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BIOTIC TURNOVER IN FOREST AND PEATLAND ECOSYSTEMS OF BOREAL AND FOREST-STEPPE ZONES IN THE EUROPEAN TERRITORY OF RUSSIA AND WESTERN-SIBERIA UNDER CLIMATE CHANGE

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Problems and uncertainties in modeling biogeochemical cycles

-incompleteness of measurements on important reservoirs and flows (e.g., microorganisms and decay rates);
- uncertainty in information on flow dependences in different conditions for many types of peatlands;
-"upscaling" problem: algorithms are needed for spreading geographically local modelling results on large territories with estimating their correctness;
- how to account for uncertainty in storage-flow values ?

Main goals in mathematical modelling of biological turnover in ecosystems on an annual time scale

- aggregation of complicated schemes of biological turnover in peatland ecosystems to simplest variants;

- design and calibration for dynamic models of carbon and combined carbon-nitrogen cycle in some types of forest and peatland ecosystems of boreal and forest-steppe zones on the basis of aggregated schemes;

- calculation of stability boundaries for steady states of single and combined cycles, study of their evolution under input flows and parameter variations initiated by climate change;

- model estimating changes in carbon and nitrogen functioning which can be considered as a reaction of peatland ecosystems to external climatic perturbations.

Biogeochemical cycles in ecosystems of boreal and forest-steppe zones

Due to structural complexity and lack of knowledge on functioning mechanisms, mathematical modeling of main ecosystem biogeochemical cycles is necessary for forecasting reactions and dynamic behavior of those ecosystems to external perturbations.

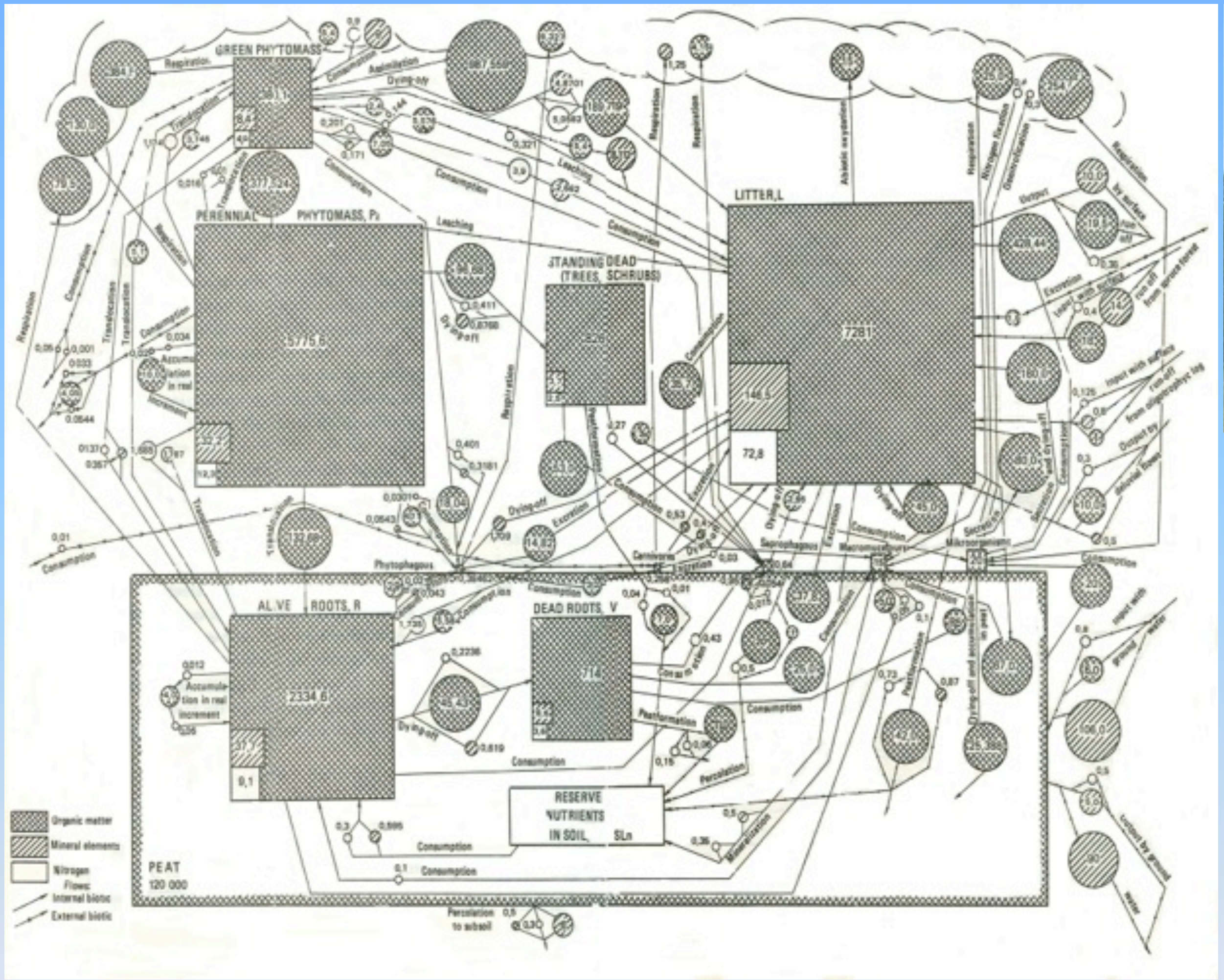
Peatlands and forests of middle and southern taiga take an important part in regulating biogeochemical cycles of carbon, nitrogen, water and mineral elements both at regional and at the global levels. Carrying out an active matter exchange with the environment they can be sources or stocks for green-house gases under the climate change and human economic and resource-extraction activities.

Model classes for biotic turnover

Detailed simulation models

Qualitative "minimal" models

Biogeochemical cycles in a peatland ecosystems of middle and southern taiga

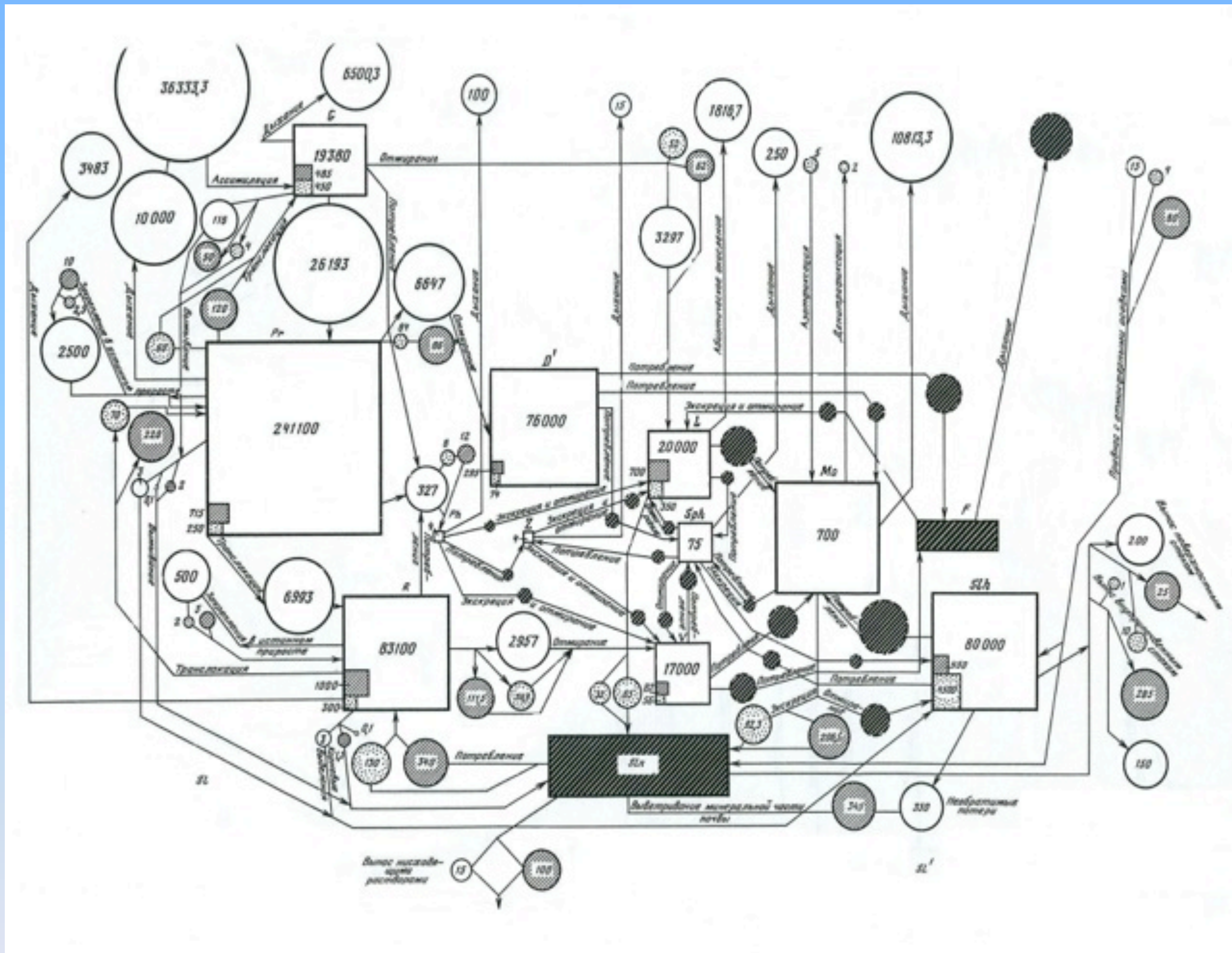


Mesotrophic peatland ecosystem in the southern taiga, European part of Russia (Novgorod region): carbon, nitrogen and mineral element biotic cycles (Bazilevich and Tishkov, 1982, 1986; Alexandrov et al., 1994)

?

