1

Terrestrial Biosphere Models

Chapter Overview

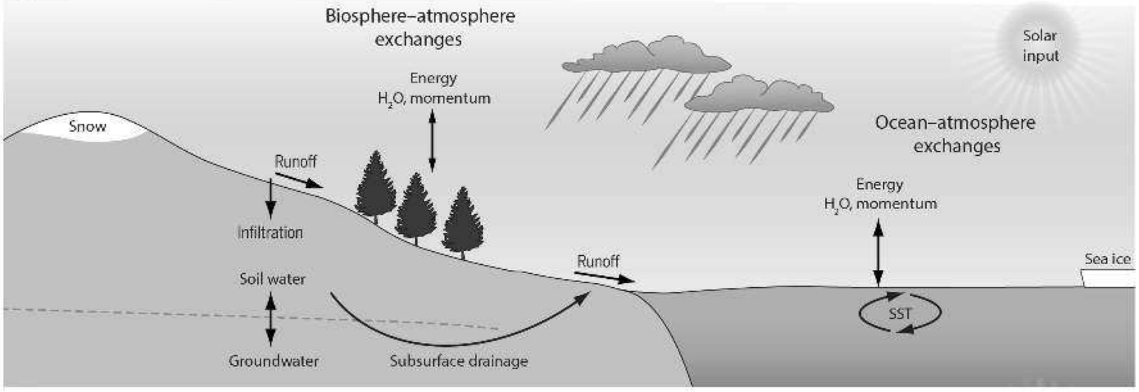
Earth system models simulate climate as the outcome of interrelated physical, chemical, and biological processes. With these models, it is recognized that the biosphere not only responds to climate change, but also influences the direction and magnitude of change. Earth system models contain component atmosphere, land, ocean, and sea ice models. The land component model simulates the world's terrestrial ecosystems and their physical, chemical, and biological functioning at climatically relevant spatial and temporal scales. These models are part of a continuum of terrestrial ecosystem models, from models with emphasis on biogeochemical pools and fluxes, dynamic vegetation models with focus on individual plants or size cohorts, canopy models with focus on coupling leaf physiological processes with canopy physics, and global models of the land surface for climate simulation. This latter class of models incorporates many features found in other classes of ecosystem models but additionally includes physical meteorological processes necessary for climate simulation. This book describes these models and refers to them as terrestrial biosphere models.

1.1 Introduction

The global nature of environmental problems has transformed our scientific understanding and study of the biosphere. Global change can be broadly taken to mean the interactive physical, chemical, and biological processes that regulate Earth as a system, maintain planetary habitability, and sustain life, and the changes that are occurring in the Earth system, both natural and anthropogenic. Terrestrial ecosystems are central to solving the environmental and socioeconomic threats posed by changes in climate, atmospheric composition, and air quality; land use and land-cover change; habitat loss, species extinction, and invasive species; appropriation of freshwater, net primary production, and other ecosystems goods and services for human uses; and anthropogenic addition of reactive nitrogen. Devising suitable solutions to these global change challenges require not only strong empirically and experimentally based research at the local scale to understand how ecosystems are structured and how they function, but also sound theoretical foundations to generalize this understanding to regional, continental, and global scales and to make projections of the future. Computer models of terrestrial ecosystems are essential to this generalization.

Models of terrestrial ecosystems take many different forms depending on scientific disciplines. Ecologists develop models of community composition and biogeochemical cycles to study ecosystem response to climate change. Hydrologists develop models of watersheds to study freshwater availability and stormflow and must represent leaves, stomata, and plant canopies in some manner to calculate evapotranspiration loss. Atmospheric chemists must include reactive gas exchanges between ecosystems and the atmosphere in their chemistry models. Likewise, atmospheric scientists have been developing models of atmospheric general circulation and planetary climate since the 1960s. These models require a

