

Working Paper

**A Set of Biogeochemical Model
Approaches for Integrated Modeling
of Climate Change Impacts**

**Biospheric Carbon
and Nitrogen Cycles**

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FOREWORD

The biospheric research component of the Forestry and Climate Change Project has had as one of its objectives to develop a concept for a coupled carbon, nitrogen and water model which can be part of integrated models for analyses of climate change. This Working Paper describes a set of such model concepts.

These models are now being tested and modified for implementation for regional analyses in the assessment phase of Siberian Forest Study.

1. INTRODUCTION AND OVERVIEW

1.1 Objective

The main objective of this paper is to outline a means of including terrestrial biogeochemical cycles (carbon and nitrogen) in an integrated model of climate change.

The terrestrial biosphere and atmosphere are coupled to each other over a wide range of time scales through the exchanges of radiation, heat, water, CO₂, N₂O and trace constituents. The simplest approach to model these complex exchange processes is to consider components that can be treated more or less as separate items. Figure 1 shows the spectrum of interactions represented by three coupled feedback loops that describes terrestrial processes by means of a biophysical model (for land surface processes), a biogeochemical model (for the description of the carbon and nitrogen cycle) and a vegetational dynamics model (for succession processes). Each of these feedback loops presented in the models is affected by a set of climate variables such as temperature, precipitation, solar radiation, etc.

The biophysical loop is the fastest and most "physical" of the three. Surface properties such as albedo, roughness and transpiration rates determine the atmosphere boundary conditions of radiation, heat, water and momentum fluxes.

The biogeochemical loop is forced by climate variables on a time scale of months to years and is affected by biophysical land surface parameters. Nutrient fluxes and pool sizes to a great part determine the fluxes of CO₂, N₂O and other trace gases to the atmosphere and also regulate some surface properties of vegetation such as leaf area index, stem area index, and so on.

The terrestrial ecological loop, which realizes changes in the composition and structure of vegetation communities, is influenced by climate, nutrient status and anthropogenic activities.

So far, with a few exceptions, only one of the loops has been modelled in detail, while the boundary conditions of the other loops has been prescribed. One of the reasons is the existence of uncertainties that are inherent to all three feedback loops when modelling the various biological processes.

Environmental scientists have made considerable progress by including vegetation into models which simulate the feedback loops. However, the reliability of the models tends to decrease as time and space scales increase, so that the models are highly empirical and reveal a maximal number of uncertainties at resolution scales relevant to ecological successions.

Understanding the biological uncertainties in the models, that describe the feedback loops mentioned, requires a hierarchy of climatological-vegetational-biogeochemical models of graded complexity ranging from a simple zonal model to a model that resolves latitude and longitude. This Working Paper deals with a set of terrestrial biogeochemical model approaches which could be implemented in the hierarchy of IIASA climate-vegetation-biogeochemical models.

A terrestrial biogeochemical model appropriate for integrated studies requires the simultaneous description of carbon, nitrogen and water cycles in the climate-vegetation-soil

system. There are only a few recent regional models dealing with the dynamics of the carbon and nitrogen cycles and with their dynamics interdependently. These models do not allow us to estimate the ecosystem-climate biophysical feedback due to their spatial limitations and, hence, they can not be implemented in an integrated model of climate change.

A set of biogeochemical model approaches is proposed to fill this gap. The main purposes of the models are

- to estimate the terrestrial CO₂ and N₂O emissions due to changed climate, taking into account the C, N and H₂O cycles simultaneously; and
- to evaluate spatial and temporal dynamics of land surface vegetation parameters regulating heat, water vapor and momentum fluxes to the atmosphere.

Therefore, each of the model approaches proposed can be considered to be an important part of an integrated model of climate change. The biogeochemical models can provide the input data for both the emission and the climate modules of an integrated model and can aid to evaluate important qualitative and quantitative ecosystem features such as global and regional carbon sequestering capacities and nutrient availabilities in soils.

In order to design the general model structure, an analysis of the major carbon and nitrogen transfer processes in the biosphere was carried out taking into account the state-of-the-art in biogeochemical modeling.

1.2 The biospheric carbon cycle

In order to predict future levels of atmospheric CO₂, and hence climate changes, it is necessary to account for all sources and sinks of CO₂, which lead to the present atmospheric concentration. The retention of carbon dioxide in the atmosphere is determined by the uptake of oceans and the concurrent storage or release in deep sea waters, by the exchange of fluxes between terrestrial ecosystems, and the storage in living as well as dead biomass.

The main carbon pools in the Earth's lithosphere and hydrosphere are carbonate (10^7 Gt C) and carbon dissolved in oceans (3.5×10^4 Gt C). The atmosphere contains 690 Gt C, while the biospheric pools contain 10^6 Gt C in the soils and 620 Gt C in the living biota (Krapivin, Svirezhev and Tarko, 1982). Despite of being the smallest carbon pool, the living biota plays a major role in the global carbon budget, because of the content of the 95-99% of the terrestrial photosynthetic autotrophs. Through the process of photosynthesis, plants remove approximately 120 Gt C from the atmosphere annually. This is about 20 times more carbon than is emitted annually by fossil fuel combustion and more than the exchange of carbon between the atmosphere and the ocean (about 100 Gt).

Approximately half of the carbon taken up by plants is returned to the atmosphere by respiration, and the remainder, known as net primary productivity flux (NPP), is incorporated into the plant tissue. The flux back into the atmosphere, which is nowadays assumed to be equal to the NPP, is due to the organic decomposition in the soil (Figure 2). If both the NPP and the organic decomposition flux are different in size, they can substantially influence the atmospheric carbon pool and, therefore, the radiative forcing. Up to now these fluxes can not

be addressed by direct measurements, leaving mathematical modeling and computer simulations as the main tool.

The role of the terrestrial biosphere within the global carbon cycle is not yet completely understood. Positive and negative feedbacks must be taken into consideration with respect to their soil-vegetation-atmosphere interactions. Changes in a variety of factors including temperature, precipitation, atmospheric CO₂ concentration will affect both the NPP and the organic decomposition flux. Inorganic nitrogen available in the soil is one of the most important limiting factors in regard to the photosynthetic organic productivity.

1.3 The biospheric nitrogen cycle

Photosynthesis is known to decrease when the amount of inorganic nitrogen available is restricted (Chapin 1991, Evans 1983, etc.). This is because nitrogen is an essential constituent of proteins and nuclei acids, both of which are known to support life. Yet nitrogen is not particularly common on Earth, with the exception of the atmosphere, which contains almost 80 volume per cent of the nitrogen (3.9 Pt N₂). The next most common gaseous form of nitrogen in the atmosphere after molecular, nitrogen is dinitrogen oxide (N₂O, 1.3 Gt), which is one of the important greenhouse gases.

The amount of nitrogen (14 Gt N₂) in the living biota (mainly terrestrial vegetation) is about three parts per million of the atmospheric nitrogen (Tamm, 1991). Other important pools are: soil organic matter 3 x 10² Gt N, rocks 1.9 x 10² Pt N, sediments 4 x 10³ Gt N, molecular nitrogen dissolved in the ocean 2.2 x 10⁴ Gt N and dead organic matter in the ocean 5.3 x 10² Gt N (Söderlund and Svensson, 1976).

