrestrial ecosystems due to global climate change and anthropogenic activities are reflected in the functioning of their biogeochemical cycles. Mass-balance schemes of carbon and nitrogen biological turnover in peatland and spruce forest ecosystems of southern taiga on the territory of European Russia created in (Bazilevich et al., 1986; Alexandrov et al., 1994) became the source of numerical data on carbon and nitrogen fluxes and storages in principal ecosystem components and a foundation of knowledge on inter- and intra-system exchange processes sensitive to climate change and human perturbations. However, such multi-component schemes are rare due to complexity of measurements necessary for their design. This is the reason for aggregating complicated storage-flow diagrams to the simpler ones that serve as a basis for “minimal” dynamic models of biological turnover. The purpose of the paper is to describe a series of such “minimal” models and obtain dynamics of the coupled carbon-nitrogen turnover in some wetland and forest ecosystems as well as to make software for analyzing the reaction of ecosystems to probable climate change.

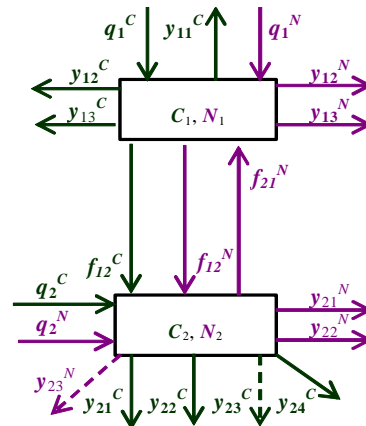
## **Models design**

The aggregation procedure accounts for biological form and functional role of each ecosystem component. It is carried out for wetlands and spruce forests of middle and southern taiga at the European territory of Russia (Alexandrov et al., 1994; Kozlovskaya et al., 1978) (fig. 1) and some types of oligotrophic bogs and pine forests of middle and southern taiga in Western Siberia (Golovatskaya, Dyukarev, 2009; Vedrova, 1997; Naumov et al., 2007) (fig. 2).



**Figure 1.**

Aggregated schemes of carbon and nitrogen biological turnover in wetland and forest ecosystems of middle and southern taiga in the European territory of Russia. Storages of carbon ( $\text{gC/m}^2$ ), nitrogen ( $\text{gN/m}^2$ ) in:  $C_1, N_1$  - vegetation,  $C_2, N_2$  - consumers and destructors,  $C_3, N_3$  - dead organic matter. Flows ( $\text{gC/m}^2\text{year}$  for carbon,  $\text{gN/m}^2\text{year}$  for nitrogen):  $q_1^C, q_1^N$  - assimilation C and N from atmosphere,  $q_3^C$  - carbon input from adjacent ecosystems,  $q_2^N$  - nitrogen fixation from atmosphere by microorganisms,  $y_1^C, y_2^C$  - respiration and consumption by phytophagues from adjacent ecosystems,  $y_1^N$  - output to adjacent ecosystems,  $y_2^N$  - denitrification,  $y_3^C$  - peat formation (for wetlands), output by runoff, abiotic oxidation,  $y_3^N$  - nitrogen export to adjacent ecosystems and peat formation,  $f_{12}^C, f_{12}^N$  - consumption of vegetation by phytophagues,  $f_{13}^C, f_{13}^N$  - litterfall,  $f_{23}^C$  - mortality of animals and microorganisms,  $f_{23}^N$  - nitrogen transformation in available form in decay processes,  $f_{32}^C$  - dead organic matter decay by destructors,  $f_{32}^N$  - nitrogen consumption by destructors,  $f_{31}^N$  - consumption by vegetation.



**Figure 2.**

Aggregated schemes of carbon and nitrogen biological turnover in wetland and forest ecosystems of middle and southern taiga in the Western Siberia.

