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Technique for Estimating the Dynamics of Water and Carbon Budgets of a Coniferous Forest Ecosystem

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Abstract—A technique for the estimation of changes in components of the water and carbon budgets of coniferous ecosystems as a result of possible anthropogenic climate changes has been developed. The technique is based on the SWAP model of heat, water, and carbon exchanges in coniferous ecosystems, which was previously developed by the authors, and the MAGICC/SCENGEN generator of climatic scenarios for various regions of the Earth. The technique is used for estimating changes in the evapotranspiration and carbon budget of the developing coniferous forest ecosystem in the Loobos experimental site (the Netherlands) in the 21st century in connection with an increase in the anthropogenic emission of greenhouse gases into the atmosphere expected in accordance with the IPCC IS92a scenario of the economic, technological, political, and demographic development of human civilization up to 2100.

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INTRODUCTION

The goal of this study is to elaborate a technique for estimating the influence of changes caused in the concentrations of atmospheric greenhouse gases and aerosols by the anthropogenic activity on the evapotranspiration and carbon budget of dark coniferous forest ecosystems in the 21st century and to verify this technique via the use of one of such ecosystems, namely, a pine forest ecosystem as an example. The outlined goal is associated with the problem (topical at present) of estimation and prevention of possible consequences of the biosphere-stability disturbance caused by an intense effect of the human population on it.

A coniferous forest ecosystem was chosen as the object of study because coniferous forests prevail in ecosystems of the boreal zone of the planet, and the results of numerous investigations of climate changes show that significant consequences of the climate changes can be expected precisely in the boreal zone, which plays an important role in the formation of the planet's carbon budget [2, 3]. This situation is associated with the fact that, first, the main reservoirs of carbon of biogenic origin are concentrated in this zone [4–6] and, second, both the widest range of climate changes due to an increase in the industrial emission of greenhouse gases and an increase in the anthropogenic activity are expected precisely in the boreal zone [7]. These factors are able to intensify the emission of considerable resources of soil carbon into the atmosphere in the given region of the planet.

At present, the boreal zone, a substantial part of which is occupied precisely by coniferous forests, is a sink of atmospheric carbon [3, 8], which compensates, to a certain extent, its emissions associated with the industrial development of mankind. However, it is unknown whether such a situation will be retained in the future. Even the sign of carbon budget that will result from possible climate changes is unknown. In turn, the processes of carbon exchange in terrestrial ecosystems are closely related to the processes of heat and water exchange [9, 10]. In this regard, we developed a tool for solving the problem formulated in this study on the basis of the method of physically based modeling of the processes of radiation, heat, water, and carbon exchanges in the ecosystems chosen. This method makes it possible to reproduce the processes of heat and mass exchanges in the soil–vegetation/snow cover–surface atmospheric layer system with consideration for their interrelations. The possibility of taking into account extensive a priori information accumulated during numerous experimental investigations is a positive feature of physically based modeling. In this case, the SWAP (Soil–Water–Atmosphere–Plants) model, which has been developed by the authors during a number of years [11–14] and belongs to the class of the so-called land surface models (LSMs) [15], more precisely, the version of this model including the block of carbon exchange in coniferous ecosystems [14], was used as the main component of the model complex, which allows the estimation of the dynamics of the heat, water, and carbon budgets of ecosystems under various conditions.

FUNDAMENTALS OF THE TECHNIQUE FOR ESTIMATING CHANGES IN THE WATER AND CARBON BUDGETS OF A CONIFEROUS FOREST ECOSYSTEM WITH THE USE OF SPECIFIED SCENARIOS OF CLIMATE CHANGE

The proposed technique makes it possible to assess the influence of anthropogenic changes in the concentrations of greenhouse gases and aerosols in the atmosphere on the water and carbon budgets of a coniferous forest ecosystem. This technique is based on comparative estimations of modeled values of components of the water and carbon budgets for analogous ecosystems that have identical initial states but were developed in different centuries—the 20th and 21st centuries. In this regard, the technique is implemented in two stages.

At the first stage, the dynamics of components of the heat, water, and carbon budgets is reproduced with the use of the SWAP model for a specific object of investigations (a coniferous forest ecosystem) in the 20th century, i.e., under real environmental conditions and at the values of soil organics and the living and dead biomasses of the ecosystem under consideration that are specified for the early years of the century. At the second stage, analogous calculations are performed for the same object under the same initial conditions but at the modified (prognostic) boundary (meteorological) conditions corresponding to the period of the 21st century. The results of calculations allow a comparison of the dynamics of formation of the carbon and water budgets for two analogous forest ecosystems growing in different time periods.

Being the actual historical realization, the meteorological conditions that are necessary for modeling ecosystem formation in the 20th century represent either data of direct observations or results of the so-called reanalysis, i.e., the technique of calculation and distribution (over cells of a global grid) of input characteristics for LSMs through the processing of considerable volumes of synoptic information regularly obtained from numerous satellite, airborne, radiosonde, and ground-based systems of observations. The technique of reanalysis is based on the spectral model of the atmospheric general circulation and the system of statistical interpolation of the results obtained over grid cells [16–18].

The preparation of meteorological forcing data corresponding to the period of the 21st century is based on their scenario prediction and represents a separate problem. One of the variants of solving this problem is considered in this study. The proposed solution can likewise be accomplished in two stages.

The hypothetical century-long dynamics of atmospheric greenhouse gases and aerosols in the 21st century and the related global changes in a number of climatic characteristics are estimated at the first stage on the basis of a scenario prediction of evolution of the emission of various greenhouse gases into the atmosphere (carbon dioxide (CO_2), carbon monoxide (CO), nitrogen dioxide (NO_2), nitrogen oxides (NO_x), sulfur dioxide (SO_2), as well as carbon halides (hydrofluorocarbons, perfluorocarbons, and others)), reflecting some or other suggestions about the economic, technological, political, and demographic development of human civilization up to 2100 (in particular, suggestions about the use of fossil fuel, development of various technologies, deforestation, etc.). One of the six alternative scenarios (IS92a–IS92f), published in the supplement to the second report of the Intergovernmental Panel on Climate Change (IPCC) in 1992 [19], was used in this study as an example.