Although being the smallest pools, the terrestrial vegetation and both the organic and inorganic soils are exchanging substantial nitrogen fluxes. Thus the annual nitrogen turnover in all terrestrial ecosystems, the terrestrial vegetation and both the organic and inorganic soils exchanges is at least one order greater than any other global nitrogen flux at the Earth (about 2 Gt N). This shows the high nitrogen demand for the Earth's ecosystems to function. Therefore, there is a visible need to investigate the terrestrial biospheric N cycle in addition to estimate the NPP and the organic decomposition carbon flux.

Nitrogen dynamics in vegetation and soils reveal a more complex behavior than carbon since nitrogen is represented in the form of different gaseous and liquid chemicals in different ecosystems (proteins, amino acids, nitrates, nitrites, ammonia, nitrosous oxides, molecular nitrogen, etc.). The biospheric nitrogen cycle includes all the transformations of these chemicals, which are of importance for the mineralization of organic nitrogen substances and for the loss or gain of nitrogen by soil. Nitrogen is stored in soil primarily in organic forms that cannot be utilized by higher plants, but that can be made available in the form of ammonia through the activities of soil microorganisms or after oxidation of ammonia to nitrate. Ammonia and nitrate may be lost to the soil by leaching or through microbial immobilization. The main sources of nitrogen in the soil are the microbial biological fixation of molecular atmospheric nitrogen and the use of fertilizers. The biospheric nitrogen cycle can be subdivided into four processes: ammonification, nitrification, denitrification and biological fixation.

Ammonification is accomplished under aerobic conditions through the participation of bacteria, fungi, actinomycetes, etc. Ammonia-nitrogen released from dead organic matter through microbial action exceeds the requirements of these organisms for growth. So when organic matter rich in nitrogen is added to soil, a considerable amount of ammonia is released, whereas organic matter poor in nitrogen yields only a little amount of ammonia. Furthermore, under the condition of highly limited nitrogen in ecosystems much of the available inorganic nitrogen will be used by rapidly developing microbial populations, rather than by vegetation. A portion of the organic nitrogen is not ammonified but becomes an integral part of the long-term soil organic matter.

Nitrification is the bacterial oxidation of ammonia to nitrate by organisms of genera *Nitrosomonas*, *Nitrosococcus* and *Nitrobacter*. A well-aerated, fertile soil provides optimal conditions for nitrification. The nitrate so formed can be used by plants and microorganisms, or may be lost from the soil by leaching.

During denitrification nitrate is reduced to nitrite, gaseous nitrous oxides and molecular nitrogen. Under the conditions of a low oxygen supply, for instance in waterlogged soils, a wide range of soil microbial species utilize nitrate as a source of oxygen and reduce it to inorganic forms, which can be lost to the atmosphere as gas or by leaching of nitrites.

Atmospheric N_2 returns to the soil primarily by means of biological fixation, which is accomplished by symbiotic or non symbiotic microorganisms. The symbiotic bacteria (belonging to genus *Rhizobium*) live in the root modules of legume plants, while free-living non symbiotic bacteria function either aerobically (*Azotobacter*) or anaerobically (*Clostridium*). Other species such as blue-green algae (*Nostoc*, *Anabena*) can also fix atmospheric nitrogen. The microorganisms most important for the fixation of nitrogen are symbiotic bacteria settling on the roots of legumes.

It becomes evident that the biological interactions involved in the terrestrial carbon and nitrogen cycles in ecosystems are interlinked by a number of feedback loops with self-regulating mechanisms. Consequently, a realistic assessment of the temporal and spatial dynamics of nitrogen that is available for plants require simultaneous modeling of the carbon and nitrogen cycles in the biosphere.

1.4 Biospheric water cycle

Water availability is likely to be the main limiting factor in regard to plant productivity for continents in both the temperate and the tropical zones. The amount of water in the soil is controlled by precipitation, evaporation and soil storage capacity on one hand, but also by plant factors that regulate transpiration and water uptake by roots on the other hand. The study of the biospheric water balance is important for at least four reasons:

1. In natural and artificial ecosystems, water availability strongly affects productivity.
2. Vegetation plays an important role at the regional hydrological scale.
3. Due to their surface properties (albedo, roughness, evaporation), vegetation impacts the on climate may alter climatic change forecasts for the next century.
4. Nutrient availability is dependent on regional hydrological parameters such as runoff and inflow.

Therefore, there is a visible need to investigate the biospheric carbon and nitrogen cycles simultaneously with the biospheric water balance.

Plant morphological characteristics can usually play a key role in the soil-vegetation-atmosphere system. Plant water content is related to the soil water content by the rates of uptake and loss. The rate of uptake depends directly on the plant water potential, root area or root density, soil water storage and conductance, root depth, and inversely on the soil water potential. The rate of loss depends directly on stomatal conductance, boundary layer air conductance, leaf area, stem area and conductance, leaf temperature and on surface air humidity. These plant and soil variables, in turn, are affected by many other environmental conditions.

The soil water balance is intimately associated with the plant water balance and depends on patterns of precipitation, interception in the canopy, throughfall, stemflow, runoff, and infiltration. Different precipitation regimes and soil textures will produce different spatial and temporal patterns of exploitable water.

Balancing water inflows and losses from an ecosystem involves the application of either mass or energy conservation principles. The quantitative methods, hydrometric (water budgeting) and energy (energy budgeting) may be used separately or in combination in order to describe water movements and phase changes that reflect interaction of physical and biological mechanisms.

1.5 Modeling of carbon and nitrogen cycles

To examine the ecological consequences of historical and future climate change, ecosystems are typically perceived in terms of carbon and nutrient pools. All of such ecosystem models simulate carbon uptake and loss associated with plant growth. The physical base of biogeochemical modeling includes the mass law of conservation and stoichiometric relationships.

All existing biogeochemical models start with aggregation of chemical pools in the form of boxes, which have the same parameters. Hence, the main hypothesis for this procedure is the homogeneity of boxes, determining the model description of the inner structure of vegetation or soil, the definition of vegetation or soil units and the spatial resolution of a model.

The inner structure of ecosystems can be represented by a different number of interlinked pools such as carbon pools for leaves, branches, stems and roots as in the Goudriaan and Ketner model (1984) and carbon pools for wooden litter and herbivorous litter in the Osnabrück biospheric model (Esser, Overdieck, 1991).

Typical vegetation units in the terrestrial biospheric models are biomes. The number of biomes varies from 5-6 in the simplest models (for instance in the Goudriaan and Ketner model) to 31-37 in more sophisticated ones (Esser, Overdieck, 1991, Ludeke et al., 1993). Soil units are often not defined in the models.

The most sophisticated biogeochemistry models deal with grids of 1° latitude by 1° longitude (McGuire et al., 1992), while more crude zero-dimensional models only take biome areas into account (Goudriaan and Ketner, 1984).

The current models utilize different semi-empirical parameterizations of annual growth (Esser, Overdieck, 1991, Krapivin et al., 1984, Smith et al., 1992) or, more rarely, seasonal growth (McGuire et al., 1992).

