Life-cycle model of terrestrial carbon exchange

Leonid L. Golubyatnikov\textsuperscript{a,*}, Yuri M. Svirezhev\textsuperscript{b}

\textsuperscript{a} Laboratory of Mathematical Ecology, A.M. Obukhov Institute of Atmospheric Physics, Russian Academy of Sciences, Pyzhevsky per. 3, Moscow, 119017, Russia
\textsuperscript{b} Potsdam Institute for Climate Impact Research, P.O. Box 601203, 14412 Potsdam, Germany

A R T I C L E   I N F O

Article history:
Received 27 August 2007
Received in revised form 22 November 2007
Accepted 7 December 2007
Published on line 20 February 2008

Keywords:
Carbon cycle
Modelling
Terrestrial ecosystems

A B S T R A C T

We present here a terrestrial carbon cycle model based on a scheme of the phytomass change, which is continuous in time. The experimental information about net primary production, living and dead phytomass, and soil organic matter for various ecosystems is used for calibration of the model. The suggested model enables to characterize terrestrial ecosystems as carbon sources or carbon sinks and to evaluate intensity of these sources and sinks. The model is applied for the European territory of Russia as a case study. Intensity of the total exchange carbon flux for this territory is evaluated. The obtained results allow to conclude that the given territory is the sink of carbon.

© 2007 Elsevier B.V. All rights reserved.

1. Introduction

Today, when human activities have an increasing impact on the biosphere, to find a balanced evolution between the anthroposphere and environment is the fundamental problem. The carbon cycle is an important component in study of climate change impact on natural vegetation and vegetation feedback on climate. At present, there are a lot of different models of the carbon cycle both for the global level and the local ecosystems. Basic structures of these models are more or less similar: they consist of three compartments (atmosphere, living, and dead organic matter) and three flows (production of organic matter, litter fall, and decomposition of dead organic matter). The carbon cycle models differ from each other by their complexity and details of parameterizations (subdividing the compartments and expanding the flows).

The so-called ‘aggregated’ models are described by a relatively small number of compartments. Usually for models of this type many results about their dynamic properties can be obtained analytically. Examples of ‘aggregated’ models are the model of Logofet and Alexandrov (1984), Kwon and Schnoor (1994), Mukherjee et al. (2002), Svirezhev and von Bloh (1997), Svirezhev et al. (1999), Svirezhev (2002), Eliseev and Mokhov (2007). Other models are based on a detailed description of both physiological and biochemical processes determining the vegetation productivity and also environmental conditions in which these processes are functioning. The models of this category require that a large number of quantitative empirically determined characteristics of the processes under study are known. These models are sensitive with respect to the choice of the governing parameters for vegetation structure. These parameters are known with a very low accuracy (Svirezhev, 2002). Analytical analysis is not available for models of such type. Typical models of this set are the model of Foley et al. (1996), Friend et al. (1997), Ito and Oikawa (2002), Komarov et al. (2003), Sitch et al. (2003), Naqvi and Wein (2006).

In the present paper, we suggest a terrestrial carbon cycle model based on a scheme of the phytomass change, which is continuous in time. This approach is a generalization of that employed in conventional compartmental carbon cycle

\textsuperscript{*} Corresponding author. Tel.: +7 495 951 5565; fax: +7 495 953 1652.
E-mail address: golub@ifaran.ru (L.L. Golubyatnikov).
0304-3800/$ – see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.ecolmodel.2007.12.001
models. In the latter models, organic matter moves from one compartment to another during its life cycle (say, from living matter to the dead one). In our model, this change is figured via change of parameter (denoted as $\tau$) describing age of phytomass and, in turn, its properties. Parameter $\tau$ serves as a ‘demographic’ marker for phytomass. To the best of the author’s knowledge, this approach has not been followed earlier in formulating carbon cycle models. An employment of this approach is a novel feature of the presented model. This method permits us to develop a simple model of carbon exchange for the terrestrial territory under study.

2. Description of model

We consider the following phytomass components in carbon units: photosynthetic (green) phytomass, perennial phytomass (stems, branches, etc.), and root (underground) phytomass. Let us denote by $B_i(t, \tau)$ the phytomass in carbon units of the $i$th component ($i = 1, 2, 3$) for $\tau$ “age” at time moment $t$.

We consider phytomass $B_i(t, \tau)$ along the axis $\tau$ (Fig. 1). Initially, we have the living phytomass. Then, at time moment $\tau^b_i$, living phytomass becomes dead and we have the dead phytomass (mortmass). The mortmass is decaying under biological and non-biological processes. At time moment $\tau^e_i$, the mortmass is transformed into organic matter in soil (humus). The humus is slowly decaying organic substance and its lifetime is very large.