The IS92a scenario, often used as the main scenario for estimating the consequences of climate change, appears to be most widespread. According to this scenario, it is supposed that the population of the Earth will increase to 11.3 billion people by 2100; the planet-average economic growth from 1990 through 2100, with the use of both traditional and renewable energy sources, will be 2.3% per year. It is this scenario that is used in our study.

To obtain the data on the dynamics of meteorological and actinometric characteristics in the 21st century that will serve as the input information for calculations within the framework of the SWAP model, we used the MAGICC/SCENGEN (Model for the Assessment of Greenhouse-Gas Induced Climate Change/A Global and Regional Climate Scenario Generator) computer program complex [20], which actually represents a generator of climatic scenarios designed for estimation of the vulnerability or adaptation of various ecosystems or biomes of the planet to climate changes.

Global predictions (obtained from the implementation of a certain scenario of the social and economic development of the human population) of the dynamics of the annual (i) carbon emission into the atmosphere, (ii) CO_2 concentration in the atmosphere, (iii) changes in the components of the incoming radiation in accordance with the increment of each constituent of greenhouse gases and aerosols in the atmosphere, and (iv) changes in the surface temperature and the ocean level for the period from 1990 through 2100 are the MAGICC output characteristics. The estimates for the dynamics of a number of the specified global characteristics corresponding to the IS92a scenario and obtained on the basis of the MAGICC are shown in Fig. 1.

The second stage of solving the problem of prediction of the dynamics of meteorological characteristics in the 21st century lies in the passage from global to regional estimations of their changes. Different variants of the implementation of this stage are possible. In this study, we applied the variant incorporating the

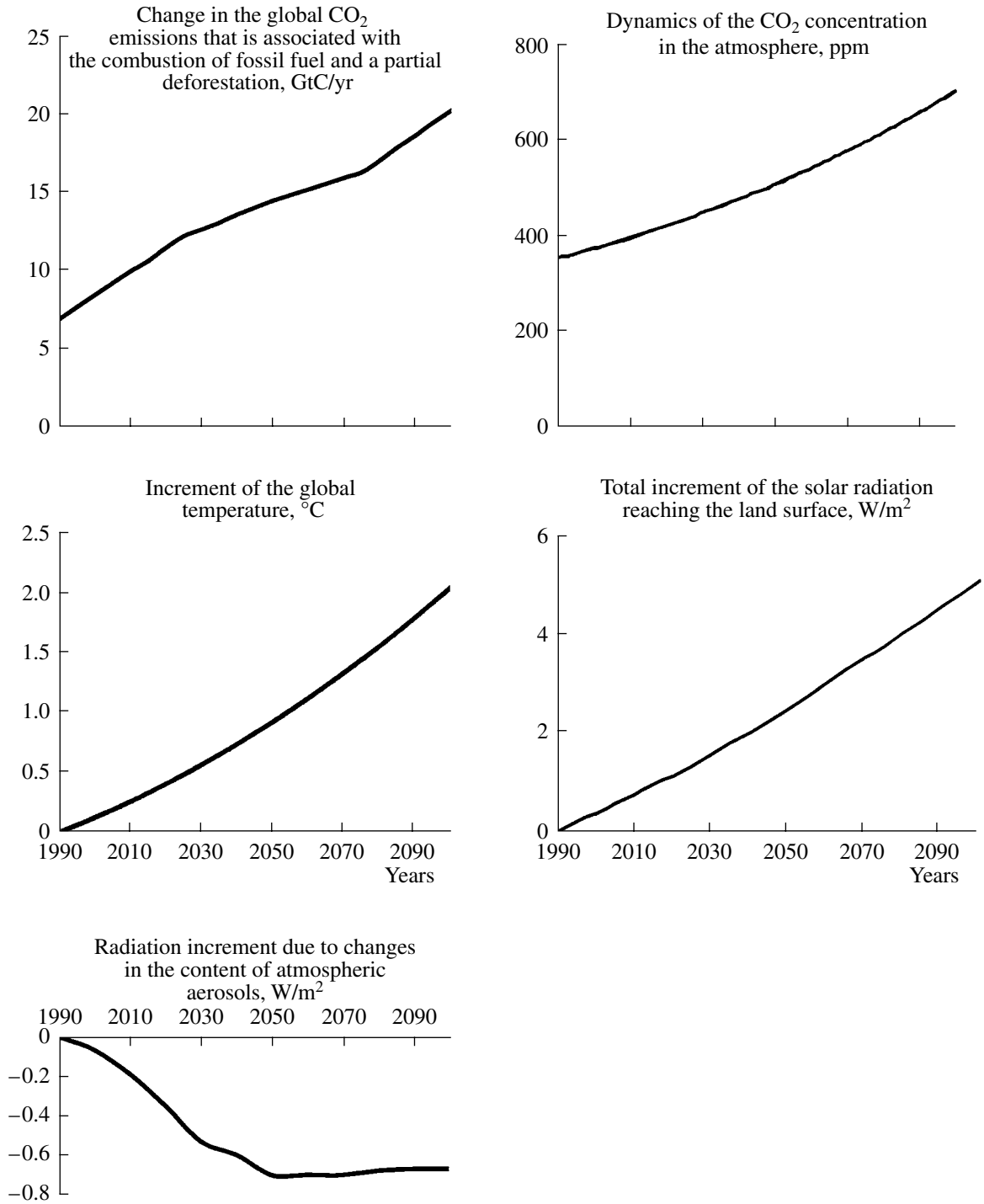

Fig. 1. Estimation of the changes in a number of global characteristics that are associated with changes in the intensity of emissions of greenhouse gases and aerosols into the atmosphere of the planet in accordance with the IPCC IS92a scenario of the social and economic development of human civilization.