The most important photosynthetic productivity fluxes (either the net primary productivity or the gross primary productivity) are estimated from algebraic equations of implementation of the Leibich principle of limiting factors. This principle states that the growth of biomass will be limited by that factor, **which is present to the least amount in relation to the required amount**. The sets of limiting factors are different for different geographical locations, but all sets include temperature T (or biotemperature), P precipitation (or soil moisture), light intensity I, nitrogen availability N, and phosphor availability Ph.

The analytical representation of the Leibich principle for net primary productivity may be written in two variants:

$$NPP = \min\{NPP(T), NPP(P), NPP(I), NPP(N), NPP(Ph)\}$$

or

$$NPP = NPP_{\max} \cdot f_1(T) \cdot f_2(P) \cdot f_3(I) \cdot f_4(N) \cdot f_5(Ph),$$

where $0 \leq f_i \leq 1$.

As all of these factors are strongly interlinked, one limiting factor can be replaced by another **as the acting limiting factor** due to climate change at a site.

In models which simulate carbon and nitrogen cycles simultaneously, the mutual dynamics of pools and fluxes is usually investigated by using stoichiometric hypotheses. For example, the Terrestrial Ecosystem Model (McGuire et al., 1992) concludes that vegetation is stressed by the availability of N, if the calculated C to N ratio resulting from production is greater than the maximal potential C to N ratio, which can be used by a vegetation type.

The terrestrial biospheric models presently available can be subdivided into two groups: regression-based models and process-based models (McGuire et al., 1993b). A regression based model uses empirical relationships between climate and NPP, while a process-based model simulates the mechanical transfer of carbon (and more rarely, nitrogen) between different ecosystem pools. Although process-based models may contain some relationships that are empirical, they differ from regression based models in that the NPP depends on a number of interacting processes such as gross primary productivity, respiration, decomposition, nutrient uptake and nutrient mineralization. Regression-based models are employed to translate predictions of dynamical carbon cycles models in geographical outputs (Esser, 1991; Lieth, 1972).

In summary, the basic principles for modeling carbon and nitrogen cycles in the terrestrial biosphere include the use of:

- a box model structure,
- mass balance equations,
- regression-based equations for annual dynamics,
- process-based equations for seasonal dynamics,
- the Leibich principle of limiting factors for photosynthetic productivity,
- a description of the C to N ratio resulting from the carbon and nitrogen cycle.

1.6 Overview of some recent models

Both regression- and process-based models are presently available to assess the response of the NPP and the soil organic decomposition geographically in the context of a flux global change. The six most well-known models are shown in Table 1.

The IMAGE 1.0 Biospheric Model (Goudriaan and Ketner, 1984; Rotmans, 1990) is a relatively simple zero-dimensional model operating with surface densities of carbon pools and fluxes for six biomes. The Osnabrück Biospheric Model (Esser, Overdieck, 1991) calculates annual production and organic decomposition employing empirical relationships of mean annual surface air temperature and mean annual precipitation and is therefore regression-based. The Moscow Biospheric Model (Krapivin et al., 1982; Krapivin, 1993) is also regression-based. It simulates the annual dynamics of the biospheric carbon and nitrogen cycles separately. The model of Smith et al. (1992) simulates the final state of carbon pools after CO₂ doubling based on hypotheses of equilibrium between climate and vegetation patterns and constant surface carbon pool densities of the biomes. The Terrestrial Ecosystem Model (TEM; McGuire, 1992) evaluates monthly production and decomposition of litter by adjusting a potential productivity for monthly irradiance, atmospheric CO₂ concentration, air temperature, soil moisture, and soil nitrogen under stable climatic conditions. In the TEM model the monthly potential evapotranspiration is prescribed and adjusted to the actual evapotranspiration using the Thornthwaite approach. The Frankfurt Biospheric Model (FBM; Ludeke et al., 1993) was intended to give a simple representation of the seasonal dynamics of the C-compartments in terrestrial ecosystems. The present version of the FBM includes a seasonal description of two forest biomes and preliminary representations of soil water dynamics and soil respiration.

All of these models have their own features, which prevent them being a part of an integrated model of climate change. For instance, the IMAGE 1.0 Biospheric Model is forced by the atmospheric CO₂ concentration and is therefore not responsive to internal climate variations. The other models also have serious restrictions in order to be used in integrated studies. However, these shortcomings should be overcome and the current models should be incorporated with a biogeochemical model, which is part of an integrated model of climate change. The shortcomings of the current models are:

- a poor representation of the seasonal dynamics
- a poor representation of available nitrogen as a limiting factor
- absence of estimates for land surface biophysical parameters (such as leaf area indexes, roughness, etc.)
- indefinite range of uncertainties in the main biogeochemical parameters.

2. A SET OF LINKED CARBON AND NITROGEN MODELS

2.1 Description and status of the models

A set of linked carbon and nitrogen models is foreseen in order to evaluate the dynamics of the major terrestrial carbon and nitrogen pools and fluxes within an integrated model of climate. There are four possible model versions, two of which incorporate an annual time step:

- 1) zonal long-term soil-vegetation model
- 2) two-dimensional long-term soil-vegetation model;

and two models with the time step equal to one month:

- 3) zonal seasonal soil-vegetation model
- 4) two-dimensional seasonal soil-vegetation model.

The climate models available at IIASA are the 2-dimensional zonal climate model ZCM (Jonas et al., 1993) and the 2,5-dimensional dynamical statistical climate model DSCM (Petoukhov and Ganopolsky, 1994).

The proposed carbon and nitrogen models are supposed to use input data from the above mentioned climate models and provide feedback, i.e. output data for the latter models. The preliminary testing and tuning of the linked carbon and nitrogen models would be realized with the ZCM, while more sophisticated simulations of changes in the carbon and nitrogen cycles would be carried out with the DSCM.

For the carbon and nitrogen models it is initially assumed that vegetation patterns are stable during climate change. At a later stage of the development the models are foreseen to also include possible shifts of vegetation zones based on ecosystem models with spatial dynamics (Belotelov et. al., 1992, Venevsky, 1992).

2.1.1 Driving variables

The driving variables of the carbon and nitrogen models are atmospheric CO₂ concentration and climate parameters such as mean annual temperature and mean annual precipitation for the two model versions with annual dynamics. Seasonal means of temperature and precipitation are the driving forces for the two model versions with seasonal dynamics. It is obvious that time-dependent simulations of Global Circulation Models (GCMs) are not appropriate for this approach since they are very time consuming and therefore do not allow investigation of the climate-vegetation interaction dynamically and in an integrated fashion. In addition, they are not able to deal with the range of uncertainties involved in all living systems. Therefore, more simplified zonal and dynamic-statistical climate models are more appropriate tools for the purpose of this approach.

2.1.2 Biome types

A high diversity of vegetation communities can be noted from various geobotanical classification schemes and maps (e.g., 172 types in vegetation atlas; Schmithüsen, 1976). A typical aggregation of these communities into biome types for purposes of biogeochemical modeling is one consisting of 31-37 types (e.g., Matthews' or Leith's aggregation; Matthews, 1983; Esser, Overdieck, 1991). The aggregation proposed to be used in this approach includes 31 types of natural biomes according to Leith's aggregation and three artificial biomes.