Local low-parametric dynamic model of coupled carbon-nitrogen cycles with climatic parameterization and steady states corresponding to the bog ecosystem types

Biogeochemical cycles in a spruce forest in southern taiga of the European territory of Russia



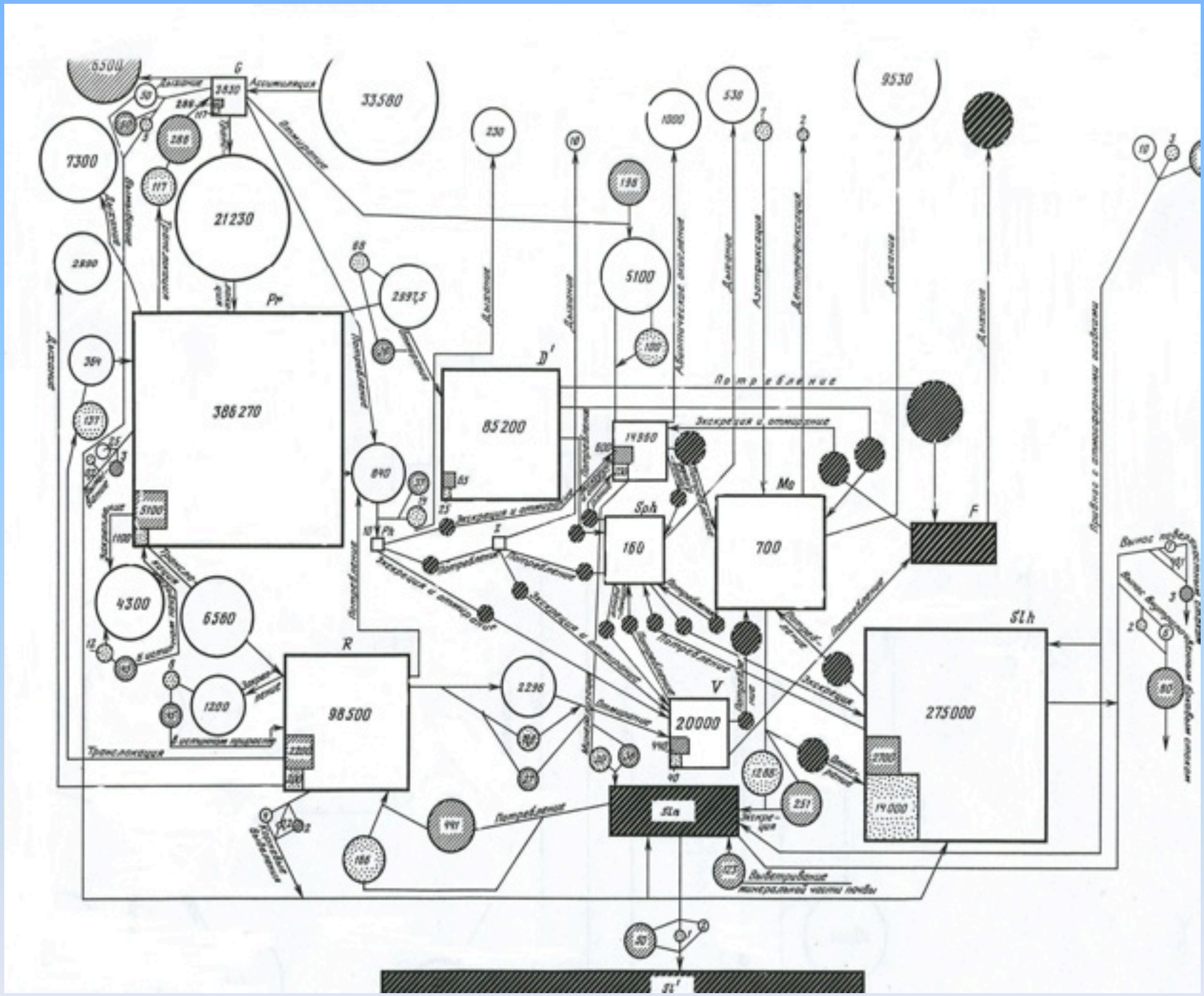
Biotic turnover in the ecosystem of the spruce forest, Central Forest Reserve (Tver Region): carbon, nitrogen and mineral element cycles (Bazilevich and Tishkov, 1982; Glazov, 2004)

?

Local low-parametric dynamic model of coupled carbon-nitrogen cycles with climatic parameterization and steady states corresponding to spruce forest types

Photo is from (Bazilevich and Titlyanova, 2008)

Biogeochemical cycles in an oak-forest in forest-steppe ecosystems



Oak forest ecosystem in the forest-steppe zone, European part of Russia : carbon, nitrogen and mineral element biotic cycles (Bazilevich et al., 1986)

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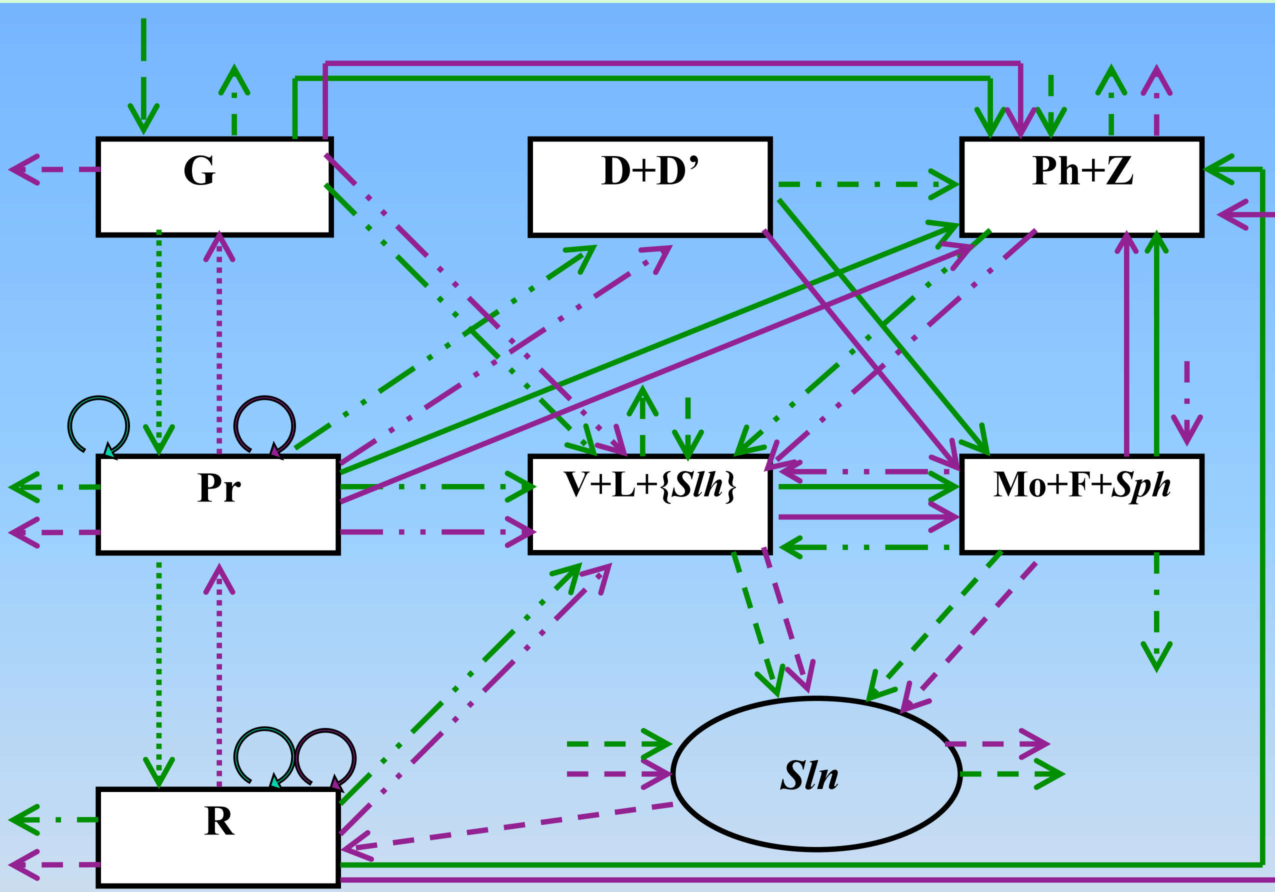
Local low-parametric dynamic model of coupled carbon-nitrogen cycles with climatic parameterization and current steady state