$C_i, N_i$  - carbon ( $\text{gC/m}^2$ ), nitrogen ( $\text{gN/m}^2$ ) in living and dead organic matter, flows ( $\text{gC/m}^2\text{year}$  for carbon,  $\text{gN/m}^2\text{year}$  for nitrogen):  $q_1^C, q_1^N$  - assimilation C and N from atmosphere,  $q_2^C$  - carbon input from adjacent ecosystems,  $q_2^N$  - nitrogen fixation by microorganisms and input with surface water,  $y_{11}^C$  - autotrophic respiration,  $y_{12}^C, y_{12}^N$  - output with runoff,  $y_{13}^C, y_{13}^N$  - consumption by phytophagues,  $y_{21}^C, y_{21}^N$  - decay of dead organic matter by destructors and denitrification,  $y_{22}^C, y_{22}^N$  - output to adjacent ecosystems and runoff,  $y_{23}^C, y_{23}^N$  - peat formation (in wetlands),  $y_{24}^C$  - abiotic oxidation,  $f_{21}^N$  - consumption of available nitrogen by vegetation from peat or soil layer,  $f_{12}^C, f_{12}^N$  - litterfall.

A sequence of dynamic compartment models for combined carbon-nitrogen cycling with elements of a hydrological cycle is obtained as a result. Carbon-nitrogen interaction is provided by two biochemical mechanisms which served as a basis for one of the first models of their turnover in a mesotrophic wetland earlier (Logofet and Alexandrov, 1984): 1) intensity of litterfall is proportional to the C:N ratio in the living phytomass that reflects nitrogen starvation of plants; 2) decay rate for dead organic matter decreases with the increase of C:N ratio in the dead organic matter. These two rules work both for peatland and forest ecosystems (Alexandrov et al., 1994). Flow functions are selected according to the rules, expert knowledge and principal laws of biological turnover (Bazilevich and Titlyanova, 2008).

For example let us describe 3-component model design for wetlands and spruce forest ecosystems of middle and southern taiga in the European part of Russia (scheme at fig. 1). According to the first principle, flow  $f_{13}^C$  is of a donor type and can be expressed as  $f_{13}^C = \alpha_{13} \cdot C_1 \cdot C_1 / N_1 = \alpha_{13} \cdot C_1^2 / N_1$ . Intensity of the corresponding nitrogen flow  $f_{13}^N$  is considered proportional to its concentration in the living organic matter and the nitrogen-carbon ratio in the litterfall:  $f_{13}^N = \alpha_{13} \cdot C_1^2 / N_1 \cdot a \cdot N_1 / C_1 = \alpha_{13} \cdot C_1$  with some coefficient  $a$ . According to the second principle, consumption of the dead organic matter from litter increases proportionally to the  $N_3/C_3$ -ratio in the litter and simultaneously to the storage  $C_3$ :  $f_{32}^C = \gamma_{32} \cdot C_3 \cdot C_2 \cdot N_3 / C_3 = \gamma_{32} \cdot C_2 \cdot N_3$ . In contrast to the previous model by Logofet and Alexandrov, this flow is also proportional to the biomass of consumers and destructors  $C_2$ . The corresponding nitrogen flow  $f_{32}^N$  is proportional to the same ratio  $N_3/C_3$  and the carbon contents in the biomass  $C_2$ :  $f_{32}^N = \gamma_{32} \cdot C_2 \cdot N_3 / C_3$ . The opposite flows have a simple donor-type form:  $f_{23}^N = a_{23} \cdot N_2$  and  $f_{23}^C = a_{23} \cdot C_2$ . Representation of the nitrogen turnover in litter has some peculiarities in this model due to a low number of compartments and indirect account of mineralization and humification processes. A part of nitrogen generated after decaying of dead organic matter becomes available for plants to be consumed from litter or a upper peat layer while the rest consists of compounds unavailable for plants and other biota and can move to adjacent ecosystems and peat or be accumulated in the litter. Output flow of runoff is linear while for adequate representation of the decay process flow  $f_{31}^N$  is needed. Its form is also determined by the second biochemical rule:  $f_{31}^N = N_3 \cdot C_1 \cdot \gamma_{31} \cdot N_3 / C_3 = \gamma_{31} \cdot N_3^2 \cdot C_1 / C_3$ , where  $\gamma_{31} \cdot N_3 / C_3$  is the quantity of nitrogen transformed into the labile form per unit of dead organic matter, while the linear flow  $y_{31}^N = m_3 \cdot N_3$  describes runoff to adjacent ecosystems, abiotic oxidation and peat formation for peatlands. For adequate reflection of competition within vegetation cover, input flow  $q_1^C$  corresponding to the carbon assimilation from the atmosphere by plants due to photosynthesis depends on the carbon content in