1. Tropical moist lowland forest
2. Tropical dry lowland forest
3. Tropical mountain forest
4. Tropical savanna
5. Tropical paramo woodland
6. Tropical paramo grassland
7. Puna formation
8. Subtropical evergreen forest
9. Subtropical deciduous forest
10. Subtropical savanna
11. Subtropical haloptytic formation
12. Subtropical steppe and grassland
13. Subtropical semidesert
14. Temperate steppe and meadow
15. Xeromorphic formation
16. Desert (tropical, subtropical, cold)
17. Mediterranean sclerophyllous forest
18. Mediterranean shrub and woodland
19. Temperate evergreen (coniferous) forest
20. Temperate deciduous forest
21. Temperate woodland
22. Temperate shrub formation
23. Temperate bog and tundra
24. Boreal evergreen coniferous forest
25. Boreal deciduous forest
26. Boreal woodland
27. Boreal shrub formation
28. Woody tundra
29. Herbaceous tundra
30. Azonal formation
31. Mangrove
32. Agricultural lands
33. Irrigated agricultural lands
34. Human area

However, this aggregation is too large to be implemented into a biophysical land surface model. Instead we proposed to use an aggregation of fourteen biome types, which is in agreement with Atmospheric Transfer Scheme (BATS; Dickinson et al., 1986). The BATS model (after improvement) allows surface parameters, which are necessary for studying the

ecosystem-climate feedbacks, to be calculated. The procedure of translating a biogeochemical aggregation scheme into a biophysical aggregation scheme is carried out for each geographical location by employing superimposing techniques.

The vegetation/land cover types proposed to be used in a biophysical model are:

1. Crop/mixed farming
2. Short grass
3. Evergreen needleleaf tree
4. Deciduous needleleaf tree
5. Deciduous broadleaf tree
6. Evergreen broadleaf tree
7. Tall grass
8. Desert
9. Tundra
10. Irrigated crop
11. Semi-desert
12. Evergreen shrub
13. Deciduous shrub
14. Mixed woodland

2.1.3 Model output

As briefly mentioned in Section 1.1, the carbon and nitrogen models will provide not only carbon and nitrogen pools and fluxes in a geographical context, but also global biogenic carbon dioxide emissions, global dinitrogen oxide emissions and spatially distributed leaf area and stem area indices as well as evaporation parameters.

2.2 Model variants

2.2.1 One-dimensional (zonal) models

Variables of these models are functions of geographical latitude φ and biome type i . Thus equations of these models operate with longitude belt densities of pools and fluxes. The distribution of biomes by latitude is described by a weight function $0 < \beta_i(\varphi) < 1$, where $\beta_i(\varphi)$ is a biome ratio at latitude belt φ_j . The output of the ZCM is given by temperature and precipitation as functions of time and latitude $T(t, \varphi_j)$, $P(t, \varphi_j)$.

2.2.2 Two-dimensional models

In this case variables are functions of geographical latitude φ , geographical longitude λ and biome type i . The existence of each biome is described by a Bulev function $\delta_i(\varphi, \lambda)$, which is equal to one for the habitats of biome type i at the geographical location φ, λ . The climate variables, $T(t, \varphi, \lambda)$ and $P(t, \varphi, \lambda)$, are output variables of the DSCM.

2.2.3 Models of long-term vegetation dynamics

These models are regression-based with annual dynamics. Hence, the NPP is calculated from mean annual temperature, mean annual precipitation and atmospheric CO₂ concentration by using regression techniques. It should be noted that there are differences in representing the actual evapotranspiration models of long-term vegetation dynamics and in models of seasonal vegetation dynamics.

2.2.4 Models of seasonal vegetation dynamics

These models are process-based with a monthly time step. The net primary productivity flux is calculated by subtracting the monthly maintenance respiration flux of plants from the monthly gross primary productivity flux. This feature is not given in the block diagram, Fig. 3, but it exists in the model equations.

2.3 General model structure

2.3.1 Block diagram of the models

The block diagram with the general model structure is shown in Figure 3. There are two subsystems involved in the model structure - the vegetation and the soil. The atmospheric chemical pools are not evaluated in the runs of the models. This can be done by a greenhouse gas emission/concentration accounting tool as part of an integrated model of climate change. There are three interacting cycles, the C, the N and the H₂O cycle, each of which is denoted by a specific drawing line. The water cycle is marked by bold lines, the carbon cycle by twin lines and the nitrogen cycle by normal lines. The model diagram is the same for each geographical location and biome type, except for the atmospheric gaseous pools, which are common for all of the terrestrial ecosystems.

2.3.2 Pools and fluxes

2.3.2.1 Pools

The model pools can be divided into three groups due to the inner structure of vegetation, litter and humus. The first group includes pools with fast dynamics:

- 1) leaf carbon pool C_{VL} ;
- 2) leaf nitrogen pool N_{VL} ;
- 3) herbaceous litter carbon pool C_{SH} ;
- 4) herbaceous litter nitrogen pool N_{SH} ;
- 5) inorganic nitrogen available for plants N_{in} ;
- 6) soil water pool W_S ;

The second group consists of pools with a somewhat slower dynamic:

- 7) stem carbon pool C_{VS} ;

- 8) stem nitrogen pool N_{VS} ;
- 9) wooden litter carbon pool C_{SW} ;
- 10) wooden litter nitrogen pool N_{SW} ;

The slowest pool belongs to the third group:

- 11) nitrogen organic long-term pool N_{Org} .

The model fluxes are calculated by means of algebraic equations. The equations proposed below do not show the dependence of model coefficients and variables from both biome type and geographical coordinates in order to indicate the readability. The fluxes can be classified into three types in accordance with their chemical content. The first letter d in further expressions denotes a flux, while the indices of a flux show: source of flux (first index), and sink of flux (second index) consequently.

2.3.2.2 Water fluxes

Water fluxes are the actual evapotranspiration flux dW_{SA} and runoff flux dW_{SO} , and precipitation P .

The actual flux evapotranspiration is calculated in a different manner for the models with an annual respectively seasonal dynamics. (Lopes, et al., 1982, Krysanova, et al, 1989). For all the models the actual evapotranspiration flux is calculated by using nonlinear equations for different approximations or tabulated data for different types of vegetation cover and soil. (Thornthwaite and Mather, 1957, Pastor and Post, 1984):

$$dW_{SA} = f_1(PET, W_s, i),$$

where i is the type of vegetation cover and PET is the potential evapotranspiration. For annual dynamics PET can be estimated as:

$$PET = k \cdot \sum_{j=1}^{12} p(\varphi) \cdot T_j.$$

This is the so-called Blaney-Criddle equation, which makes use of mean monthly temperature T_j (in Fahrenheit), $p(\varphi)$ as the percentage of monthly daytime hours divided by 100, and k as a consumption use coefficient known from hydrological handbooks.

For seasonal dynamics it is assumed to be better to calculate the PET by means of Thornthwaite's equation:

$$PET = 1.6 \cdot (10 \cdot T_j / TE)^a$$

where T_j is the mean monthly temperature (in degrees Celsius); $TE = \sum_{j=1}^{12} (T_j / 5)^{1.514}$ is a heat index; and a is a polynomial of TE :

$$a = 0.00000675 \cdot (TE)^3 - 0.000771 \cdot (TE)^2 + 0.01792 \cdot TE + 0.49239.$$

The runoff flux can be calculated from the non-linear equation:

$$dW_{SO} = f_2(P, W_s),$$

which becomes different for models with annual and respectively seasonal dynamics (see, e.g., Lebedev, 1982; SCS, 1975).