According to this scheme, we can write the following equations for the living phytomass, mortmass, and humus:

$$L(t) = \sum_{i=1}^{3} \int_{0}^{\tau^b_i} B_i(t, \tau) \, d\tau,$$

$$M(t) = \sum_{i=1}^{3} \int_{\tau^b_i}^{\tau^e_i} B_i(t, \tau) \, d\tau,$$

$$D(t) = \sum_{i=1}^{3} \int_{\tau^e_i}^{\infty} B_i(t, \tau) \, d\tau.$$

The mass conservation law for the phytomass $B_i(t, \tau)$ takes on the following form:

$$\frac{\partial B_i}{\partial t} + \frac{\partial B_i}{\partial \tau} = -d_i(\tau)B_i - q(\tau)B_i,$$  \hspace{1cm} (4)

where $d_i(\tau)$ are the coefficients of decay and $q(\tau)$ is the coefficient of abiotic loss:

$$d_i(\tau) = \begin{cases} 0, & \text{if } \tau < \tau^b_i \\ \mu_i, & \text{if } \tau^b_i \leq \tau < \tau^e_i \\ \eta, & \text{if } \tau \geq \tau^e_i \end{cases}$$

$$d_i(\tau) = \begin{cases} 0, & \text{if } \tau < \tau^b_i \\ q, & \text{if } \tau \geq \tau^b_i \end{cases}$$  \hspace{1cm} (5)

We assume that a fraction of the dead organic matter for any age $\tau \geq \tau^b_i$ is lost due to non-biological processes. Boundary conditions for the conservation law have the following form:

$$B_i(t, 0) = p_iP(t).$$

where $p_i$ is fraction of $i$th phytomass component ($i = 1, 2, 3$), $P(t)$ is annual net primary production (or, productivity) at some given time $t$.

According to Eqs. (4)–(7), the phytomass $B_i(t, \tau)$ can be represented as follows:

$$B_i(t, \tau) = \begin{cases} p_iP(t - \tau), & \text{if } 0 \leq \tau < \tau^b_i \\ p_iP(t - \tau)e^{-\mu_i(t - \tau^b_i)}, & \text{if } \tau^b_i \leq \tau < \tau^e_i \\ p_iP(t - \tau)e^{-\eta(t - \tau^e_i)}e^{-q(t - \tau^b_i)}, & \text{if } \tau^e_i \leq \tau \end{cases}$$  \hspace{1cm} (8)

where $\mu_i = \mu_i + q$ and $\eta = \eta + q$.

Taking into account Eq. (8), Eqs. (1)–(3) are rewritten in the following forms:

$$L(t) = \sum_{i=1}^{3} \int_{0}^{\tau^b_i} P(t - \tau) \, d\tau,$$

$$M(t) = \sum_{i=1}^{3} \int_{\tau^b_i}^{\tau^e_i} P(t - \tau)e^{-\mu_i(t - \tau^b_i)} \, d\tau,$$

$$D(t) = \sum_{i=1}^{3} \int_{\tau^e_i}^{\infty} P(t - \tau)e^{-\eta(t - \tau^e_i)} \, d\tau.$$  \hspace{1cm} (9)

If the values of $\tau^b_i$, $\tau^e_i$, $\mu_i$, and $\eta_i$ and time dynamics $P(t)$ are known, then we can calculate the magnitudes of $L(t)$, $M(t)$, and $D(t)$.

Productivity of terrestrial ecosystems $P(t)$ depends on climatic and environmental conditions, in particular on the total amount of atmospheric carbon $C(t)$. In reality, the atmospheric carbon concentration continues to rise (Solomon et al., 2007) and function $C(t)$ is characterized by an exponential dependence on time (Krapivin et al., 1982; Tarko, 2005). This argument allows us to assume the following temporal curve for productivity:

$$P(t) = \begin{cases} P_0, & \text{if } t < t_0 \\ P_0e^{\lambda(t - t_0)}, & \text{if } t \geq t_0 \end{cases}$$  \hspace{1cm} (10)

where $\lambda$ is parameter determining impact of the carbon concentration in the atmosphere on vegetation, $t_0$ is the beginning
of the industrial era. It should be noted that a response of the different vegetation patterns, biomasses, and ecosystems to increase of the carbon in the atmosphere differs from each other.

Thus, we have a closed system of equations for the description of carbon dynamics in terrestrial ecosystems.