(a) Climate model



(b) Earth system model

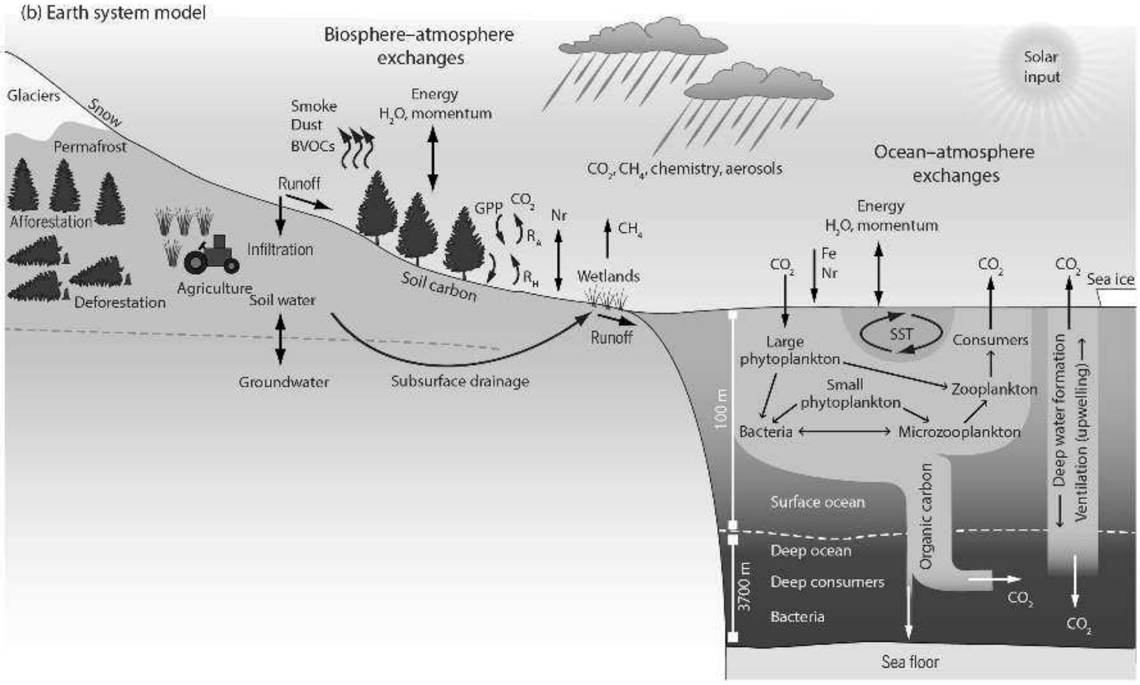


Figure 1.1 Scientific scope of (a) climate models and (b) Earth system models. Climate models simulate biogeophysical fluxes of energy, water, and momentum on land and also the hydrologic cycle. Terrestrial and marine biogeochemical cycles are new processes in Earth system models. The terrestrial carbon cycle includes carbon uptake through gross primary production (GPP) and carbon loss from autotrophic respiration R_A, heterotrophic respiration R_H, and wildfire. Many models also include the nitrogen cycle. Anthropogenic land use and land-cover change are additional processes. The fluxes of CO_2, CH_4, Nr, aerosols, biogenic volatile organic compounds (BVOCs), and wildfire chemical emissions are passed to the atmosphere to simulate atmospheric chemistry and composition. Nitrogen is carried in freshwater runoff to the ocean. Adapted from Bonan and Doney (2018)

mathematical formulation of the exchanges of energy, water, and momentum between land and atmosphere to solve the equations of atmospheric physics and dynamics. These fluxes are mediated by plants, and so models of Earth's climate and its land surface require depictions of terrestrial ecosystems. In climate models, vegetation is represented by plant canopies with a focus on physical flux exchanges with the atmosphere, soil moisture hydrology, and snow. With the broadening of the science from the physical climate system to the Earth system, the models have expanded to include biogeochemical cycles, biogeography, and dynamic vegetation – typically the realm of ecosystem models (Figure 1.1).