For the first steps of the study, the runoff flux can be estimated by the so-called rational formula (Ven Te Chow, 1964), well-known from the end of nineteenth century:

$$dW_{SO} = c P(t) A,$$

where $P(t)$ is the rainfall intensity (in inches per time interval), A is the drainage area (in acres), and c is a coefficient ($0.05 < c < 0.35$).

2.3.2.3 Nitrogen fluxes

The nitrogen cycle demands the most complex representation in the models.

There are two fluxes entering the vegetation nitrogen pools N_{VL} and N_{VS} , namely: dN_{VA} and dN_{inV} , and one flux leaving this pool dN_{VS} .

dN_{AV} is the biological fixation flux (see 1.3). It was assumed that this flux is split into two fluxes, one entering the leaves pool, another entering the stem pool, with constant ratio. The flux can be evaluated by means of a linear function from the net primary productivity flux (Krapivin, 1993, Krapivin et.al., 1982):

$$dN_{AV} = \mu \cdot dC_{AV} \cdot (p_L + p_S),$$

where p_L, p_S are partition coefficients; $p_L + p_S = 1$; $0.00000134 \text{ [gN/gC]} < \mu < 0.0000506 \text{ [gN/gC]}$ (Krapivin, 1992).

dN_{inV} is the inorganic nitrogen uptake by plants from the soil. This flux is a biological fixation flux and also sub-divided into two parts, as biological fixation flux. Even if the physiological need for nitrogen is satisfied, roots of plants continue to absorb ammonium and nitrate ions. However, the further increase of nitrogen concentrations in the plant tissue will result in toxic effects. Such dependence can be represented by the Michaelis-Menten equation, which is a slightly modified version of the Rastetter et al. function (1991) equation for dN_{inV} :

$$dN_{inV} = dN_{inmax} \cdot \frac{N_{in}}{K_n + N_{in}} \cdot F_{str}(dC_{AV}),$$

where dN_{inmax} is the maximal possible nitrogen uptake by roots, estimated to be about 6 gN m⁻²yr⁻¹ (Kirschbaum, 1993); K_n is the half saturation constant .

The uptake of nitrogen should monotonously decrease as the potential C to N ratio of production decreases below P_{CN} (McGuire et.al.,1992). P_{CN} , the maximal C to N ratio of plant production is commonly measured in ecological studies. If the calculated production ratio C to N, after taking into account all the limiting factors except nitrogen, is greater than P_{CN} in conditions the vegetation is stressed by the limitations of N. This stress can be expressed by a nitrogen stress function (McGuire et. al., 1992, Kirshbaum, 1993):

$$F_{st} = 1, \text{if } \frac{dC_{AV}}{dN_{inV}} \leq P_{CN} ;$$

$$F_{st} = 1 - a \cdot \left(\frac{dC_{AV}}{dN_{inV}} \right)^2, \text{if } \frac{dC_{AV}}{dN_{inV}} > P_{CN} .$$

It should be noted that in the case of the nitrogen uptake flux the dC_{AV} flux is assumed to be calculated, while dN_{inV} is the one calculated without being multiplied by the stress function.

dN_{VS} is the nitrogen litter production flux. It is divided into two parts, one coming from the nitrogen leaf pool and another leaving the nitrogen stem pool. It is assumed that the C to N ratio in falling litter is constant, therefore, this flux can be calculated as:

$$dN_{VS} = \frac{N_{VL}}{\tau_L} + \frac{N_{SV}}{\tau_S},$$

where τ_L is the carbon turnover time for the leaf pool and τ_S is the carbon turnover time for the stem pool (Goudriaan and Ketner, 1984; Krapivin et. al., 1982).

The most important nitrogen pool for plants is the inorganic soil nitrogen pool. There are three fluxes entering this pool: $dN_S in$, the flux of inorganic nitrogen realized by the decomposition of organic matter; $dN_O in$, the flux of nitrogen due to mineralization of humus by humivores microbial communities; $dN_H in$, the flux due to external human fertilization. Three fluxes are leaving the pool: dN_{inV} , the nitrogen uptake by plants; dN_{inA} , the denitrification flux of dinitrogen oxide (see Section 1.3); dN_{inO} , inorganic nitrogen, leaving the pool by runoff.

The amount of inorganic nitrogen, realized by litter decomposition, is simulated by:

$$dN_{Sin} = dec_H \cdot N_{SH} + dec_W \cdot N_{SW},$$

where dec_W is the decay rate for wooden litter, ($0.03 < dec_H < 0.1$); and dec_H is the decay rate for herbaceous litter (Pastor and Post, 1986):

$$dec_H = 0.9804 + 0.0935 \cdot dW_{SA} + [0.4956 - 0.001927 \cdot dW_{SA}] \cdot \left(\frac{f}{N_{SH}} - \frac{g \cdot C_{SH}}{N_{SH}} \right).$$

The term in brackets presents a ratio of lignin in dead organic leaf matter (Pastor and Post, 1986), and f and g are constants.

The external fertilization flux is assumed to be constant and equally distributed over land in these models. It could be calculated by a global economic model at a later stage of the model development.

The nitrogen mineralized by humivoreus is estimated according to Aber et. al. (1982):

$$N_{oin} = \gamma \cdot N_{org},$$

where γ approximately is 0.09 (Aber et. al., 1982).

According to Krapivin (1993), the flux of nitrogen lost by runoff is equal to:

$$dN_{inR} = \lambda \cdot N_{in} \cdot (1 - \exp(-k \cdot dW_{SO})),$$

where $k = 1.367$, $\lambda = 0.708$. Dinitrogen oxide lost to the atmosphere due to microbially governed denitrification (see Section 1.3) can be obtained by the Michaelis-Menten equation:

$$dN_{inA} = \omega \cdot \theta^{\delta T} \cdot W_S \cdot \frac{N_{in}}{K_D + N_{in}},$$

where $\omega = 0.495$ and $K_D = 0.556$; θ is the temperature coefficient; and W_S is the soil moisture pool (Krapivin, 1992).

The long term organic nitrogen pool loses nitrogen in the process of mineralization and gains nitrogen in the processes of humification and microbial immobilization. The humification flux will start when

$$\frac{C_{SH} + C_{SW}}{N_{SH} + N_{SW}} > 2 \cdot P_{CN}.$$

In this case the flux of organic nitrogen coming from the litter nitrogen pools to the organic nitrogen long-term pool can be calculated according to Kellomiaki, et al., 1992:

$$dN_{Sor} = \left(\frac{N_{VL}}{\tau_L} - dec_H \cdot N_{SH} \right) + \left(\frac{N_{VS}}{\tau_S} - dec_W \cdot N_{SW} \right) + imm_H \cdot (N_{SH} + N_{SW}),$$

where imm is a constant rate of immobilization in the interval [0.01 g/g, 0.02 g/g] (Pastor and Post, 1986).