Universality of biotic turnover in terrestrial ecosystems and aggregation principles

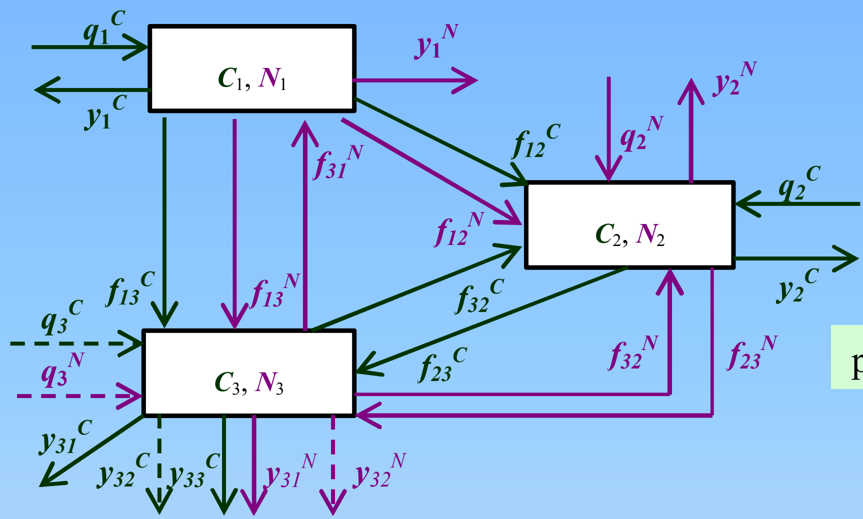


Carbon and nitrogen flows in an ecosystem:
photosynthesis,
respiration,
denitrification and nitrogen fixation
consumption,
litterfall, excretion
accumulation in real increment,
import and export, abiotic oxidation,
translocation

Reservoirs: G – green phytomass, Pr – perennial phytomass, R – living roots, D+D’- dead standing phytomass, V+L+{*Slh*} – dead roots + litter + {humus}, Ph+Z – phyto- and zoophages, Mo+F+*Sph* – microorganisms+fungi+saprophages, *Sln* – soil reserve nutrients.

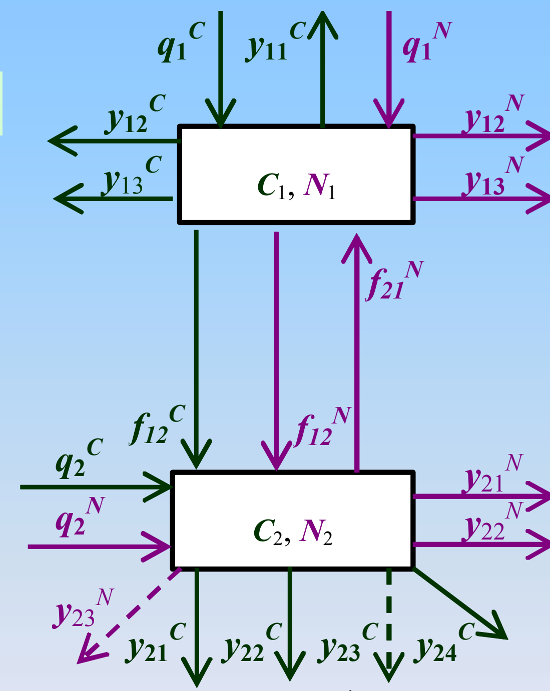
Aggregation principles: 1) division of living and dead organic matter;
2) division of above- and underground living organic matter;
3) consumers (*C*=Ph+Z) and destructors (*Ds*=Mo+F+*Sph*) are aggregated into separate units independently on where they live.

Minimal aggregated compartment schemes of carbon and nitrogen cycles in forest and peatland ecosystems



Storages :
C_1, N_1 - phytomass; C_2, N_2 – phytophages and destructors (animals, fungi, bacteria); C_3, N_3 – dead organic matter of litter and root-based peat layer

possible aggregation



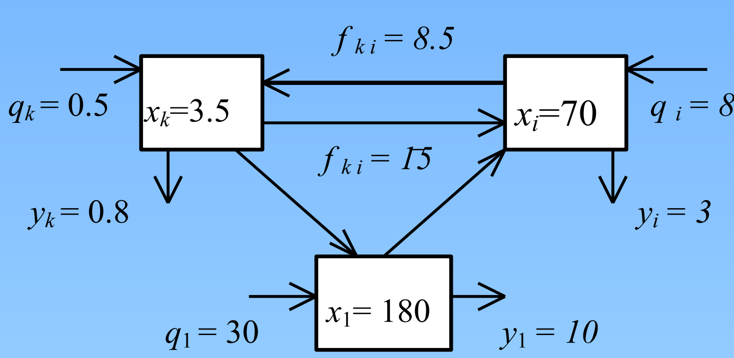
Flows :
q_1^C– carbon assimilation from the atmosphere, q_1^N, q_2^N– nitrogen input from adjacent ecosystems with atmospheric nitrogen fixation by microorganisms, q_2^C– dead organic matter input from adjacent ecosystems, y_{11}^C – autotrophic respiration, y_{12}^C, y_{12}^N – export and run-off, y_{13}^C, y_{13}^N – consumption by phytophages, y_{21}^C, y_{21}^N – decay of dead organic matter by destructors with denitrification, y_{22}^C, y_{22}^N – export and run-off, y_{23}^C, y_{23}^N – peat formation, y_{24}^C – abiotic oxidation of dead organic matter, f_{21}^N – nitrogen uptake by vegetation from available soil compounds, f_{12}^C, f_{12}^N – litterfall.

Storage :
C_1, N_1 – living organic matter;
C_2, N_2 – dead organic matter

Data availability of biotic turnover in peatland and forest ecosystems of the European territory of Russia and Western Siberia

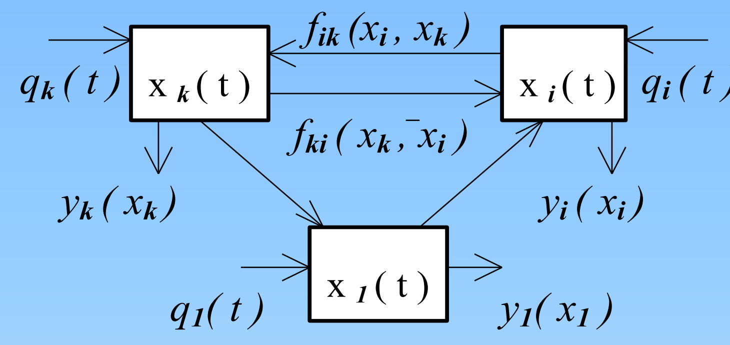
Ecosystem	Carbon cycle	Nitrogen cycle	References
European territory of Russia			
Oligo- and mesotrophic peatlands, pine forest in middle taiga	a number of components	a number of components	Kozlovskaya et al., 1978
Mesotrophic pine-shrub-sphagnum peatland in southern taiga	все компоненты	все компоненты	Bazilevich and Tishkov, 1982, 1986;
Oligotrophic, eutrophic grass, eutrophic forest peatlandsin southern taiga	a number of components	not available	Tishkov, 1986
Spruce forest with bilberry in southern taiga	a number of components	a number of components	Tishkov, 1979; Bazilevich et al., 1986; Glazov, 2004
Spruce forests with green mosses and grasses in southern taiga	a number of components	not available	Glazov, 2004
Pine forest in southern taiga	a number of components	a number of components	Bazilevich and Titlyanova, 2008
Oak forest in forest-steppe zone	a number of components	a number of components	Bazilevich et al., 1986
Western Siberia			
Main types of oligotrophic petlands in southern taiga (ryams, fen)	a number of components	not available	Golovatskaya, Dyukarev, 2009; Valutskii and Khramov, 1977
Eutrophic fen in southern taiga	a number of components	not available	Golovatskaya, 2009
Mesotrophic fen in southern taiga	a number of components	a number of components	Bazilevich and Titlyanova, 2008
Oligotrophic peatlands in middle taiga	a number of components	a number of components	Naumov et al., 2007; Kosykh et al., 2010; Makhatkov et al., 2007
Mesotrophic fen in middle taiga	a number of components	a number of components	Kosykh et al., 2010
Pine forest in southern taiga	a number of components	not available	Vedrova, 1997
Grass peatland in forest-steppe zone	a number of components	a number of components	Titlyanova, 1979; Naumov et al., 2009

General problem of a dynamic model design by a given «storage-flow» diagram



a set of compartment schemes for time moments $t_0, t_1, \ldots,$ collected from field studies

?



dynamic model for storages in reservoires

The main problem: how to make dynamic model from measured static schemes?