SCENGEN program complex mentioned above. This complex uses, first, the output characteristics of the MAGICC complex and, second, global distributions of major meteorological elements obtained with the aid of global atmospheric general circulation models (AGCMs) with a high spatial resolution. For the entire land surface, the SCENGEN complex can yield two types of predictions for the period 1990–2100 (in accordance with the IPCC IS92a social–economic scenario chosen):

(1) prediction of the dynamics of absolute monthly mean values of the air temperature and humidity, pre-

Atmospheric general circulation models of a high resolution that are used in the SCENGEN model complex

HadCM2	Hadley Centre Unified Model 2 Transient Ensemble-mean (UK)
UKTR	UK Met. Office/Hadley Centre Transient
CSIRO-TR	Commonwealth Scientific and Ind. Research Org., Transient (Australia)
ECHAM4	European Centre/Hamburg Model 4 Transient (Germany)
UKHI-EQ	UK Met. Office High Resolution
CSIRO2-EQ	Commonwealth Scientific and Ind. Research Org., Mark 2 (Australia)
ECHAM3	European Centre/Gamburg Model 3 Transient (Germany)
UIUC-EQ	University of Illinois at Urbana Champaign (USA)
ECHAM1	European Centre/Hamburg Model 1 Transient (Germany)
CSIRO1-EQ	Commonwealth Scientific and Ind. Research Org., Mark 1 (Australia)
CCC-EQ	Canadian Climate Centre (Canada)
GFDL-TR	Geophysical Fluid Dynamics Laboratory Transient (USA)
BMRC-EQ	Bureau of Meteorology Research Centre (Australia)
CGCM1-TR	Canadian Climate Centre for Modelling and Analysis 1 Transient (Canada)
NCAR-DOE	National Centre for Atmospheric Research (DOE) Transient (USA)
CCSR/NIES	Centre for Climate Research Studies/NIES (Japan)

cipitation, cloudiness, and wind velocity (i.e., nearly all meteorological characteristics necessary for calculations within the framework of LSMs) with the resolution of $1° \times 1°$; and

(2) prediction of the increments (changes) of the meteorological elements listed above with respect to 1990 with the resolution $5° \times 5°$ (because the increments of the specified characteristics are smoother spatial functions than the characteristics themselves).

In this study, we used the predictions of increments of meteorological elements because the increments, in combination with the actual realization of the corresponding meteorological elements in 1990 at a concrete point of the land, can ensure a more accurate prediction for the point under consideration than the prediction of absolute values of meteorological elements obtained for $1° \times 1°$ AGCM calculation grid cells.

Note that, in calculations by the SCENGEN program, we used not one AGCM but an ensemble of such models presented in the table, because, as is noted in [7, 21], the calculations of the present-day climate and seasonal climatic predictions are more successful if they are averaged over an ensemble of independent models (the opposite opinion exists also).

Further, since the calculations within the framework of the SWAP model were performed by us with a 3-h calculation step (in order to improve the calculation accuracy by taking into account the diurnal trend of the processes under consideration), it was necessary to pass from monthly mean values of meteorological characteristics to their values with a higher time resolution. For this purpose, we derived calculation formulas approximating the annual course of meteorological elements on the basis of information about the monthly mean dynamics of their changes. The formulas have the following form:

$$\Delta y(n, i) = \Delta T_{gl}(n) F_y(i), \quad (1)$$

where $\Delta y(n, i)$ is the change of the meteorological characteristic y (in absolute units for the air temperature and in relative units for the precipitation, wind speed, air humidity, and cloudiness) for the ith day of the nth year (measured from 1990); ΔT_{gl} is the change of the global temperature for the nth year (compared to the temperature of 1990); and $F_y(i)$ is the approximating polynomial, whose coefficients were obtained from the estimates (with the use of the SCENGEN) for monthly mean values of changes in the corresponding characteristic.

The above formulas make it possible to estimate long-term components of changes in meteorological characteristics and can be used for a direct calculation of these characteristics themselves for the entire 21st century in accordance with the IPCC IS92a prediction if series of meteorological information (with a 3-h step) over the period of the 20th century are available for the region under investigation.

A realization of the stationary component of the temporal variation of a meteorological element in the 20th century is obtained for each meteorological element from the series of variations of its values over the

period of the 20th century (through the elimination of the temporal trend of the corresponding element calculated for the specified period also with the use of the MAGICC/SCENGEN program). Further, this stationary component, which reflects its intraannual, synoptic, and intradiurnal variabilities, is "transferred" to the period of the 21st century and is combined with the long-term trend of this element in the 21st century calculated from Eq. (1). The combination lies either in the addition of the absolute values of $\Delta y(n, i)$ to the value of the stationary component y (for air temperature) or in the multiplication of y by the quantity $[1 + \Delta y(n, i)]$ (for precipitation, wind speed, air humidity, and cloudiness), a technique that allows us to obtain one of the possible realizations of the series of meteorological elements predicted, for example, in accordance with the IS92a scenario, for the 21st century.

As for the longwave radiation $R_{LW}\downarrow$ reaching the land surface, its relative changes are calculated with the use of the technique described in [22] with consideration for both the present-day values of the air temperature in the region under consideration and its changes for the period of the 21st century. Changes in the incoming shortwave radiation $R_{SW}\downarrow$ are estimated on the basis of global data about its decrease (caused by an increase in the concentration of aerosols in the troposphere, Fig.1), which are corrected proportionally to the ratio of the annual mean local value of $R_{SW}\downarrow$ in the region under consideration to the annual mean global value of $R_{SW}\downarrow$. It should be noted that the accuracy of the estimate for the influence (both direct and indirect, i.e., associated with changes in cloudiness and water-droplet sizes in clouds) of the concentration of anthropogenic aerosols in the troposphere on the incoming radiation is not high compared to the accuracy of the estimate for the influence of other factors on the climatic system [6]. However, although anthropogenic aerosols make a smaller contribution to changes in the system characteristics than other factors, the estimates for the influence of aerosols on the incoming radiation were, nevertheless, used in the solution of the formulated problem.

Note that, in this study, the widespread so-called weather generators could not be employed to obtain prognostic values of meteorological elements, because a set of variables used in these generators is very far from the set of meteorological characteristics necessary as the input data for LSMs.

Before passing to the specification of the initial conditions of the problem, we have to touch briefly on the issue of the dependence of the stomatal conductance g_c and potential transpiration of vegetation EP on the carbon dioxide concentration in the ambient air c_a. The point is that, in the SWAP version presented in [14], this dependence was disregarded owing to small changes in the CO_2 concentration in the atmosphere over the period considered in [14]; however, if CO_2 concentration changes are substantial, it is impossible to correctly model the dynamics of the carbon and water budgets of an ecosystem without incorporation of the specified dependence into the model.