If the inequality is not true, then:

$$dN_{Sor} = imm \cdot (N_{SH} + N_{SW}).$$

2.3.2.4 Carbon fluxes

Carbon fluxes are the most important fluxes for an integrated model of climate change. As mentioned earlier, there are two fluxes, the NPP flux and the litter production flux, which are responsible for changes in the vegetation pool.

The NPP can be approximated by a regression-based equation as given by Esser et. al. (1991):

$$\begin{aligned} dC_{AV} &= F_1(C_A) \cdot F_{st}(dN_{inv}) \cdot \min[F_2(T), F_3(P)] \\ F_1(C_A) &= 3.6365 \cdot (1 - \exp(-0.00134 \cdot (C_A \cdot \kappa - 80))) \\ F_2(T) &= 3000 / (1 + \exp(1.315 - 0.119 \cdot T)) \\ F_3(P) &= 3000 \cdot (1 - \exp(1 - 0.000664 \cdot P)) \end{aligned}$$

for models with annual dynamics, or as the difference between the gross primary productivity (GPP) and the maintenance respiration flux (RS) for models with seasonal dynamics.

The RS flux can be estimated according to McGuire (1992) by

$$RS = K_{RS} \cdot (C_{VL} + C_{VS}) \cdot \exp(0.0693 \cdot T),$$

where K_{RS} is the respiration rate per biomass, while the GPP is given by:

$$\begin{aligned} GPP &= GPP_{\max} \cdot F_4(L) \cdot F_5(T) \cdot F_6(C_A) \cdot F_{st}(dN_{inv}) \\ F_4(T) &= 1 - \exp(-ex \cdot S \cdot C_{VL}) \\ F_5(P) &= 1 / (1 + \exp(1.693 - 0.1047 \cdot T)) \\ F_6(C_A) &= \frac{\phi \cdot \kappa \cdot C_A - \Gamma}{\phi \cdot \kappa \cdot C_A + 2 \cdot \Gamma} \end{aligned}$$

where ex is the light extinction coefficient; S is the leaf area per unit of carbon; ϕ is a constant less than one, different for C-3 and C-4 plants; and Γ is a term determined by the biochemical constants of Rubisco. This constant can be calculated from activation energies of biogeochemical reactions, Kirschbaum, (1993):

$$\Gamma = 40.6 \cdot \exp(9.46 \cdot (T - 25) / (T + 273.2)).$$

The litter production flux is assumed to be (Goudriaan and Ketner, 1984):

$$dC_{VS} = \frac{C_{VL}}{\tau_L} + \frac{C_{VS}}{\tau_S},$$

where τ_L and τ_S are the carbon turnover times for litter and stems (see Section 2.3.2.3).

The organic decomposition flux from the soil to the atmosphere is given by:

$$dC_{SA} = dec_H \cdot C_{SH} + dec_W \cdot C_{SW},$$

where dec is the decomposition rate differing for herbaceous and wooden litter parts (see Section 2.3.2.3).

2.4 Model equations

All the proposed models have the same general structure and are based on general modeling principles as described in Sections 1-6. The models capture the dynamics of eleven pools by using a system of eleven non-linear differential equations for one type of biome at a specific geographical location. The equations are summarized below:

$$\begin{aligned} \frac{dC_{VL}}{dt} &= p_L \cdot dC_{AV} - \frac{C_{VL}}{\tau_L} \\ \frac{dC_{VS}}{dt} &= p_S \cdot dC_{AV} - \frac{C_{VS}}{\tau_S} \\ \frac{dN_{VL}}{dt} &= p_L \cdot (dN_{inv} + \mu \cdot dC_{AV}) - \frac{N_{VL}}{\tau_L} \\ \frac{dN_{VS}}{dt} &= p_S \cdot (dN_{inv} + \mu \cdot dC_{AV}) - \frac{N_{VS}}{\tau_S} \\ \frac{dC_{SH}}{dt} &= \frac{C_{VL}}{\tau_L} - dec_H \cdot C_{SH} \\ \frac{dC_{SW}}{dt} &= \frac{C_{VL}}{\tau_S} - dec_w \cdot C_{SW} \\ \text{if } \frac{C_{SH} + C_{SW}}{N_{SH} + N_{SW}} < 2 \cdot P_{CN} \text{ then } \frac{dN_{SH}}{dt} &= \frac{N_{VL}}{\tau_L} - dec_H \cdot N_{SH} - imm \cdot N_{SH} \\ \text{else } \frac{dN_{SH}}{dt} &= 0 \\ \text{if } \frac{C_{SH} + C_{SW}}{N_{SH} + N_{SW}} < 2 \cdot P_{CN} \text{ then } \frac{dN_{SW}}{dt} &= \frac{N_{VS}}{\tau_S} - dec_w \cdot N_{SW} - imm \cdot N_{SH} \\ \text{else } \frac{dN_{SW}}{dt} &= 0 \\ \frac{dN_{in}}{dt} &= dec_H \cdot N_{SH} + dec_w \cdot N_{SW} + dN_{Hin} + dN_{oin} - dN_{inR} - dN_{inA} \\ \frac{dN_{or}}{dt} &= dN_{Sor} - dN_{oin} \\ \frac{dW_s}{dt} &= P - dW_{SA} - dW_{SO} \end{aligned}$$

3. APPLICATION OF THE BIOGEOCHEMICAL MODELS IN CONNECTION WITH INTEGRATED MODELS OF CLIMATE CHANGE

3.1 Evaluation of greenhouse gas emissions

Greenhouse gas emissions to the atmosphere (primarily carbon dioxide emissions) are the key variables in any integrated modeling of climate change. These variables allow integrated models to be used as policy-oriented tools, and enable the model user to assess different policy options and their socio-economic consequences. Indeed, the rate of greenhouse gas emissions from the energy, agricultural and industrial sectors depend on the global economical growth rates and political restrictions. These emissions rates should be calculated by a special emission module as part of an integrated model, as, e.g., done by the Industry/Energy System within the IMAGE 2.0 model. This Industry/Energy System provides information on the emissions for carbon oxide, carbon dioxide, methane, nitrogen oxides and chlorfluorcarbon (Alcamo et. al., 1994). The Industry/Energy System of IMAGE 2.0 or another accounting tool for greenhouse gas emissions might be borrowed for the integrated study of climate change impacts.

The natural greenhouse gas emissions originate from the oceanic and terrestrial parts. The carbon dioxide emission from the oceans to the atmosphere has recently been incorporated into the ocean models of the IIASA climate models, and further oceanic greenhouse gas emissions will be accounted for in the near future. As is evident from Section 2, the proposed biogeochemical models estimate: 1) the carbon dioxide emissions from terrestrial ecosystems to the atmosphere; and 2) the dinitrogen oxide emissions from the soil to the atmosphere. The terrestrial CO₂ emissions are calculated as the difference between the global net primary productivity and the global organic decomposition flux, while the terrestrial dinitrogen oxide emissions can be calculated as a constant fraction of the global denitrification flux.

The sum of anthropogenic, oceanic and natural terrestrial greenhouse gas (GHG) emissions then need to be converted into GHG concentrations, which, in turn, provide the required input for the climate models (ZCM or DSCM).