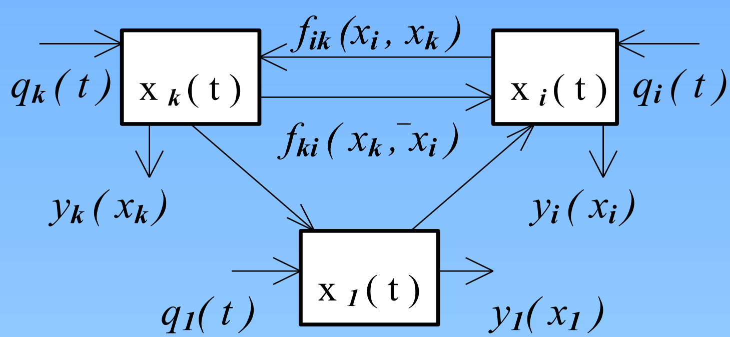
$$\frac{dx_i}{dt} = q_i - y_i + \sum_{k=1, k \neq i}^{n} (f_{ki} - f_{ik})$$

Two main approaches to the dynamic model design

“Global”

“Local”

Two approaches to a dynamic model design by given «storage-flow» diagrams



Mass-balance equations: $\dfrac{dx_i}{dt} = q_i - y_i + \sum_{k=1, k\neq i}^{n} (f_{ki} - f_{ik})$

"Global" approach

1) any number of static schemes for various time moments can be a source for a dynamic model;

2) $y_i = m_i x_i$ – output flows are linear;

3) $q_i = q_i(x_i)$, $f_{ki} = f_{ki}(x_k, x_i)$; $f_{ik} = f_{ik}(x_i, x_k)$ – flow functions are selected using <u>biological information and expert knowledge,</u> e.g., $\alpha_{ij} x_i$ - donor type, $\beta_{ij} x_j$ - recipient type, $\gamma_{ij} x_i x_j$ - Lotka-Volterra type, saturation types:

$$\frac{K_{ki} x_k x_i}{L_{ki} + x_i}, \quad \frac{K_{ki} x_k x_i}{L_{ki} + x_k}, \quad \frac{K_{ki} x_k x_i}{(L_{ki} + x_k)(N_{ki} + x_i)}$$

"Local" method

1) $\mathbf{q}^* + \mathbf{f}^* = \mathbf{y}^*$ - at least one of the given diagrams is a <u>dynamic equilibrium</u>;

2) $y_i = m_i x_i$ – output flows are linear;

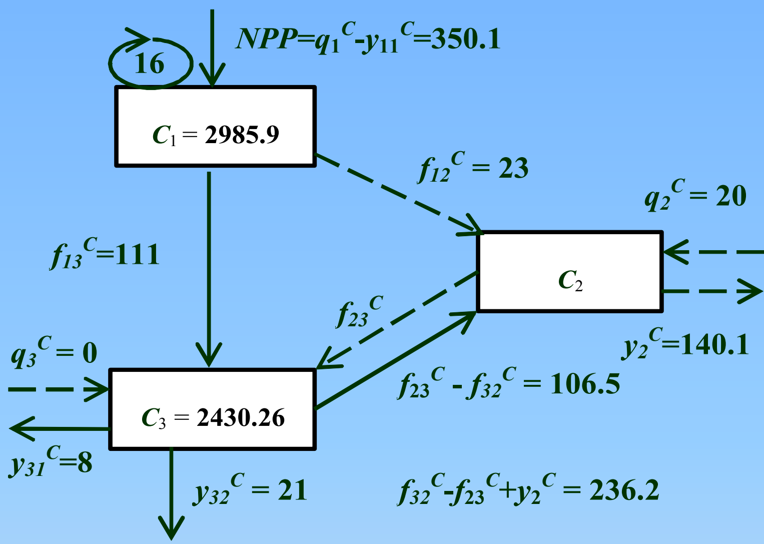
3) $f_{ki} = f_{ki}(x_k, x_i)$; $f_{ik} = f_{ik}(x_i, x_k)$ – flow functions are represented asymptotically <u>near the given equilibrium</u>, $\tilde{x}_i = x_i - x_i^*$:

$$f_{ij}(x^* + \tilde{x}) = f_{ij}^* + \alpha_{ij}\tilde{x}_i + \beta_{ij}\tilde{x}_j + \gamma_{ij}\tilde{x}_i\tilde{x}_j + \xi_i\tilde{x}_i^2 + \eta_i\tilde{x}_j^2 + \ldots$$

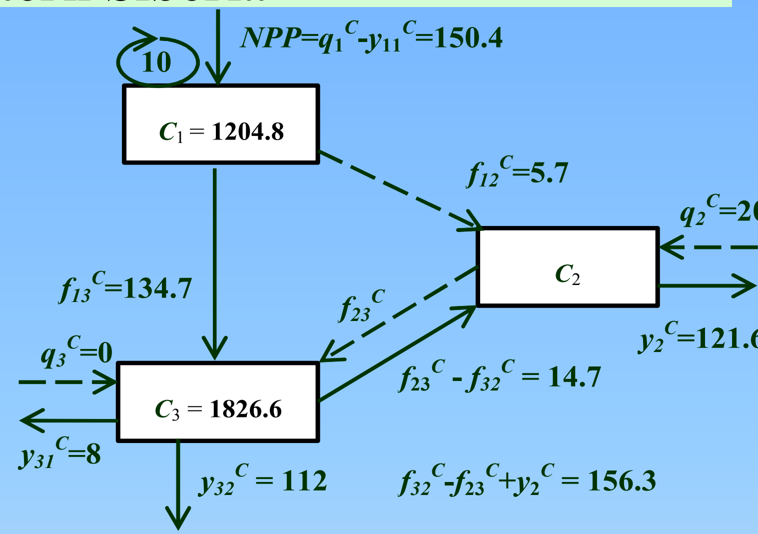
$$\frac{d\tilde{x}_i}{dt} = \tilde{x}_i \sum_{j\neq i} \beta_{ji} - \alpha_{ij} + \sum_{j\neq i} \tilde{x}_j(\alpha_{ji} - \beta_{ij}) + $$
$$+ \sum_{j\neq i} (\gamma_{ji} - \gamma_{ij})\tilde{x}_i\tilde{x}_j + \sum_{j\neq i} \tilde{x}_j^2(\xi_j + \eta_j) + \ldots$$

Biomass and Net Primary Production in the biological turnover

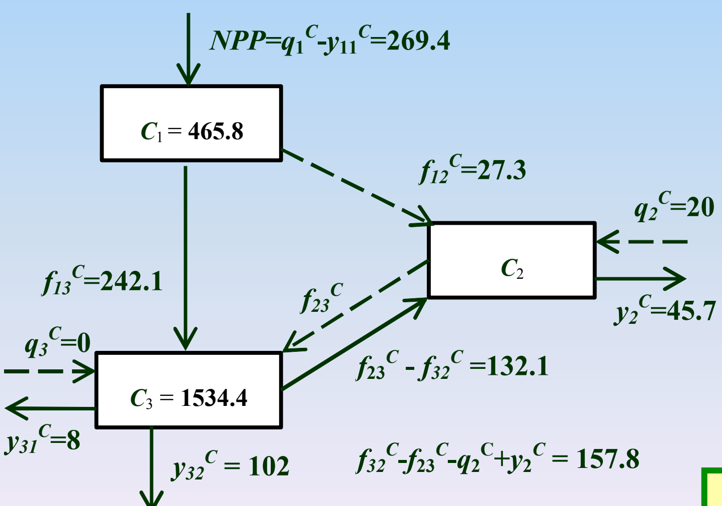
Minimal static schemes of carbon cycle in peatland ecosystems of southern taiga in Western Siberia