Analysis of experimental data for a number of crops (see, for example, [23, 24]) shows that in the range $c_a = 200$–900 ppm, the dependence $g_c(c_a)$ can be approximated well by the exponential function

$$g_c/g_{c0} = \exp[-\mu_i(c_a - c_{a0})], \quad (2)$$

where g_{c0} is the stomatal conductance (m s^{-1}) of phytoelements of a certain vegetation type, corresponding to the present-day CO_2 content in the atmosphere c_{a0}, which is assumed to be ≈350 ppm, and μ_i is an empirical parameter depending on the vegetation type (specified by the index i) and controlling the rate of g_c changes with c_a changes. The review of investigations for 23 species of arboreus vegetation presented in [25] showed that the doubling of the CO_2 concentration in the atmosphere decreases the stomatal conductance by 23% on average; meanwhile, for coniferous (*Pinus radiata, Pinus taeda, Picea abies*), such a decrease is relatively small and amounts to 10 ± 2% on average. It is this value that was used in our study for estimation of μ_i for coniferous trees.

Since changes occurring in the stomatal conductance owing to changes in the CO_2 content in the atmosphere affect not only the rate of photosynthesis but also the transpiration of vegetation, this factor must also be incorporated into the model (the previous versions of the model were oriented to the present-day CO_2 content). The specified factor was taken into account through the use of the semiempirical theory proposed by A.I. Budagovskii [26–28] for the description of transpiration. This allowed us to derive an expression for the dependence of the potential transpiration EP_i of the ith type of vegetation on c_a (all other meteorological conditions being equal) in the following form:

$$EP_i = 2.25EP_{0i}/\{2.0 + 0.25\exp[\mu_i(c_a - c_{a0})]\}, \quad (3)$$

where EP_{0i} is the potential transpiration of the ith type of vegetation at the present-day CO_2 content in the atmosphere.

We will now consider the problem of model initialization, i.e., the specification of initial conditions of the problem necessary for long-term calculations, both with the actual set of meteorological forcing data and with their scenario prediction. Long-term calculations with the SWAP model require the specification of initial values of (i) characteristics associated with the water and heat regimes of ecosystems (temperature, moisture, and ice content of the soil, depths of its freezing or thawing, snow resources) and (ii) carbon stores in various reservoirs (pools) of an ecosystem (in elements of living and dead biomasses in the soil).

The use of measurements [29] is the best variant of the initialization of the above characteristics. However, such data are not always available. In this case, the method of iterative "marching" of the first calculation year until the state of the so-called "quasi-equilibrium year" is reached is applied to the first group of characteristics mentioned above. However, such a method is unacceptable for estimation of the initial carbon stores in various reservoirs of an ecosystem because there is no assurance that the ecosystem under consideration is at equilibrium (in particular, the establishment of carbon equilibrium in the soil can continue for thousands of years). Therefore, in the absence of measurements, other variants of carbon store initialization are necessary.

As for the carbon stores (or the organic matter, from which the carbon content can be estimated) in the living biomass, the situation is more or less satisfactory. There are different types of regional or global databases on the terrestrial vegetation [30, 31] from which the corresponding information can be extracted. However, the situation with the estimation of carbon stores in the soil is more complicated. In some cases, it is possible to obtain a fairly representative soil database related to forest-type groups [32]. There are also generalizations associated with the estimation of soil carbon stores by climatic characteristics (long-term mean values of temperature, precipitation, potential evaporation) [33]. However, these estimates are rather rough. Therefore, in each specific case, the initialization of the model through the use of edaphic conditions is a separate problem, which is solved on the basis of the available information.

APPLICATION OF THE DEVELOPED TECHNIQUE FOR ESTIMATING THE DYNAMICS OF EVAPOTRANSPIRATION AND CARBON BUDGET OF A PINE FOREST ECOSYSTEM IN THE CENTRAL NETHERLANDS

Object of Investigations

The above technique for estimating the dynamics of water and carbon budgets of a coniferous forest ecosystem with the use of real meteorological data obtained on the basis of climate change scenarios is designed to be applied to a wide spectrum of physical and geographical conditions. In this study, the technique was verified on a concrete geographical object, namely, on a pine forest ecosystem located in one of the research areas of the CarboEuroFlux network. The Loobos experimental site (the central Netherlands) is described in [14]. The technique was used for comparative modeling of the century-long evolution of two analogous pine forest ecosystems. The pine forest of the first ecosystem was actually planted in the area of the geographical object in the early 20th century. An analogous modeled forest growing at the same place but planted in the early 21st century formed the second ecosystem. Comparison of the results obtained allows us to make conclusions about changes in the dynamics of carbon budget of the developing pine ecosystems if the concentrations of greenhouse gases and aerosols in the atmosphere change as a result of the anthropogenic activity.

In the ecosystem chosen, the upper stratum of vegetation is represented by Scotch pine (*Pinus sylvestris*) and the lower stratum (undergrowth), by the grass community (*Deschampsia flexuosa*). Series of data on the air temperature and humidity, precipitation, wind velocity, and incoming longwave and shortwave radiation served as the meteorological forcing data for the calculations for the period of the 20th century. These data were provided by the organizers of the Project for Intercomparison of Land-Surface Parametrization Schemes, Carbon 1 (PILPSC-1), in which the authors of this paper took part. Additionally, the data on some soil characteristics (soil texture, root-layer depth, density, a number of hydrophysical characteristics, etc.) were used for the estimation of soil parameters of the model. Since both modeled ecosystems represented a forest planted on sand dunes, there were no problems with the specification of initial conditions for the carbon content in the soil and vegetation. In both cases, the initial carbon content in the soil and vegetation elements was assumed to be close to zero.