Many types of models consider terrestrial ecosystems, and the particular way in which terrestrial ecosystems are depicted varies among disciplines (Table 1.1). The next three sections examine how ecosystems are represented in ecological models, atmospheric models, and hydrologic models. For ecologists, the focus may be biogeochemical cycling and the distribution of carbon and nitrogen within an ecosystem. For an atmospheric scientist, this may be the manner in which terrestrial ecosystems affect weather, climate, and atmospheric composition through energy, water, and chemical flux exchanges with the atmosphere. Both disciplines use mathematics to describe and model terrestrial ecosystems, their functioning, and their response to environmental changes but with very different meaning to ecologists and climate scientists.

The distinction between ecological and atmospheric depictions of ecosystems has become blurred over the past few decades, and these two viewpoints of terrestrial ecosystems are merging into a common depiction of the global terrestrial biosphere, particularly as atmospheric scientists have embraced a broad Earth system perspective to understand planetary climate (Figure 1.2). This book describes this type of model, hereafter referred to as a terrestrial biosphere model. In this sense, terrestrial biosphere models is used broadly to represent the intersection among the atmosphere, hydrosphere, geosphere, and biosphere. Such models have become an essential, albeit imperfect, research tool to study global change. Bonan (2016) reviewed the influence of terrestrial ecosystems on climate and more broadly their role in the Earth system, and also provided an introduction to terrestrial biosphere models and how they are used to study climate. The present book is concerned with how to model the terrestrial biosphere.

Table 1.1 Classes of terrestrial ecosystem models

Type of model	Description	Example
Biogeochemical	Ecosystem models with emphasis on biogeochemical pools and fluxes (e.g., C, N, P) using prescribed biogeography	TEM, CASA, BIOME-BGC, CENTURY, CASA-CNP
Forest gap models	Individual trees, population dynamics, demography, community composition	JABOWA, FORET
Ecosystem demography	As in gap models, but cohort based	ED
Dynamic global vegetation models	Biogeochemistry, community composition, global biogeography	IBIS, LPJ, SDGVM, LPJ-GUESS, SEIB-DGVM
Land surface models	Global models of the land surface for weather and climate simulation with an emphasis on hydrometeorological processes and biogeophysical coupling with the atmosphere; the models now additionally include biogeochemical cycles and vegetation dynamics	See Table 1.2
Plant canopy	Multilayer canopy-scale models with focus on coupling leaf physiological processes and canopy physics	CUPID, CANOAK
Canopy–chemistry	Plant canopy models that additionally include chemical transport and reactions in the canopy airspace	CACHE, CAFE, ACCESS, FORCAsT
Ecohydrology	Similar to land surface models (without coupling to atmospheric models), but spatially distributed within a watershed and with lateral flow connectivity	RHESSys