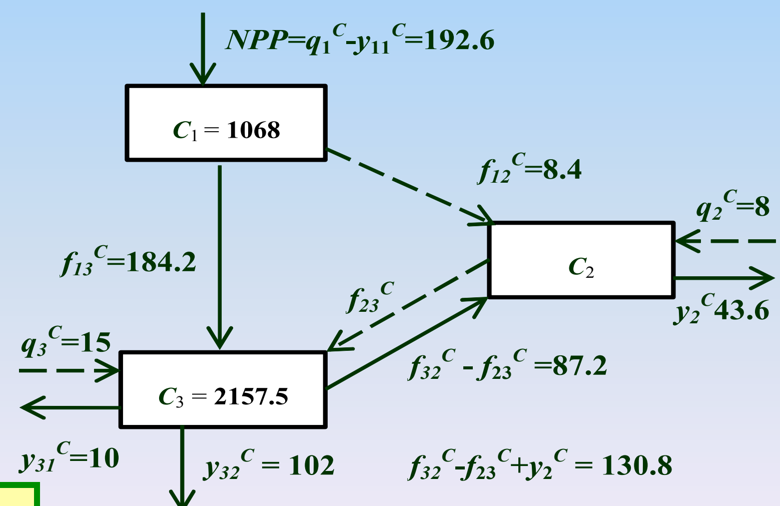
Oligotrophic pine-shrub-sphagnum



Oligotrophic low pine-shrub-sphagnum



Oligotrophic sedge-sphagnum fen

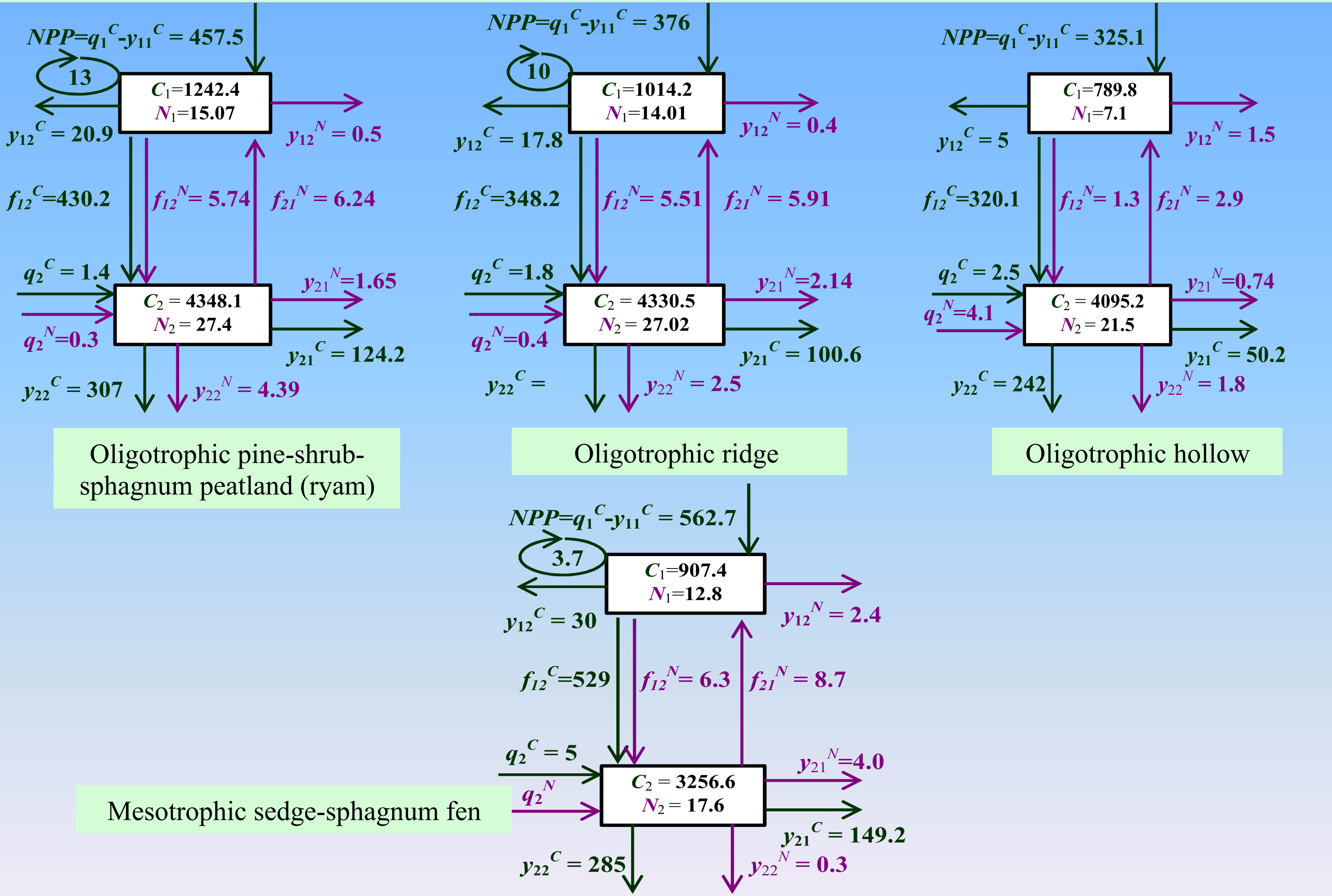


Eutrophic sedge-sphagnum fen

Storages - gC/m^2,
flows - gC/m^2·year.

Data from (Golovatskaya, Dyukarev, 2009; Golovatskaya, 2010; Valutskii, Khramov, 1977).

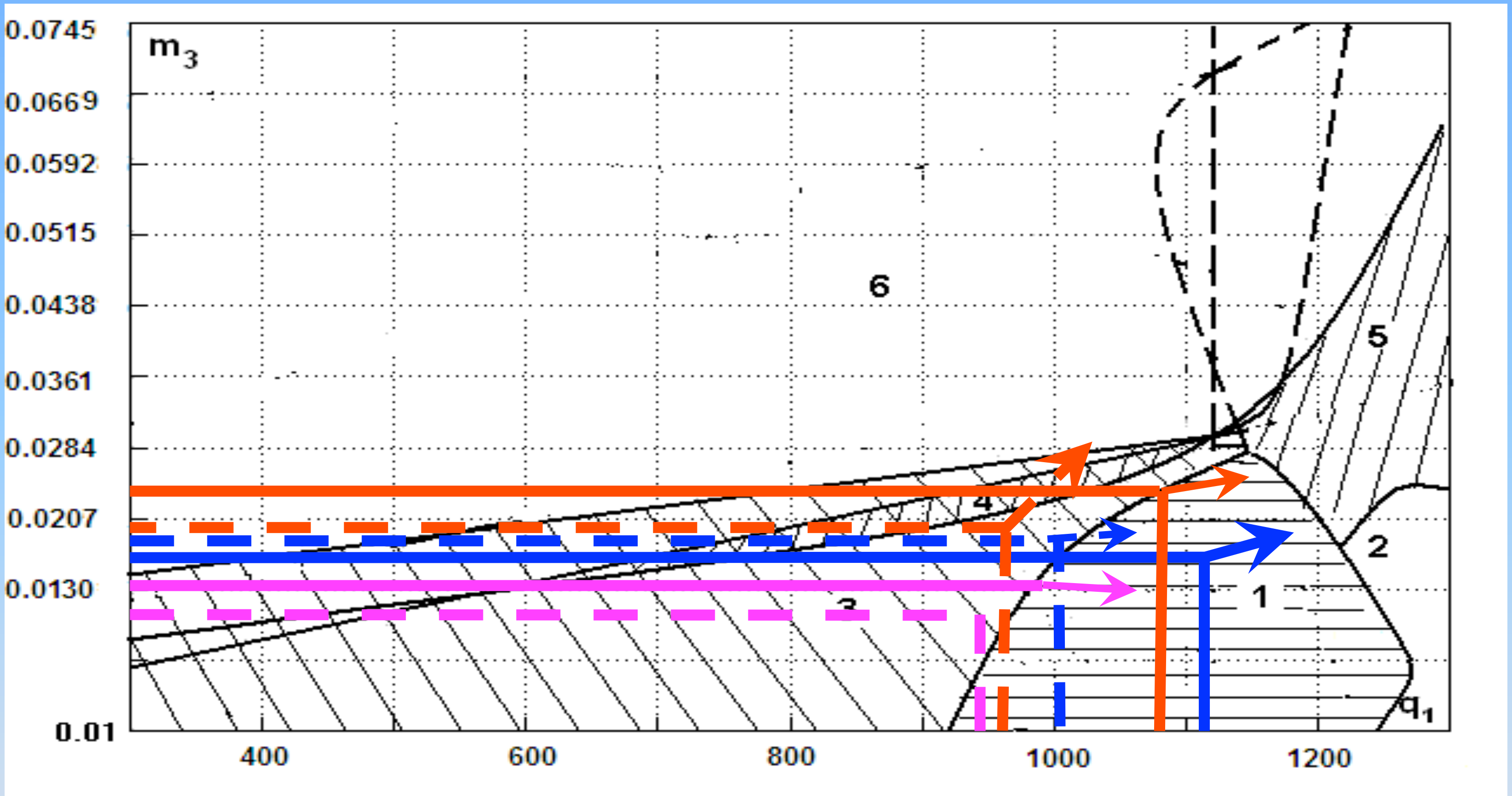
Carbon and nitrogen cycles in peatland ecosystems of middle taiga in Western Siberia



Data from (Kosykh, Mironycheva-Tokareva, Parshina, 2010; Makhatkov, Kosykh, Romantsev, 2007; Makhatkov, Kosykh, 2010).