Results

The long-term annual mean values of precipitation and evapotranspiration in the Loobos site in the 20th and 21st centuries are shown in Fig. 2a. As is seen from the results presented, the differences between the specified characteristics for the two neighboring centuries are not large (in the 21st century, precipitation increased, on average, by 3.6%, while evaporation changed, only by 1.3%). This result is expected because very small changes in the 21st century are predicted for all meteorological elements in the Loobos site, which is actually located in the temperate zone (as distinct from the boreal zone). The climatic changes here are small, and, therefore, the so-called indirect (through changes in the climatic characteristics in the given region) influence of changes in the concentrations of greenhouse gases and aerosols on the heat, water, and carbon regimes of local ecosystems is also small. Thus, if only changes in meteorological elements are taken into account in the modeling of the specified regimes in the 21st century, while the CO_2 concentration dynamics is assumed to be the same as in the 20th century, the calculated long-term evaporation will increase only by 0.4%. Such factors as the mean secular increment of the incoming shortwave and longwave radiation (by 1.3% compared to the 20th century) and the mean secular increase in air

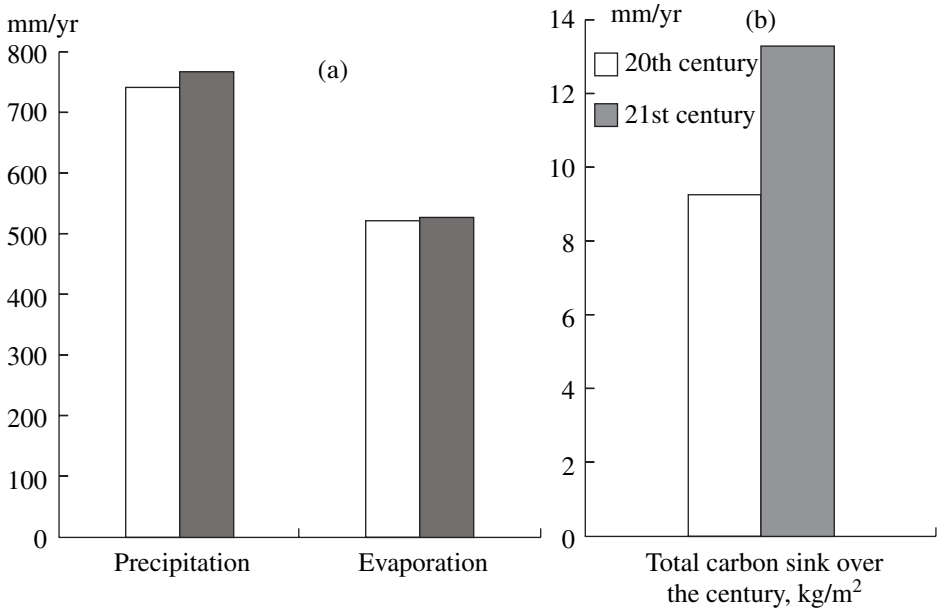

Fig. 2. (a) Mean secular annual precipitation and evaporation and (b) the total (over a century) carbon sink for the coniferous forest ecosystem planted in the Loobos site area in the early 20th (calculation with the use of actual input data) and 21st (calculation with the use of the scenario prediction of input data) centuries. Note that the observed carbon sink over the 20th century (very approximately estimated from the present-day carbon stores in the living and dead biomasses of the ecosystem in accordance with the data of the PILPSC-1 organizers) is about 11 ± 2 kgC/m^2 against the value 9.3 kgC/m^2 calculated with the use of the SWAP model.

tempreture (by about 1.1°C), favoring an increase in the evapotranspiration E, are compensated to a certain extent by an air-humidity increase (on average, by 7.5% over the 21st century), which decreases E. In this case, the carbon budget virtually does not change.

However, if climatic changes are disregarded and only a direct action of the CO_2 concentration increase in the atmosphere (on average, from 320 ppm in the 20th century to 510 ppm in the 21st century, i.e., by about 60%) on the evapotranspiration is estimated, the changes in the latter will also be insignificant (its mean secular value will increase by 0.9%). This outcome is due, on the one hand, to an increase in the ecosystem biomass (see below)—a change that leads to a small increase in the transpiration—and, on the other hand, to a decrease in the stomatal conductance, a change that slightly decreases the transpiration, only one of the components of the evapotranspiration.

As for the carbon exchange, its characteristics (as distinct from the heat and water exchanges) will change significantly if changes in all forcing factors, including both climatic changes and a considerable increment of the CO_2 content in the atmosphere, are taken into account. Thus, the total carbon sink over the 21st century in the developing pine forest ecosystem (if the trees were planted in the early years of this century) is 44% larger than the carbon sink in an analogous ecosystem over the 20th century (Figs. 2b, 3, 4). In this case, changes in the CO_2 concentration in the atmosphere directly affect the carbon budget of the pine forest in the Loobos site area, whereas very small climatic changes virtually have no influence on its formation. A noticeable increase in the difference between the CO_2 concentrations in the ambient air and in the intercellular intrastomatal space of photosynthesizing elements plays the decisive role in carbon-budget changes, while the influence of changes in the stomatal conductance plays a less important role. For example, if we hypothesize that the stomatal conductance for all vegetation types of the ecosystem under consideration remains the same as in the 20th century, the total carbon sink in the system over the 21st century will increase by 53% compared to that in the 20th century (i.e., larger by 9% than with consideration for changes in the stomatal conductance).

The reason for the secondary role of the influence of changes in the stomatal conductance on the carbon regime of the ecosystem under consideration is associated with the fact that, with the increasing content of atmospheric carbon, the stomatal conductance decreases to a smaller extent than the atmospheric CO_2 concentration increases. For example, on average, for the 21st century, g_c of the grassy undergrowth (playing a noticeable role in the carbon budget only during the first 10–20 yr of ecosystem formation) decreases by 24% compared to its mean value in the 20th century (when, as is noted above, the CO_2 concentration in the atmosphere increases by 60%), whereas for needles of pine trees, which play the main

role in the formation of the ecosystem's carbon budget, the g_c decrease amounts only to 5.5%.