3. Calibration: method, material, and discussion

The strong assumption that any local carbon cycle is in a steady state – the so-called steady-state hypothesis – was used in calibrating many existing dynamic models of the global carbon cycle. In other words, it was assumed that, before some moment, which is referred to as a beginning of the industrial era, all local carbon cycles were balanced. For example, this hypothesis was used in calibrating spatial patterns of the global carbon cycle created within the framework of such models as the Moscow Global Biosphere Model (Krapivin et al., 1982; Sviridov et al., 1985), the Frankfurt Biosphere Model (Ludeke et al., 1994), the Vegetation Continuous Description Model (Brovkin et al., 2002), the Lund–Potsdam–Jena Dynamic Vegetation Model (Sitch et al., 2003).

In our model, in contrast, the steady-state hypothesis is not employed. The model is applied for the European territory of Russia (ETR) as a case study. The European part of Russia is a vast territory with area approximately $3.7 \times 10^6$ km$^2$ that is located between $30^\circ$ and $60^\circ$ eastern longitude and $45^\circ$ and $70^\circ$ northern latitude. We consider six ecosystems on this territory: tundra, taiga forest, broadleaved forest, meadow steppe, true steppe, and semi-desert. The proportions between the areas occupied by these ecosystems are given in Fig. 2. It should be noted that forest ecosystems occupy more than one-half of the territory under consideration.

In order to calibrate the model, we have used extensive experimental information about annual net primary production, annual litter fall, density of the living phytomass and mortmass (Bazilevich, 1993; Bazilevich et al., 1986; Bobkova and Galenko, 2001; Tishkov, 2005; Usoltsev, 2001, 2007), and density of the humus (Orlov et al., 1996; Orlov, 1999). Using specific carbon concentrations for different ecosystems (Golubyatnikov et al., 1998; Orlov et al., 1996; Titlyanova et al., 2005) (Table 1) we have expressed empirical data in the carbon units (Table 2).

### Table 1 – Specific carbon concentrations (%) for different ecosystems

<table>
<thead>
<tr>
<th>Ecosystem</th>
<th>Phytomass</th>
<th>Mortmass</th>
<th>Organic matter in soil and peat in bog</th>
<th>Peat in fen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tundra</td>
<td>56%</td>
<td>61%</td>
<td>58%</td>
<td>56%</td>
</tr>
<tr>
<td>Taiga forest</td>
<td>40%</td>
<td>45%</td>
<td>58%</td>
<td>56%</td>
</tr>
<tr>
<td>Broadleaved forest</td>
<td>53%</td>
<td>56%</td>
<td>58%</td>
<td>56%</td>
</tr>
<tr>
<td>Meadow steppe</td>
<td>37%</td>
<td>42%</td>
<td>58%</td>
<td>–</td>
</tr>
<tr>
<td>True steppe</td>
<td>38%</td>
<td>43%</td>
<td>58%</td>
<td>–</td>
</tr>
<tr>
<td>Semi-desert</td>
<td>45%</td>
<td>47%</td>
<td>58%</td>
<td>–</td>
</tr>
</tbody>
</table>

### Table 2 – Characteristics for ecosystems of the European territory of Russia

<table>
<thead>
<tr>
<th>Ecosystem</th>
<th>Living phytomass</th>
<th>Net primary production</th>
<th>Mortmass</th>
<th>Litter fall</th>
<th>Humus</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kg C/m$^2$</td>
<td>Gt C per year</td>
<td>kg C/m$^2$</td>
<td>Gt C per year</td>
<td>kg C/m$^2$</td>
</tr>
<tr>
<td>Tundra</td>
<td>0.84</td>
<td>0.21</td>
<td>0.11</td>
<td>0.03</td>
<td>2.82</td>
</tr>
<tr>
<td>Taiga forest</td>
<td>9.17</td>
<td>19.45</td>
<td>0.34</td>
<td>0.72</td>
<td>2.61</td>
</tr>
<tr>
<td>Broadleaved forest</td>
<td>18.28</td>
<td>6.76</td>
<td>0.64</td>
<td>0.24</td>
<td>2.28</td>
</tr>
<tr>
<td>Meadow steppe</td>
<td>1.71</td>
<td>0.36</td>
<td>0.71</td>
<td>0.15</td>
<td>1.09</td>
</tr>
<tr>
<td>True steppe</td>
<td>0.45</td>
<td>0.22</td>
<td>0.48</td>
<td>0.24</td>
<td>0.49</td>
</tr>
<tr>
<td>Semi-desert</td>
<td>0.58</td>
<td>0.13</td>
<td>0.33</td>
<td>0.08</td>
<td>0.40</td>
</tr>
</tbody>
</table>
It should be noted that the ages for various phytomass components of the ecosystems (Fig. 3).