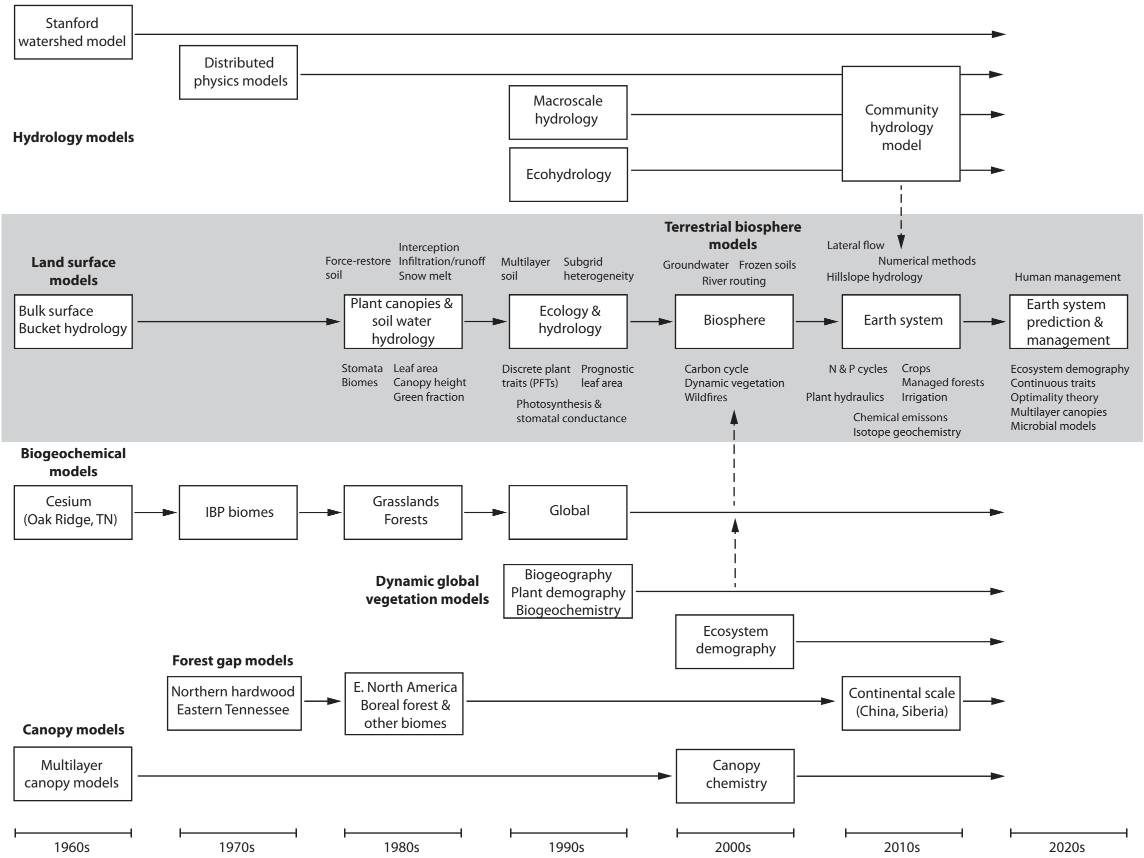


Figure 1.2 Timeline of model development. Shown are the broad classes of hydrology, biogeochemical, dynamic global vegetation, individual-based forest gap models, canopy, and land surface models. For each class of models, boxes denote major model developments and approximate timelines. The shading highlights land surface models, and the text around these boxes describes model capabilities. Vertical dashed lines show when the various classes of models merged with land surface models. The most significant is the incorporation of biogeochemical and dynamic global vegetation models in the 2000s to form terrestrial biosphere models. A community hydrology model has been discussed as a means to more authentically represent hydrologic processes in land surface models.

1.2 The Ecological Ecosystem

The archetypal ecological view of an ecosystem emphasizes material flows. The structure of an ecosystem is measured by the amount of carbon, nitrogen, or other materials in various compartments. The functioning of an ecosystem is measured by the cycling of materials among these compartments. Odum's (1957) study of Silver Springs, an aquatic spring ecosystem in Florida, is a classic example of this type of ecosystem analysis (Figure 1.3). Odum abstracted the ecosystem into five trophic groups of producers, herbivores, carnivores, top carnivores, and decomposers and described energy transfers (in the sense of caloric value of biomass) among these groups. Energy flows into the ecosystem via photosynthesis, cycles among the various trophic groups, is lost as respiration, or accumulates as biomass in the ecosystem. Odum later formalized this view of energy flows as analogous to an electrical circuit using Ohm's law (Odum 1960).

This conceptualization of an ecosystem lends itself to a system of first-order, linear differential equations to describe material flows among various compartments. This type of model, known as a box or compartment model, came to dominate ecosystem modeling in the late 1960s and early 1970s with the advent of systems ecology. One of the first examples was a model of differential equations to simulate