Thus, a relatively small influence of the function $g_c(c_a)$ on changes in the carbon budget (compared to the influence of the difference between the CO_2 content in the ambient air and in the intercellular intrastomatal space on this budget) in the Loobos site area is largely due to the fact that it is the coniferous ecosystem that is present here, because, as is noted above, the influence of the CO_2 concentration on the stomatal conductance of the predominant species of such ecosystems is much smaller than its influence on the stomatal conductances of many other vegetation types. For this reason, in elaborating the strategy for increasing the sink of carbon compensating its content increase in the atmosphere, the development of plantings of coniferous species is more preferable than plantings of other vegetation types.

In accordance with the IS92a scenario, the total (over the 21st century) density of carbon emissions, i.e., the total volume of carbon supplied into the atmosphere owing to the combustion of fossil fuel and a decrease in the area of forests divided by the Earth's surface area, is 2.7 kgC/m^2. The results obtained show that for the coniferous ecosystems developing in the Loobos site area during the specified period, even the increment of the carbon sink in comparison with its value over an analogous period of the 20th century, which is equal to 4.1 kgC/m^2, exceeds the density of carbon emissions into the atmosphere caused by the anthropogenic effect. The absolute value of the carbon-sink density in the above ecosystem over the 21st century (13.3 kgC/m^2) exceeds fivefold the global mean density of anthropogenic emissions during this period nearly. Thus, it can be inferred that developing ecosystems in which coniferous species prevail are the best compensators of CO_2 content increases in the atmosphere.

It should be emphasized once more that the conclusions about small climatic changes in the 21st century and, accordingly, the virtual absence of their influence on the carbon regime of the coniferous forest ecosystem under consideration relate solely to the region of the Netherlands. In other regions located farther north, climatic changes and their influence on the carbon regime can be more noticeable because the spatial distribution of changes of meteorological characteristics over the globe (owing to the anthropogenic increase in the contents of greenhouse gases and aerosols in the atmosphere) is extremely nonuniform. In particular, in regions of northern Eurasia (i.e., for a considerable part of Russia) and Canada above the 60th parallel, the increments of annual mean values of the surface air temperature and precipitation in the period 2040–2060 (calculated with the use of the MAGICC/SCENGEN complex in accordance with the IS92a scenario) can attain 2.0–2.5°C and 10–15%, respectively. Such changes can lead to noticeable changes in components of the heat and water budgets of ecosystems in these regions and, accordingly, to the

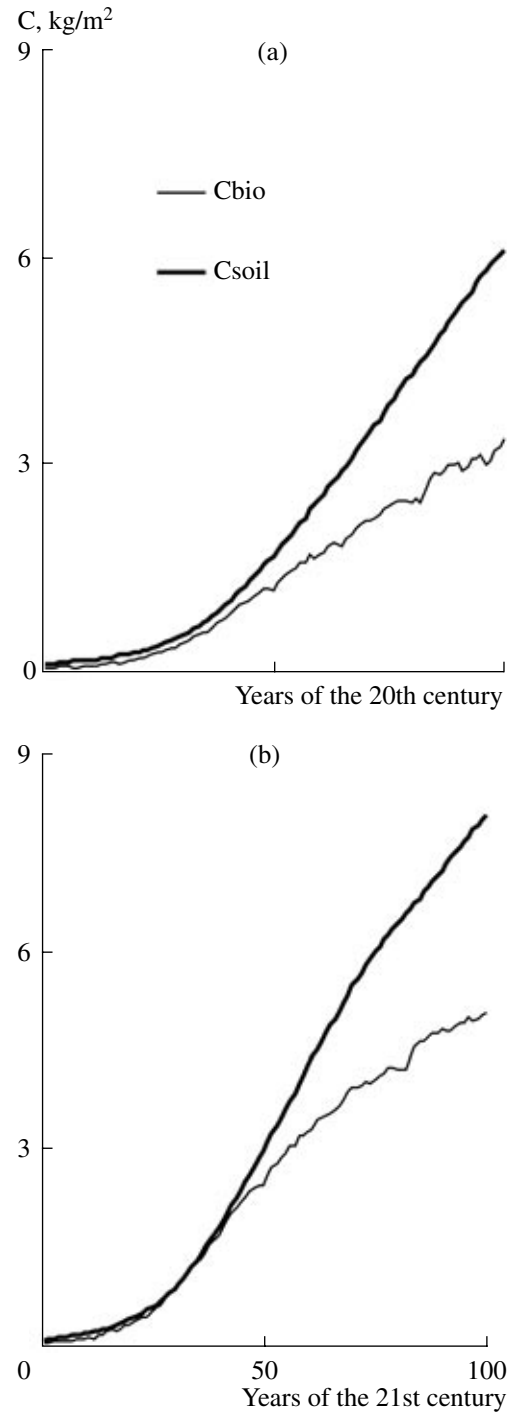

Fig. 3. Dynamics of the accumulation of carbon mass in the living (leaves, pine needles, trunks, branches, roots) (C_{bio}) and dead (litter, detritus, humus) (C_{soil}) biomasses of the pine plantings in the (a) 20th and (b) 21st centuries in the Loobos site area.