3.1.1. Models of long-term vegetation and climate dynamics

These models are regression-based. The implementation of biogeochemical models will consist of two major steps. In the first step only the terrestrial carbon model is implemented in the integrated model, using simple assumptions with respect to the temporal evolution of land surface parameters and a slightly modified BATS model for boundary microclimatological conditions. This will allow the overall structure of the integrated model to be tested. A preliminary, qualitative study of the overall geosphere-biosphere system can even be done by a zero-dimensional model.

The second step includes the terrestrial nitrogen cycle, which will be added to the integrated models designed during the first step. Regions short of nitrogen will be identified geographically for further investigations by means of more sophisticated seasonal models.

3.1.2 Seasonal models of vegetation and climatic dynamics

These models are processes-based. There are three main steps involved in designing seasonal models. During the first step the dynamics of climate and the terrestrial carbon cycle with a time step of one month should be investigated simultaneously. Then, the terrestrial nitrogen cycle should be implemented, employing the results of the long-term integrated models. Finally, an appropriate soil moisture model will allow to include the biospheric part of the global water cycle, which also needs to be considered in an integrated study.

4. CONCLUSIONS AND OUTLOOK

Policy-oriented computer tools aimed at supporting decision making processes related to global climate change require the design of a new methodology in global modeling based on simplified models with a fast turnaround time. As a consequence, the quality of information in terms of its spatial and temporal resolution decreases with simplification. The only way in an integrated modeling study, therefore, is to carry out a sequence of experiments with models of increasing complexity in order to find an optimal level of simplification.

The set of models designed could become an important part of an integrated model of climate change as the set incorporates models ranging from a simple long-term dynamic model up to a sophisticated seasonal model. Further investigations should show whether it is possible to concentrate scientific efforts only on the three main biogeochemical cycles: carbon, nitrogen and water, or also to deal with other elements such as phosphor and sulfur.

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LIST OF BIOGEOCHEMICAL MODELS

MODELS	AUTHORS	PUBLICATIONS
IMAGE Biospheric	Goudariaan & Ketner	1984, 1990
Osnabrück Biospheric	Esser, et al.	1984, 1992
Frankfurt Biospheric	Kohlmair, et al.	1993
Terrestrial Ecosystem	McGuire, et al	1993
Moscow Biospheric	Svirezhev, Moiseev, et al.	1980, 1993
Bioclimatic Biospheric	Smith, et al.	1992

BASIC PRINCIPLES

- BOX STRUCTURE
- MASS BALANCE EQUATIONS
- REGRESSION-BASED EQUATIONS FOR ANNUAL DYNAMICS
- PROCESS-BASED EQUATIONS FOR SEASONAL DYNAMICS
- LEIBICH PRINCIPLE OF LIMITING FACTORS FOR PHOTOSYNTHETIC PROD.
- USING OF C/N RATIO FOR CARBON AND NITROGEN CYCLES SIMULTANEOUSLY

TABLE 1

Breakdown of models dealing with soil-vegetation-climate interactions separated by time-scale (in years).