Storages - gC/m^2, gN/m^2,
flows - gC/m^2·year, gN/m^{2}year.

Possible evolution of peatland turnover under atmospheric CO_2 doubling climate change

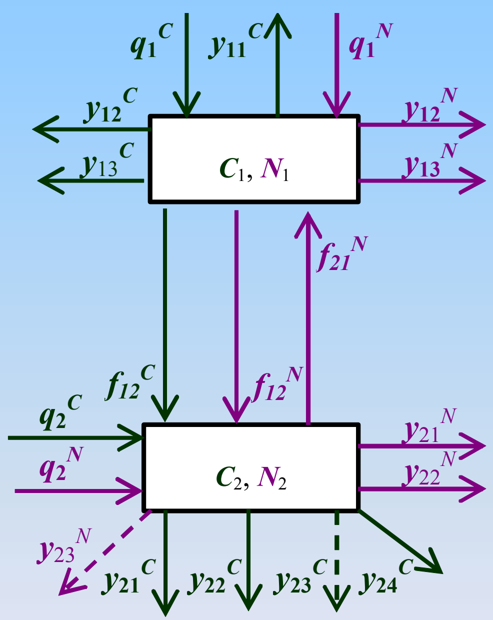


Mesotrophic	Zone	Raised
———	West-Siberian southern taiga	– – –
———	West-Siberian middle taiga	– – –
———	West-Siberian forest-steppe	– – –

1 – oligotrophic bog – “ryam”; 2 – mesotrophic mire; 3 – oligotrophic fen; 4 – mesotrophic fen; 5 – sphagnum pinery; 6 – eutrophic mire

Modelling a combined carbon-nitrogen turnover in forest and peatland ecosystems: biological mechanisms

<u>Carbon and nitrogen interaction is provided by two mechanisms</u> (Logofet, Alexandrov, 1984):
1) intensity of litterfall (f_{12}^{C}) is proportional to the C_1/N_1 ratio in the living phytomass that reflects nitrogen starvation of plants;
2) decay rate for dead organic matter decreases with the increase of C_3/N_3 ratio.



<u>Mathematical form for coupled *N-C* потоков</u> (Alexandrov et al., 1994):

1) Litterfall :

- carbon flow: $f_{12}^{C} = \alpha_{12}^{C}\dfrac{C_1^2}{N_1}$, nitrogen flow: $f_{12}^{N} = \alpha_{12}^{N} C_1$

2) Decomposition of dead organic matter:

- carbon flow: $y_{21}^{C} = d_2^{C} N_2$, - nitrogen flow: $y_{21}^{N} = d_2^{N}\dfrac{N_2^2}{C_2}$

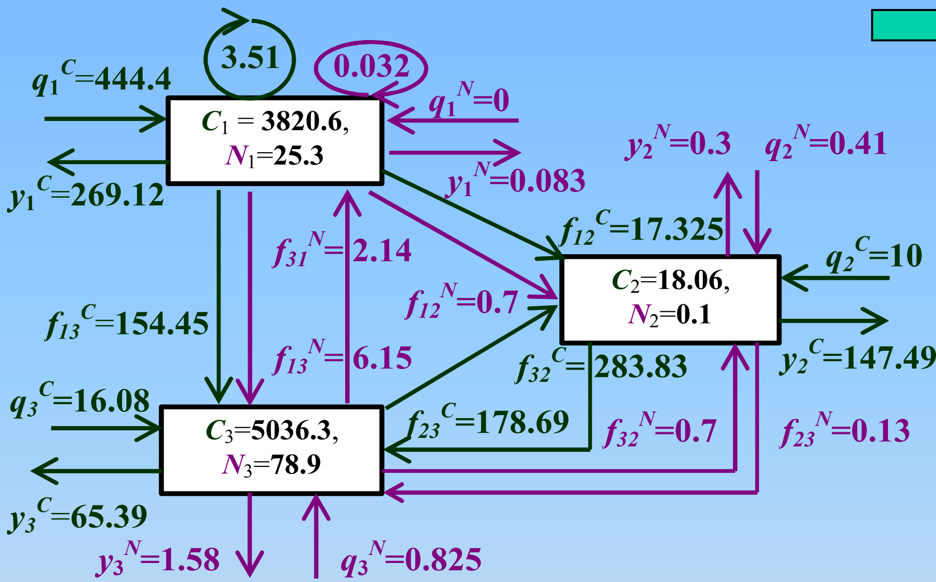
<u>Other intercompartment flows</u>:

- nitrogen uptake from soil by plants: $f_{21}^{N} = \gamma_{21}^{N}\dfrac{N_2^2}{C_2}C_1$
- carbon assimilation from the atmosphere by vegetation: $q_1^{C} = \dfrac{K_{01}^{C} C_1 N_1}{L_{01}^{C} + C_1 + P_{01} N_1}$
- consumption of living phytomass by phytophages:

  $\boldsymbol{y_{12}^{C}=\alpha_{12}^{C}C_1}$, $\boldsymbol{y_{12}^{N}=\alpha_{12}^{N}N_1}$;
- peat formation process: $\boldsymbol{y_{23}^{C}=m_{23}^{C}C_2}$, $\boldsymbol{y_{23}^{N}=m_{23}^{N}N_2}$;
- export to other systems and run-off: $\boldsymbol{y_{22}^{C}=m_{22}^{C}C_2}$, $\boldsymbol{y_{23}^{N}=m_{22}^{N}N_2}$.

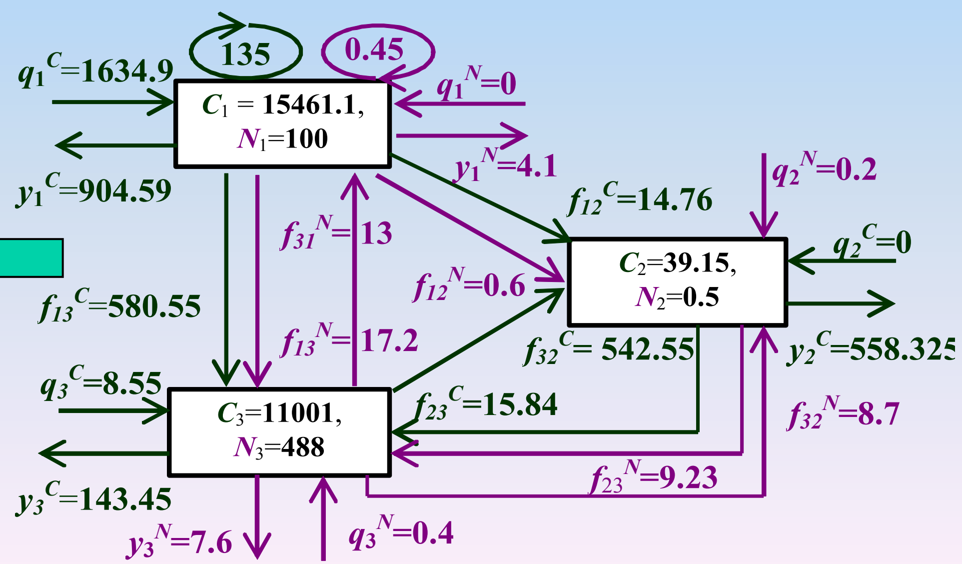
Minimal schemes of carbon and nitrogen cycles in peatland and spruce forest ecosystems of southern taiga in the European territory of Russia

Mesotrophic peatland



Peatland type	*NPP, gC/ m²year*	*C_1, gC/ m²*	*N_1, gN/ m²*	*C_3, gC/ m²*
Mesotrophic	175	3821	25	5036
Oligotrophic	99	2305	15	3785
Eutrophic grass	45	175	-	405
Eutrophic forest	232	3956	26	1516
Pinery	550	23000	68	5500

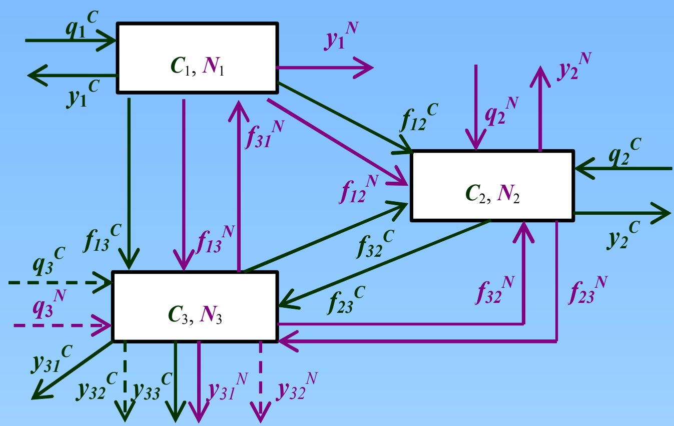
Spruce forest with bilberry



Forest type	*NPP, gC/ m²year*	*C_1, gC/ m²*	*N_1, gN/ m²*	*C_3, gC/ m²*
Spruce forest with bilberry	562	15461	100	11001
Spruce forest with mosses	377	10860	55	8845
Spruce forest with grass	612	15640	-	9548

Storages - g*C*/m², g*N*/m²,
flows - g*C*/m²·year, g*N*/m²year.