According to experimental data, the total annual productivity of the European territory of Russia is 1.4 Gt. Note that simulated estimations of carbon flux from the atmosphere into living phytomass for ecosystems of ETR we have obtained the following estimation for this flux: every year tundra ecosystem absorbs about 0.03 Gt of carbon, taiga ecosystem absorbs about 0.7 Gt of carbon, meadow steppe ecosystem absorbs about 0.15 Gt of carbon, true steppe and broadleaved forest ecosystems absorb about 0.2 Gt of carbon, and semi-desert ecosystems absorb smaller than 0.08 Gt of carbon. According to experimental data, the total annual carbon flux from the atmosphere into living phytomass for ecosystems of ETR is 1.4 Gt. Note that simulated estimations of the flux for this region vary between 0.9 and 1.8 Gt carbon per year (Golubyatnikov and Denisenko, 2001).

Part of the living phytomass becomes dead and enters to mortmass storage. The lowest annual litter fall per unit area is registered in tundra ecosystem (about 100 g C/m² per year), and the highest value is noted in meadow steppe ecosystem (about 490 g C/m² per year). The annual carbon flux from the living phytomass into mortmass is about 1 Gt. The mortmass reaches highest values per unit area in tundra ecosystem where lowest destruction rates of dead organic matter are stipulated by low temperature. The value of the mortmass per unit area smoothly decreases from northern ecosystems to the southern one. For ecosystems of ETR, we have estimated the carbon content in mortmass as high as 7.7 Gt.

According to Orlov et al. (1996), the carbon storage in the uppermost meter of soil of ETR is more than 85 Gt. Soils of taiga and meadow steppe ecosystems are characterized by the higher values of the carbon storage (about 26 kg/m²). Semi-desert soils have low level of carbon content (about 7 kg/m²).

Using the conditions \( t_i^b = B_i/P_i \), we can calculate the ages \( t_i^b \) for various phytomass components of the ecosystems (Fig. 3). It should be noted that the ages \( t_i^b \) are the residence times for carbon in the fractions of living phytomass. The maximal carbon residence times are characteristic for forest ecosystems of ETR where the carbon storage in the living perennial phytomass has the highest values.

Following (Berg and Agren, 1984; Grishina et al., 1990; Kobak, 1988; Semenov et al., 2004), we assume that mortmass decomposition rate is characterized by an exponential curve in time. From this hypothesis and empirical data on mortmass and litter fall (Bazilevich, 1993; Bazilevich et al., 1986), we can estimate the coefficients of decay \( d_i(t) \) and the respective time \( t_i^{dec} \) for ecosystems on the territory under consideration.

We have obtained the estimates of mortmass decay time \( t_i^{dec} \) for ecosystems of ETR (Fig. 4). The maximal time is characteristic for tundra ecosystem, where low temperature does not permit micro-organisms to decay organic matter. The minimal time of mortmass decay is characteristic for true steppe ecosystem, where climatic conditions and chemical composition of mortmass are optimal for destructive processes. It is noted that the estimates of mortmass decay time for forest and steppe ecosystems are known from the field experiments of other authors (Bazilevich, 1993; Bobkova and Galenko, 2001; Grishina et al., 1990; Storozhenko, 2000). According to those experimental data, time of decay for dead photosynthetic and perennial phytomass are 3–8 and 20–45 years, respectively, in forest ecosystems and 1–2 and 3–15 years, respectively, in steppe ecosystems. Our model estimates of mortmass decay time are 3.7–8.8 and 1.4–2.2 years for dead photosynthetic phytomass of forest and steppe ecosystems, respectively, and 27.9–39.0 and 2.5–11.2 years for perennial phytomass of the same ecosystems, respectively. Thus, our estimates of these time markers coincide closely much with the field experiments results.

If time scales \( t_i^b \) and \( t_i^{dec} \) are known, we can estimate ages \( t_i^b \) and \( t_i^{dec} \). Thus, we have two Eqs. (10) and (11) in two unknowns \( \lambda \) and \( q \). Using empirical data on the magnitudes of mortmass, humus, and productivity we can find these parameters as well.