vegetation as a function with saturation:  $q_1^C = \frac{K_{01} C_1}{L_{01}^C + C_1}$ , where  $K_{01}$  is a maximal rate

of photosynthesis,  $L_{01}^C$  is a half-saturation constant on carbon content in vegetation per unit square. According to (Tonitto, Powell, 2006), the maximal photosynthesis rate  $K_{01}$  in the simplest case linearly depends on the nitrogen content in the vegetation:  $K_{01}(N_1) = K_{01}^C N_1$ . All output flows are assumed linear functions of their storages. Taking into account this relation one can obtain the system of ordinary differential equations describing a combined turnover of carbon and nitrogen in forest and wetland ecosystems for the annual time scale:

$$\left\{ \begin{array}{l} dC_1 / dt = C_1 \left( \frac{K_{01}^C N_1}{L_{01}^C + C_1} - m_1^C - \gamma_{12}^C C_2 - \alpha_{13}^C \frac{C_1}{N_1} \right) \\ dN_1 / dt = -m_1^N N_1 - \gamma_{12}^N C_2 N_1 - \alpha_{13}^N C_1 + \gamma_{31}^N C_1 \frac{N_3^2}{C_3} \\ dC_2 / dt = C_2 \left( -m_2^C + \gamma_{12}^C C_1 - \alpha_{23}^C + \gamma_{32}^C N_3 \right) \\ dN_2 / dt = q_2^N C_2 - m_2^N N_2 - \alpha_{23}^N N_2 + \gamma_{12}^N C_2 N_1 + \gamma_{32}^N \frac{N_3^2}{C_3} C_2 \\ dC_3 / dt = q_3^C - m_3^C C_3 + \alpha_{13}^C \frac{C_1^2}{N_1} + \alpha_{23}^C C_2 - \gamma_{32}^C C_2 N_3 \\ dN_3 / dt = q_3^N - m_3^N N_3 + \alpha_{13}^N C_1 + \alpha_{23}^N N_2 - \gamma_{31}^N \frac{N_3^2}{C_3} C_1 - \gamma_{32}^N C_2 \frac{N_3^2}{C_3} \end{array} \right. \quad (1)$$

Analogously, dynamic equations can be constructed for the 2-component carbon-nitrogen cycle scheme designed by data for western siberian wetlands (fig. 2).

Flows can depend on climatic variables – annual temperature and precipitation over vegetation period. Stationary points of each model reflect climax states of biological succession while stability loss corresponds to transitions between these states. Methods of bifurcation theory allow determine stability boundaries for steady states of each model in the space of parameters depending on climatic variables and some hydrologic characteristics. The most important among them are carbon assimilation, peat formation and decay of dead organic matter rates. The modeling system for analysis of a biological turnover in ecosystems and numerical experiments on its dynamics includes modules realizing the compartment scheme design, algorithms for selection of flow functions, bifurcation analysis for possible equilibria, climatic dependencies evaluation, numerical integration and estimating future trajectories for all carbon and nitrogen storages and flows. Expert knowledge is used for estimation of equilibria evolution under climate change and human perturbations.

### Conclusions

For modeling consequences of climate change we use a set of scenarios formed by some climate models (MPIM-ECHAM5, UKMO-HADGEM1) participating in CMIP3 and included in the 4<sup>th</sup> IPCC Report (2007) (Denman et al., 2007). The typical feature of one scenario is CO<sub>2</sub> doubling in the atmosphere with 1% annual rate and a constant content after the doubling until 2100. Another numerical experiments are carried out with localizations of standard A2, B1, A1B scenarios. In result, a part of oligotrophic bogs in western-siberian middle taiga can be transformed into fir forests while meso- and eutrophic peatlands are probable to shift into a fen state. However, raised bogs (ryams) in southern taiga can convert both into pine forests and into grass fen. In European territory of Russia simulations show possible transformations of oligotrophic bogs into mesotrophic state and eutrophication of mesotrophic accompanying by spruce forest spreading. At the same time, a part of oligotrophic bogs are transformed in pine forest states. Anthropogenic perturbations (fires and peat mining) can correct natural trajectories of peatland and forest ecosystems evolution.

### ACKNOWLEDGMENTS

The work is supported by the Program 12 of the Earth Sciences Department of the Russian Academy of Sciences and Russian Fund of Basic Research (project 10-05-00265a).

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