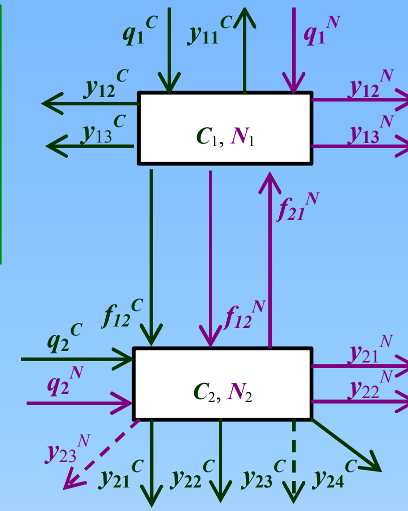
Dynamic equations of the combined carbon and nitrogen turnover in forest and peatland ecosystems (“global” method)



Mass-balance equations:

$$\frac{dC_i}{dt} = q_i^C - y_i^C + \sum_{k=1,k\neq i}^{n} (f_{ki}^C - f_{ik}^C) \qquad i = 1,\ldots,n$$

$$\frac{dN_i}{dt} = q_i^N - y_i^N + \sum_{k=1,k\neq i}^{n} (f_{ki}^N - f_{ik}^N)$$



Dynamic equations of a three-component model:

$$\begin{cases} dC_1/dt = C_1\left(\dfrac{K_{01}^C N_1}{L_{01}^C + C_1 + P_{01}N_1} - m_1^C - \gamma_{12}^C C_2 - \alpha_{13}^C \dfrac{C_1}{N_1}\right) \\ dN_1/dt = -m_1^N N_1 - \gamma_{12}^N C_2 N_1 - \alpha_{13}^N C_1 + \gamma_{31}^N C_1 \dfrac{N_3^2}{C_3} \\ dC_2/dt = K_2^C C_2 + C_2\left(-m_2^C + \gamma_{12}^C C_1 - \alpha_{23}^C + \gamma_{32}^C N_3\right) \\ dN_2/dt = K_2^N C_2 - m_2^N N_2 - \alpha_{23}^N N_2 + \gamma_{12}^N C_2 N_1 + \gamma_{32}^N \dfrac{N_3^2}{C_3} C_2 \\ dC_3/dt = q_3^C - m_3^C C_3 + \alpha_{13}^C \dfrac{C_1^2}{N_1} + \alpha_{23}^C C_2 - \gamma_{32}^C C_2 N_3 \\ dN_3/dt = q_3^N - m_3^N N_3 + \alpha_{13}^N C_1 + \alpha_{23}^N N_2 - \gamma_{31}^N \dfrac{N_3^2}{C_3} C_1 - \gamma_{32}^N C_2 \dfrac{N_3^2}{C_3} \end{cases} \qquad (1)$$

Dynamic equations of a two-component model:

$$\begin{cases} dC_1/dt = C_1\left(\dfrac{K_{01}^C N_1}{L_{01}^C + C_1 + P_{01}N_1} - m_1^C - \alpha_{13}^C - \alpha_{12}^C \dfrac{C_1}{N_1}\right) \\ dN_1/dt = -m_1^N N_1 - \alpha_{13}^N N_1 - \alpha_{12}^N C_1 + \gamma_{21}^N C_1 \dfrac{N_2^2}{C_2} \\ dC_2/dt = q_2^C - m_2^C C_2 - d_2^C N_2 + \alpha_{12}^C \dfrac{C_1^2}{N_1} \\ dN_2/dt = q_2^N - m_2^N N_2 + \alpha_{21}^N C_1 - \gamma_{21}^N \dfrac{N_2^2}{C_2} C_1 - d_2^N \dfrac{N_2^2}{C_2} \end{cases} \qquad (2)$$

Parameter calibration for dynamic models of coupled carbon-nitrogen cycle in peatland ecosystems and climate-induced values

The main idea for calibrating coefficients $K_{01}{}^{C}$ and $L_{01}{}^{C}$ is to use the net primary productivity (NPP) of living phytomass for two ecosystems, adjacent in state:

$$NPP = \frac{K_{01}^{C} C_1 N_1}{L_{01}^{C} + C_1} - m_1^{C} C_1 \Rightarrow \begin{cases} (NPP^m + m_1^m C_1^m)(L_{01}^C + C_1^m) = K_{01}^C C_1^m N_1^m & \text{- for basic peatland} \\ (NPP^o + m_1^o C_1^o)(L_{01}^C + C_1^e) = K_{01}^C C_1^o N_1^o & \text{- for calculated peatland} \end{cases} \quad (2)$$

For example, from (2) for oligotrophic (index ^{o}) and mesotrophic (index ^{m}) peatlands coefficients of the flow $q_1{}^{C}$ can be calculated easily:

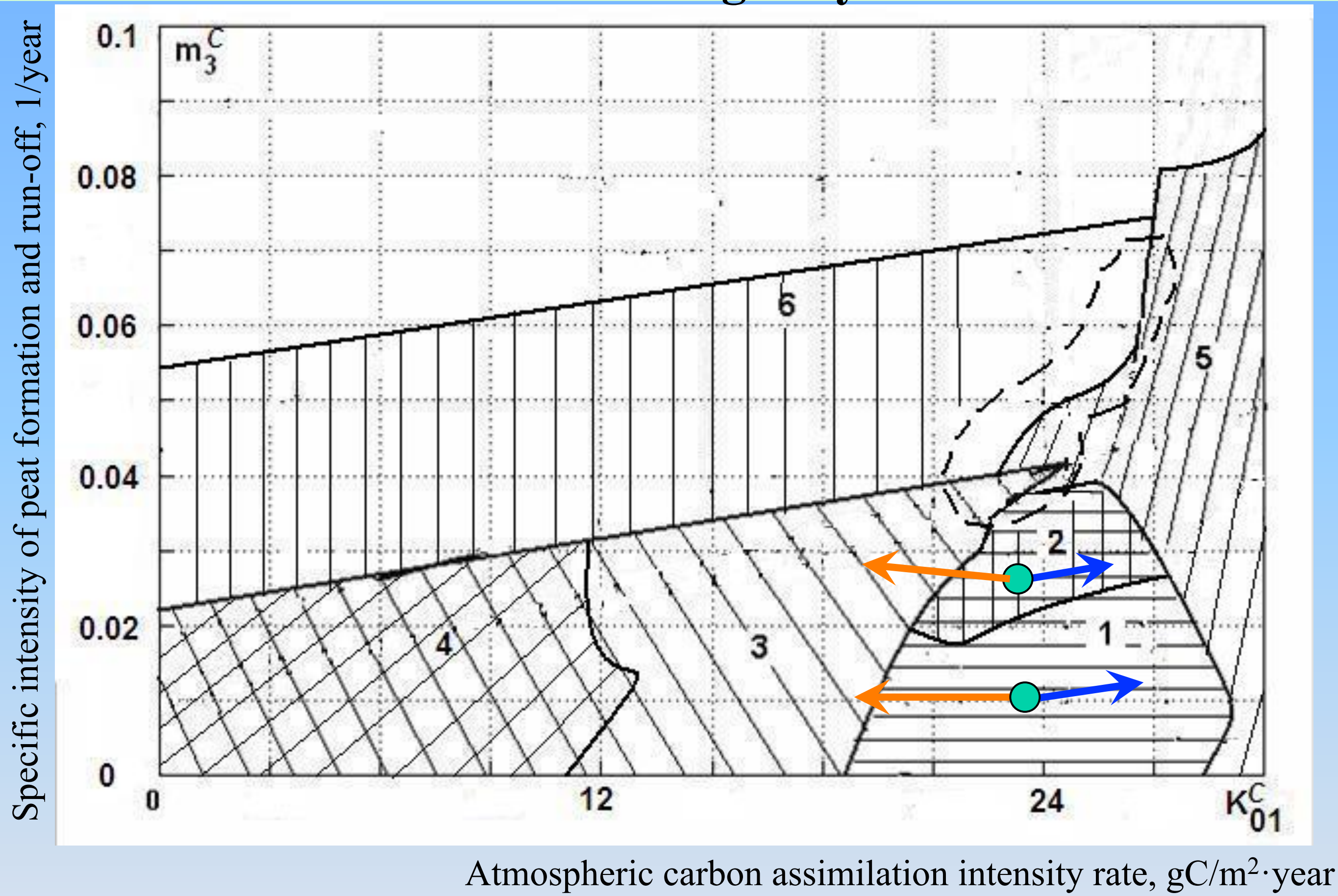
$$L_{01}^{C} = \frac{C_1^m \left[(NPP^o + m_1^o C_1^o)\dfrac{N_1^m}{N_1^o} - NPP^m - m_1^m C_1^m \right]}{NPP^m + m_1^m C_1^m - (NPP^o + m_1^o C_1^o)\dfrac{C_1^m N_1^m}{C_1^o N_1^o}}, \quad K_{01}^{C} = \frac{q_1^C (L_{01}^C + C_1^m)}{C_1^m N_1^m}$$