According to our computations, the deviations of the model result from its observational values for living phytomass, mortmass, and humus no more than 2–4%.
4. Estimation of the total exchange carbon flux for ecosystems of ETR

The suggested model permits us to characterize terrestrial ecosystems as carbon sources or carbon sinks and to evaluate intensity of these sources and sinks. Earlier (Golubyatnikov et al., 1998) we approached this problem by modelling the total exchange carbon flux for terrestrial ecosystems. We defined this flux as the difference between carbon income into the net primary production and its emission from dead organic matter (mortality and humus) due to both biological and non-biological processes. According to this definition and our carbon cycle model, we can represent the total exchange flux of carbon by:

\[ W(t) = P(t) - \sum_{i=1}^{3} \mu_i P_1 \int_{t_1}^{t_2} P(t - r) e^{-\mu_i(t-r)} dr - \eta \sum_{i=1}^{3} \int_{t_1}^{t_2} \int_{t_1}^{\infty} P(t - r) e^{-\eta(r-t)} dr. \]  \hspace{1cm} (13)

From Eqs. (12) and (13) we get an analytic solutions for \( W(t) \). For instance, if \( t_1 < t - t_0 < t_2 \) then the total exchange carbon flux is as follows:

\[ W(t) = P(t) \left[ 1 - \sum_{i=1}^{3} \mu_i P_1 \left[ \frac{1}{\lambda + \mu_i} e^{-\lambda t} + \frac{\lambda}{\mu_i (\lambda + \mu_i)} e^{\mu_i t} - (\mu_i^\prime + \mu_i) (t-t_0) \right] \right] - \frac{\eta}{\eta} e^{-\lambda(t-t_0)} \sum_{i=1}^{3} \mu_i P_1 e^{-\mu_i (t-t_0)} \]  \hspace{1cm} (14)

If value of \( W(t) \) at a particular time \( t \) for a given ecosystem is positive, then carbon release into the atmosphere is smaller than its absorption and an ecosystem serves as sink of carbon. In contrast, if value of \( W(t) \) at a particular time \( t \) for a given ecosystem is negative, then carbon release into the atmosphere is higher than its absorption and this ecosystem is a source of carbon.

Using the experimental data over the second half of the 20th century, we have calculated the annual total exchange carbon flux for ETR ecosystems (Fig. 5). The maximum magnitude of this carbon flux is characteristic for broadleaved forest (about 44 g C/m² per year); the minimum magnitude is characteristic for tundra (about 10 g C/m² per year).

We have found that the territory of European Russia between 55° and 60° northern latitude exhibits the high magnitudes of the annual total exchange of carbon. This territory is occupied by forest phytocenoses of southern taiga and broadleaved forests. We have shown that a significant role of carbon accumulators belongs to forest ecosystems of ETR, which deposit about 100 Mt carbon per year. This value is in agreement with estimates obtained by other authors for forest ecosystems (Isaev and Korovin, 1999; Zamolodchikov et al., 2005; Zavarzin, 2007). According to our calculations, steppe ecosystem absorbs up to 16 Mt carbon per year. In semi-desert ecosystem, annual carbon sink magnitude decreases to 4 Mt. Tundra ecosystem is characterized by the minimal difference between carbon absorption and its emission into the atmosphere, about 2.5 Mt per year. The annual total exchange carbon flux for ETR is evaluated as 124 Mt C. Thus, at the end of the last century for the European territory of Russia carbon release into the atmosphere was smaller than its absorption and, hence, this territory was a carbon sink. The obtained estimates are in agreement with those of other authors (Mokronosov and Kudoyarov, 1997; Zavarzin, 2001, 2007 and other) that European Russia is a sink of carbon.

5. Conclusion

A carbon cycle model is presented which allows us to get an analytic solution and does not employ the steady-state hypothesis for preindustrial local carbon cycle. The model is based on a scheme of phytomass change, which is continuous in time. It is calibrated using extensive experimental information on living and dead phytomass, soil organic matter, plant productivity, and litter fall. In our model, organic matter stock changes are described via changes of phytomass age. This approach is a novel feature of the model.

The proposed model is a new tool to describe and understand complex interactions in terrestrial ecosystems. It enables us to study of carbon dynamics in different pools of terrestrial ecosystems under the climate change and to estimate the respective carbon budget.

The suggested model permits us to characterize a particular terrestrial territory as a source or a sink for carbon. Our research has shown that the European territory of Russia was a carbon sink at the end of the 20th century. We have evaluated the intensity of this sink as 124 Mt of carbon per year. We have found that a significant role of carbon accumulators belongs
to forest ecosystems of European Russia. These ecosystems accumulate about 100 Mt carbon per year.

Certainly, the model cannot take into account the whole set of productive and destructive processes for organic matter. Therefore, the results obtained represent some estimates but they nevertheless give an idea of the qualitative pattern of the carbon balance for the territory under study.

**Acknowledgements**

We are indebted to A.V. Eliseev for his helpful comments and discussions. We thank anonymous reviewers for constructive comments on the draft version of this manuscript. This work has been supported by the Russian Foundation for Basic Research (grants 05-05-65167 and 08-05-00282), the basic research program of the Russian Academy of Sciences.

**References**