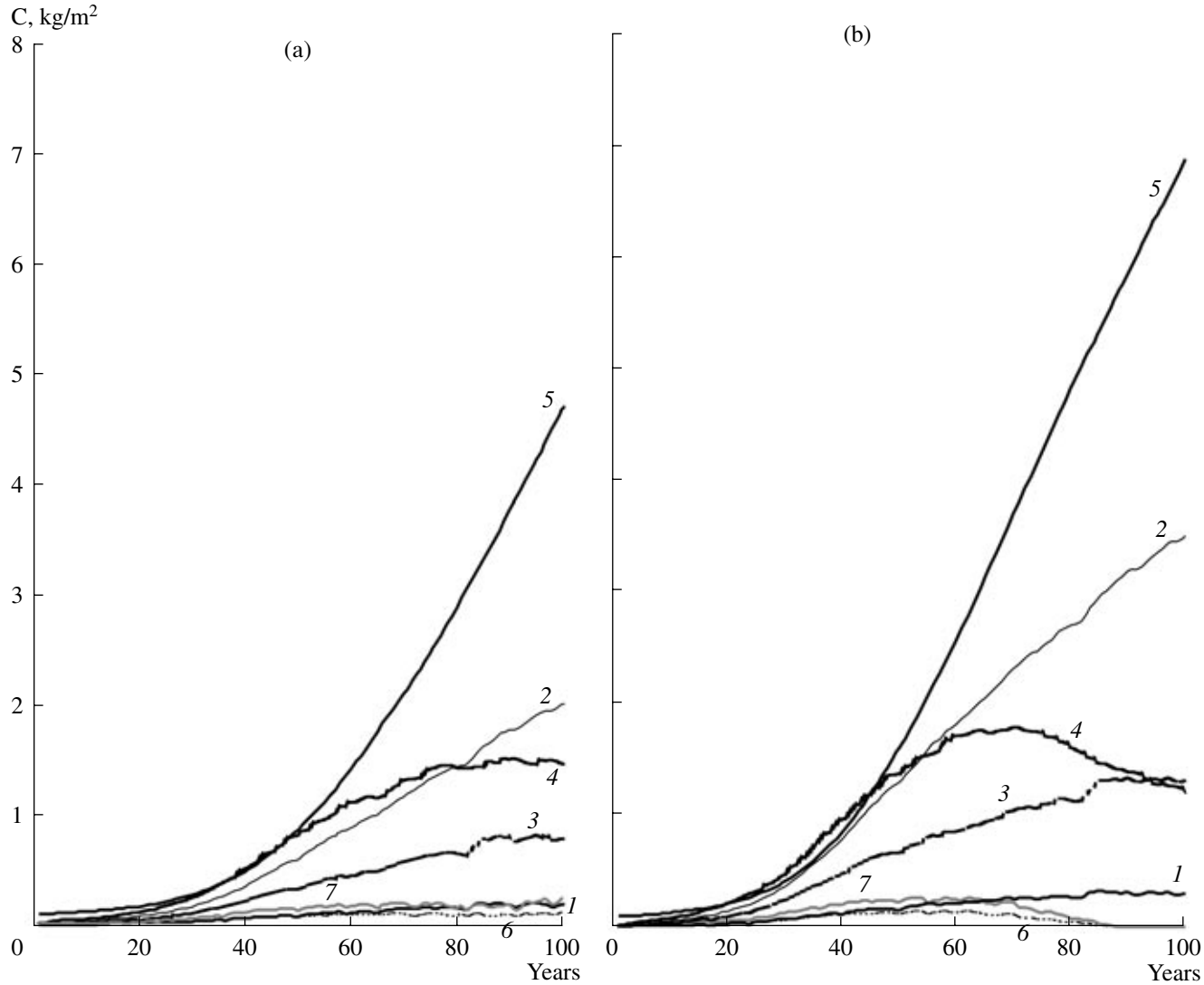

Fig. 4. Dynamics of the accumulation of carbon mass in its different reservoirs for the ecosystems of developing pine forests planted in the early (a) 20th and (b) 21st centuries in the Loobos site area: (*1*) pine needles, (*2*) trunks and branches, (*3*) tree roots, (*4*) litter and detritus, (*5*) humus, (*6*) above ground grass biomass, and (*7*) underground grass biomass.

influence of these changes on the carbon budget of the territory.

CONCLUSIONS

The study allows us to make the following conclusions.

(1) A technique for estimating changes occurring in components of the water and carbon budgets of coniferous ecosystems as a result of possible anthropogenic climate changes has been elaborated. This technique is based on the SWAP model treating heat, water, and carbon exchanges in coniferous ecosystems, which was developed by the authors, as well as on the MAGICC/SCENGEN generator of climatic scenarios for various regions of the Earth.

(2) The developed technique was verified. As a result, it was possible to estimate changes in the evapotranspiration and carbon budget of the developing coniferous forest ecosystem in the area of the Loobos experimental site (the Netherlands) in the 21st century and to compare these estimates with the evapotranspiration and carbon budget of an analogous ecosystem in the 20th century in connection with the expected increase in the emission of greenhouse gases into the atmosphere in accordance with the IPCC IS92a scenario of the economic, technological, political, and demographic development of human civilization up to 2100. It should be noted that the IS92a scenario is taken as an example. Clearly, it is also possible to use any other scenarios of social and economic development (if the arguments for their implementa-

tion is sufficiently convincing), including, among other factors, the control of anthropogenic emissions.

(3) The results obtained show that, under the IS92a scenario, elements of the water budget (precipitation, evapotranspiration) of the growing coniferous forest ecosystem in the region in the 21st century virtually do not differ from those of an analogous ecosystem in the 20th century. The absolute value of the carbon budget of the ecosystem (which in both cases is a considerable sink of atmospheric carbon) in the 21st century will be higher than that in the 20th century by 44%.