Coefficients of flow functions depending on the single storage are calculated from the given scheme:

$$\alpha_{ki} = \frac{f_{ki}^*}{x_k^*}; \quad \beta_{ki} = \frac{f_{ki}^*}{x_i^*}; \quad \gamma_{ki} = \frac{f_{ki}^*}{x_i^* x_k^*}; \quad m_i = \frac{y_i^*}{x_i^*};$$

Temperature dependent model parameters with change according to scenarios of global climate model MPIM-ECHAM5 of CO_2 concentration doubling in the atmosphere:
$q_1{}^{C} = q_1{}^{C}(C_1)$- carbon assimilation by plants increases under atmospheric CO_2 content; $m_3{}^{C} = m_3{}^{C}(T)$– peat formation intensity, $m_2{}^{C} = m_2{}^{C}(T,H)$ – heterotrophic respiration intensity and $\gamma_{32}{}^{C} = \gamma_{32}{}^{C}(T,H)$ – intensity of decay for dead organic matter depend on the annual air temperature and precipitation sum in a polynomial form.

Stability boundaries for dynamic regimes in two-component models of coupled carbon-nitrogen cycle



Stability boundaries of stationary dynamic regime of the biological turnover:

1 – oligotrophic bog – "ryam"; 2 – mesotrophic mire; 3 – mesotrophic fen; 4 – oligotrophic fen; 5 – sphagnum pinery; 6 – eutrophic mire

Conclusions

1) **method of dynamic compartment model design by static "storage-flow" schemes helps in constructing coupled models of carbon-nitrogen cycle functioning in peatland ecosystems based on two most important connections: litterfall dependence on *C*/*N* relation in living organic matter and increase of decomposition rate under *C*/*N* decrease in dead organic matter;**

2) including nitrogen cycle in the model of ecosystem functioning allows to reflect biologically possible states of bog and forest more adequately than it was for single carbon cycle models, although not all steady states appear under the particular set of coefficients;

3) under the doubling of the atmospheric CO_2 content, accompanied by annual temperature increase, oligotrophic peatlands (ryams) of the middle and southern taiga in Western Siberia can be transformed into sphagnum pineries, if precipitation would decrease, and into fens in the opposite case;

4) mesotrophic peatlands under this climate scenario can be transformed into oligotrophic ones, or sphagnum pineries.

Thank you for attention !

Classification elements of ecosystems in boreal and forest-steppe zones

Элементы классификации лесов в моделях

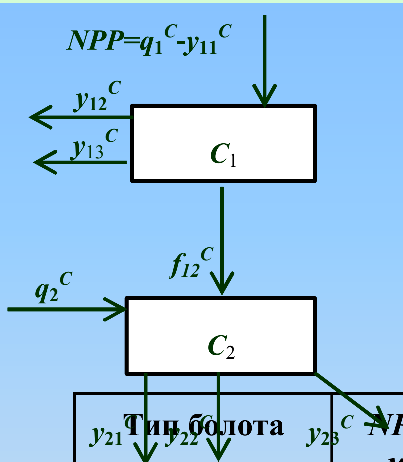
- **березняки**
- **сосняки**
- **ельники**
  - **кисличники**
  - **зеленомошники**
  - **разнотравные**

States of peatlands to be accounted in models

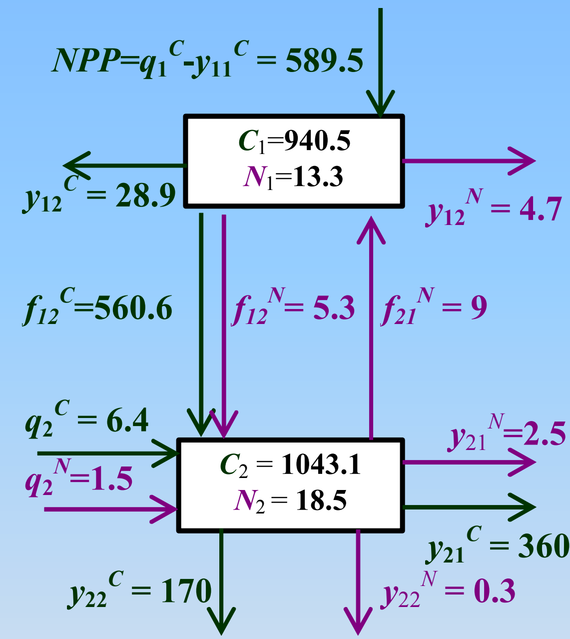
- **by nutrient regime**
  - **oligotrophic**
  - **mesotrophic**
  - **eutrophic**
- **by water regime**
  - **forest**
  - **forest-fen**
  - **fen**

Минимальные схемы углеродного и азотного циклов в болотных экосистемах южной тайги Западной Сибири

Сосняк бруснично-лишайниковый



Мезотрофная осоково-кустарничково-сфагновая топь



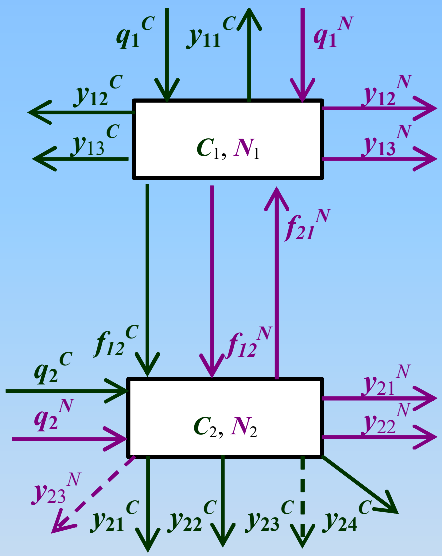
Тип болота	*NPP, гC/м²год*	*C_1, гC/м²*	*N_1, гN/м²*	*C_3, гC/м²*
Мезотрофное	589.5	940.5	13.3	1043
Олиготрофная топь	269.4	465.8	-	1534.4
Низкий рям	313.4	1204.8	-	1826.6

Данные мезотрофного из (Базилевич, Титлянова, 2008).

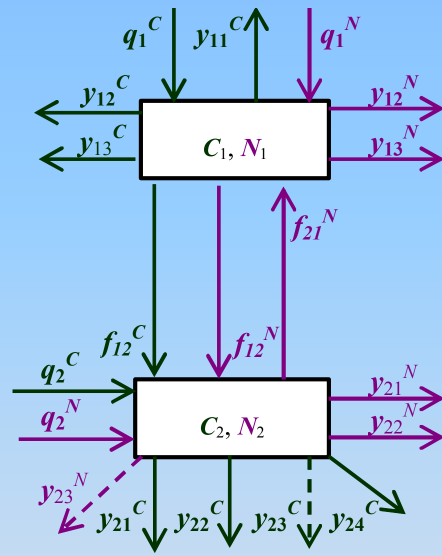
Запасы - гN/м², гC/м²,
потоки - гN/м²·год, гC/м²·год.

Carbon and nitrogen cycles in peatland and forest ecosystems of forest-steppe zone in European Russia and Western Siberia

Дубрава осоково-снытевая (Базилевич и др., 1986; Базилевич и Титлянова, 2008)



Травяное болото в Западной Сибири (Титлянова, 1979)



Данные для .

Reservoirs - g*N*/m², g/m² of dry organic matter,
Flows - g*N*/m²·year, g/m²·year of dry organic matter.