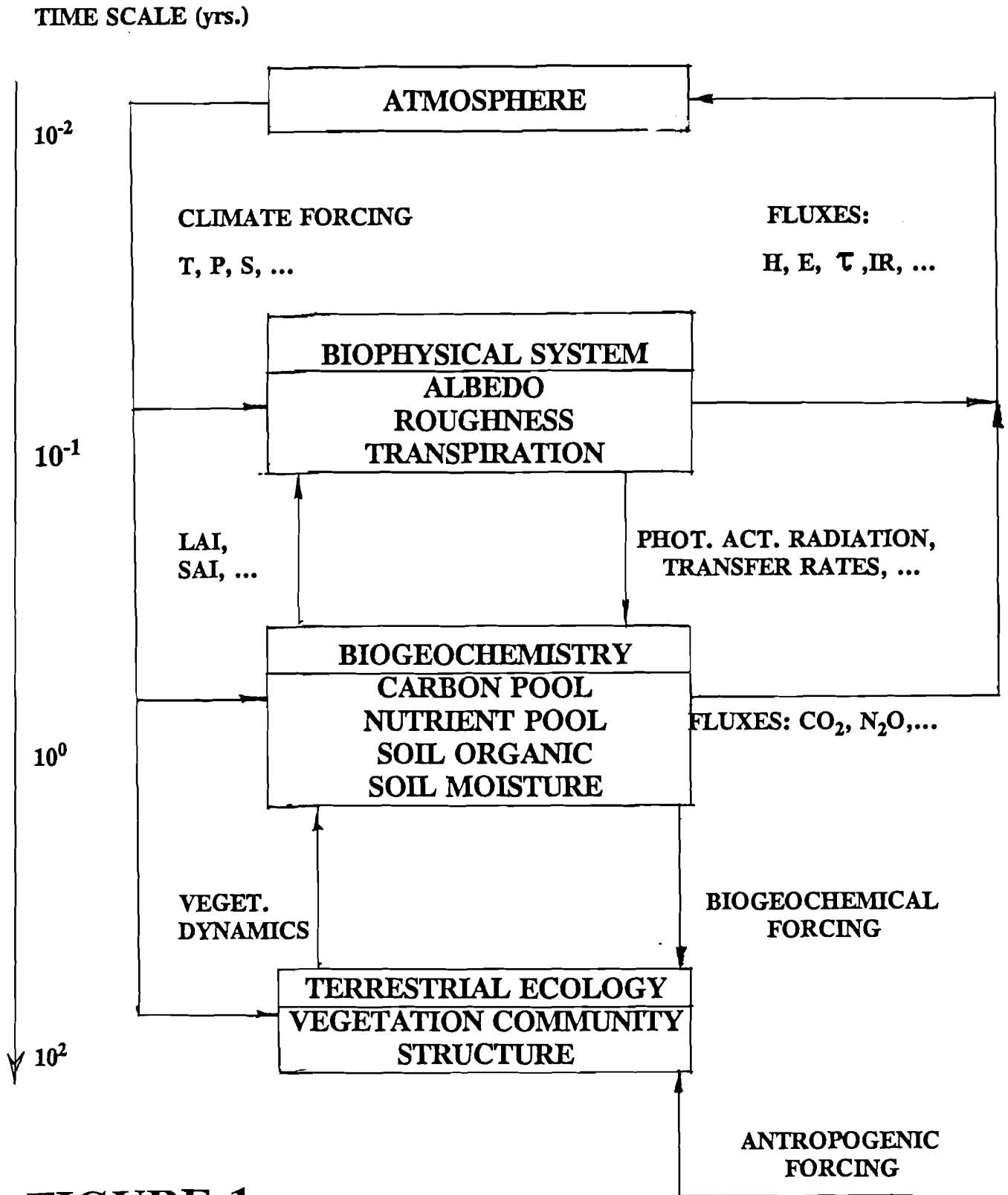


FIGURE 1

**BOX STRUCTURE
MAIN POOLS AND FLUXES. (Gt and Gt/yr)**

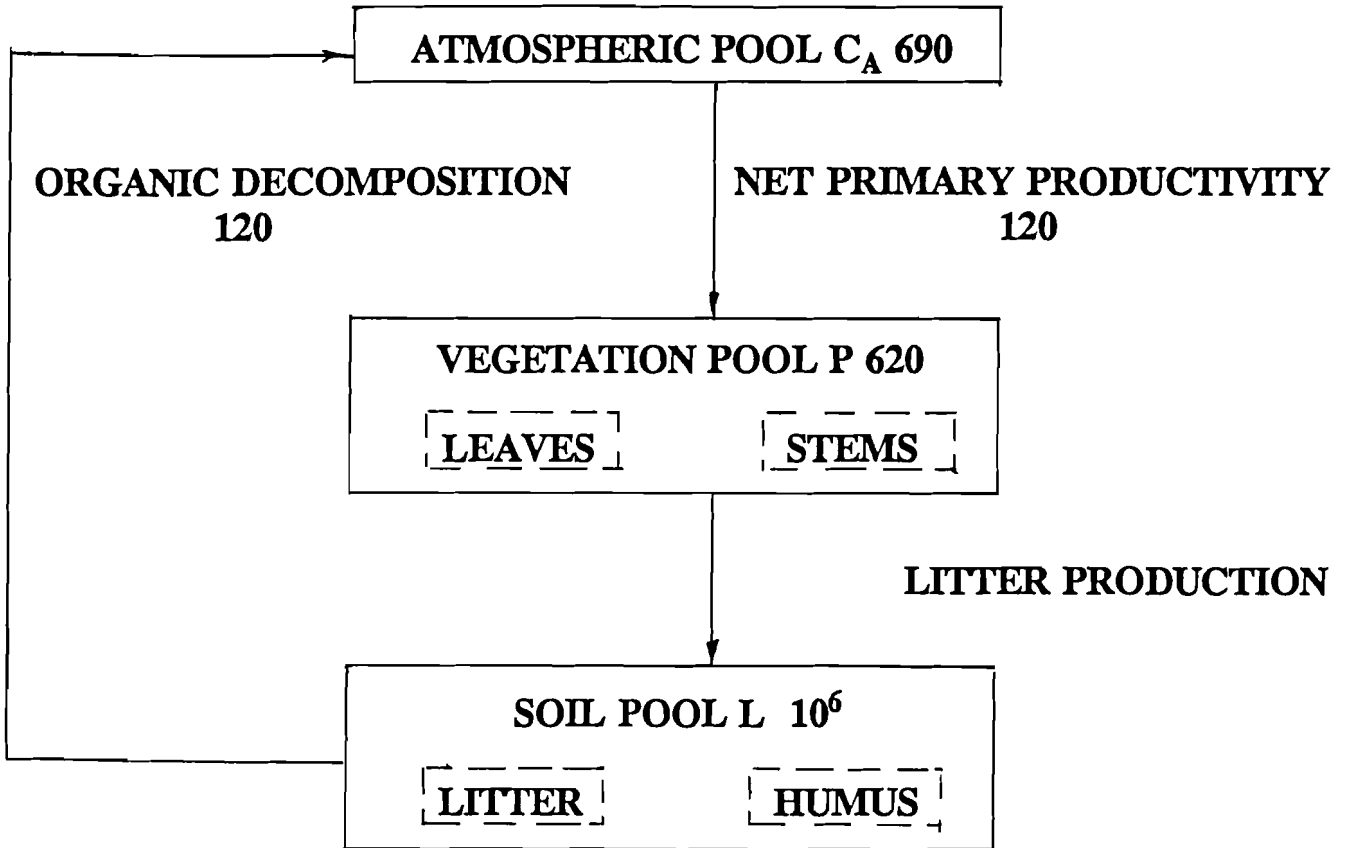


FIGURE 2

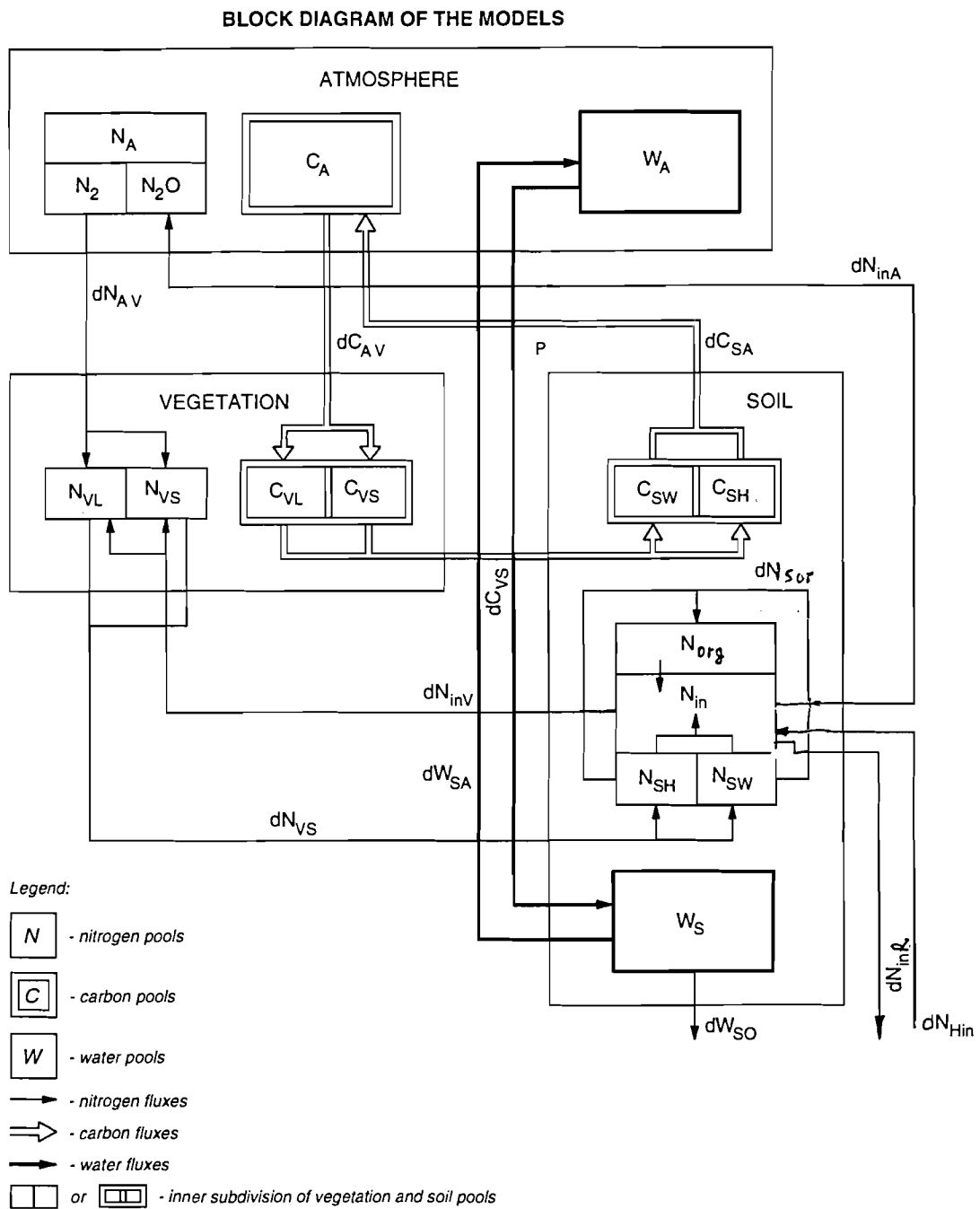


FIGURE 3