REFERENCES

1. *Kyoto Protocol to the United Nations Framework Convention on Climate Change* (Conference of the Parties, Third Session, Kyoto, 1997).
2. C. D. Keeling, J. F. S. Chin, and T. P. Whorf, "Increased Activity of Northern Vegetation Inferred from Atmospheric CO_2 Observations," Nature (London) **382**, 146–149 (1996).
3. S. Fan, M. Gloor, J. Mahlman, et al., "A Large Terrestrial Carbon Sink in North America Implied by Atmospheric and Oceanic Carbon Dioxide Data and Models," Science (Washington, DC, **282**, 442–446 (1998).
4. G. A. Zavarzin, "Preface," in *Soil Respiration* (NTsBI RAN, Pushchino, 1993), pp. 3–10 [in Russian].
5. G. L. Ajtay, P. Ketner, and P. Duvigneaud, *The Global Carbon Cycle, SCOPE 13*, B. Bolin, E. Degens, S. Kempe, and P. Ketner, Eds. (Willey, Chichester, 1979), pp. 129–182.
6. *IPCC, 2001: Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, Ed. by J. T. Houghton, Y. Ding, D. J. Griggs, et al. (Cambridge Univ. Press, Cambridge, 2001).
7. V. P. Meleshko, G. S. Golitsyn, V. A. Govorkova, et al., "Possible Anthropogenic Changes in the Climate of Russia in the 21st Century: Estimations from an Ensemble of Climate Models," in *Proceedings of World Conference on Climate Change* (Moscow, 2003) [in Russian].
8. R. B. Myneni, J. Dong, C. J. Tucker, et al., "A Large Carbon Sink in the Woody Biomass of Northern Forests," Proc. Natl. Acad. Sci. USA **98**, 14 784–14 789 (2001).
9. T. A. Black, W. J. Chen, A. G. Barr, et al., "Increased Carbon Sequestration by a Boreal Deciduous Forest in Years with a Warm Spring," Geophys. Rev. Lett. **27**, 1271–1274 (2000).
10. M. A. Arain, T. A. Black, A. G. Barr, et al., "Effects of Seasonal and Interannual Climate Variability on Net Ecosystem Productivity of Boreal Deciduous and Conifer Forests," Can. J. For. Res. **32**, 878–891 (2002).
11. Ye. M. Gusev and O. N. Nasonova, "The Simulation of Heat and Water Exchange in the Boreal Spruce Forest by the Land-Surface Model SWAP," Hydrology **280**, 162–191 (2003).
12. Ye. M. Gusev and O. N. Nasonova, "Modelling Heat, Water, and Carbon Exchange Processes within Boreal Forest Ecosystems: SWAP Model," in *Hydrology: Science and Practice for 21st Century* (British Hydrological Society, 2004), Vol. 2, pp. 106–112.
13. E. M. Gusev and O. N. Nasonova, "Problems of Studying and Modeling Heat and Water Exchange in the Soil–Vegetation and Snow Cover–Surface Air System," Vodn. Resur. **31** (2), 148–164 (2004).
14. E. M. Gusev, O. N. Nasonova, and L. Ya. Dzhogan, "Modeling of Heat-, Water-, and Carbon-Exchange Processes in a Pine Forest Ecosystem," Izv. Akad. Nauk, Fiz. Atmos. Okeana **41**, 227–241 (2005) [Izv., Atmos. Ocean. Phys. **41**, 203–216 (2005)].
15. J. Polcher, "The Global Land–Atmosphere System Study (GLASS)," BAHC/GEWEX News Joint Issue, GEWEX News **11**, No. 2, 5–6 (2001).
16. M. Kanamitsu, "Description of the NCEP Global Data Assimilation and Forecast System," Weather Forecast. **4**, 334–342 (1989).
17. M. Kanamitsu and J. C. Alpert, et al., "Recent Changes Implemented into the Global Forecast System at NCEP," Weather Forecast. **6**, 0001–0012 (1991).
18. D. F. Parrish and J. C. Derber, "The National Meteorological Center's Spectral Statistical Interpolation Analysis System," Mon. Weather Rev. **120**, 1747–1763 (1992).
19. J. Leggett, W. J. Pepper, and R. J. Swart, *Emissions Scenarios for IPCC: An Update, Climate Change 1992. The Supplementary Report to the IPCC Scientific Assessment*, Ed. by J. T. Houghton, B. A. Callander, and S. K. Varney (Cambridge Univ. Press, Cambridge, 1992).
20. T. M. L. Wigley, S. C. B. Raper, M. Hulme, and M. Salmon, "Concepts and Design;" T. M. L. Wigley, S. C. B. Raper, and T. J. Osborn, "Model Development and Scientific Programming;" M. Salmon "Graphical User Interface" in *Model for the Assessment of Greenhouse-Gas Induced Climate Change* (Climatic Research Unit, Univ. of East Anglia and the National Communications Support Programme, UNDP/GEF, New York, 2000).
21. V. P. Meleshko, G. S. Golitsyn, V. A. Govorkova, et al., "Possible Anthropogenic Changes in the Climate of Russia in the 21st Century: Estimations from an Ensemble of Climate Models," Meteorol. Gidrol., No. 4, 38–49 (2004).
22. L. T. Matveev, *Course of General Meteorology. Atmospheric Physics* (Gidrometeoizdat, Leningrad, 1979) [in Russian].
23. H. W. Polley, H. B. Johnson, and H. S. Mayeux, "Leaf Physiology, Production, Water Use, and Nitrogen Dynamics of the Grassland Invader *Acacia smallii* at Elevated CO_2 Concentrations," Tree Physiol. **17**, 89–96 (1997).
24. H. Maherali, C. D. Reid, H. W. Polley, et al., "Stomatal Acclimation over a Subambient to Elevated CO_2 Gradient in a C_3/C_4 Grassland," Plant, Cell Environ. **25**, 557–566 (2002).
25. C. B. Field, R. B. Jackson, and H. A. Mooney, "Stomatal Responses to Increased NI_2: Implications from the Plant to the Global Scale," Plant, Cell Environ. **18**, 1214–1225 (1995).
26. A. I. Budagovskii, "Evaporation of Soil Waters," in *Physics of Soil Waters* (Nauka, Moscow, 1981), pp. 13–95 [in Russian].

27. A. I. Budagovskii, "Semiempirical Theory of the Transpiration and Water Regime of Vegetation," Vodn. Resur., No. 2, 5–17 (1989).
28. E. A. Lozinskaya, "Method and Results of Determining the Parameters of a Model of Evapotranspiration," Vodn. Resur., No. 4, 17–23 (1988).
29. J. S. Kimball, P. E. Thornton, M. A. White, et al., "Simulating Forest Productivity and Surface–Atmosphere Carbon Exchange in the BOREAS Study Region," Tree Physiol. **17**, 589–599 (1997).
30. T. A. Stone, P. Schlesinger, and V. A. Alexeyev, "RLC Forest Stand Carbon Map of Russia. Data Set 2003. Available at http://www.daac.ornl.gov
31. N. I. Bazilevich and L. E. Rodin, *Geographic Patterns of the Productivity and Cycle of Chemical Elements in the Main Types of the Earth's Vegetation: General Theoretical Problems of Biological Productivity* (Nauka, Leningrad, 1969) [in Russian].
32. O. G. Chertov, A. S. Komarov, G. L. Andrienko, et al., "Integrating Forest Simulation Models and Spatial–Temporal Interactive Visualization for Decision-Making at Landscape Level," Ecol. Model. **148**, 47–65 (2002).
33. L. R. Holdridge, *Life Zone Ecology* (Tropical Science Center, San Jose, 1967).