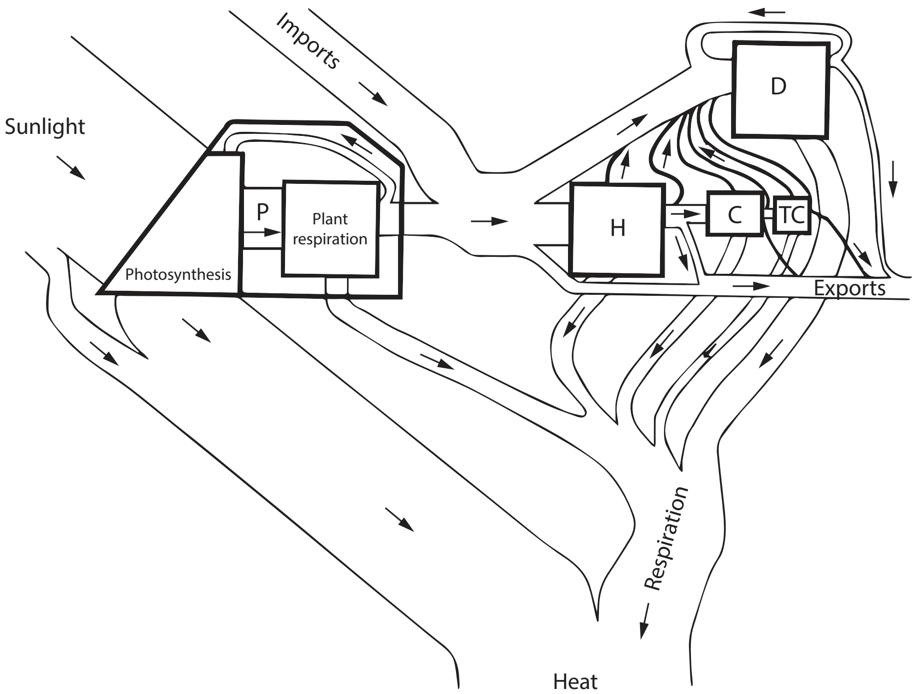


Figure 1.3 Energy flow in the Silver Springs ecosystem (Odum 1957). The five tropic levels are producers (P), herbivores (H), carnivores (C), top carnivores (TC), and decomposers (D). Redrawn from Odum (1960)

cesium in a forest (Olson 1965), and box models gained prominence during the International Biological Program (IBP). The IBP was a coordinated research program in the late 1960s and early 1970s that studied various biomes with an emphasis on biomass, nutrient, and water flows and the development of computer models to simulate these flows (Patten 1975). The models were extraordinary in their mathematical representation of ecosystems but did not achieve their goals or fulfill their potential; they were seen as too large and unnecessarily mathematically complex but biologically simple (Golley 1993; Kwa 1993, 2005). The grassland biome model, for example, consisted of submodels of plant productivity, mammalian and insect consumption, decomposition, nitrogen and phosphorus cycles, and temperature and water in the plant canopy and soil (Innis 1975, 1978). It used 120 state variables and more than 1000 parameters (Kwa 1993). The coniferous forest biome model employed 29 state variables connected by 65 flows to model water and carbon dynamics (Sollins et al. 1979) and was also considered unsuccessful (Long 2005).

Despite the shortcomings of the IBP models, compartment models remain in use today, known now more generally as biogeochemical models, and are commonly used to simulate the terrestrial carbon cycle in Earth system models. Biogeochemical models simulate the carbon balance of terrestrial ecosystems given a specified geographic distribution of biomes as input to the model. The models represent an ecosystem by aggregate pools of foliage, stem, and root biomass without regard to individual plants or species and use additional pools to represent litter and soil carbon (Figure 1.4). Flows among the pools are described in terms of net primary production, allocation, and other plant physiological and microbial processes specific to the different biomes. Concurrent with carbon flows are transfers of nitrogen and other nutrients. A typical model time step is daily to monthly. Early such models include: CENTURY for grasslands (Parton et al. 1987, 1988, 1993), which was subsequently modified from a monthly to daily time step with DAYCENT (Parton et al. 1998; Del Grosso et al. 2005b, 2009; Hartman et al. 2011); FOREST-BGC for forests (Running and Coughlan 1988; Running and Gower 1991) and subsequently the more generalized BIOME-BGC model (Running and Hunt 1993; Thornton et al. 2002); the Terrestrial

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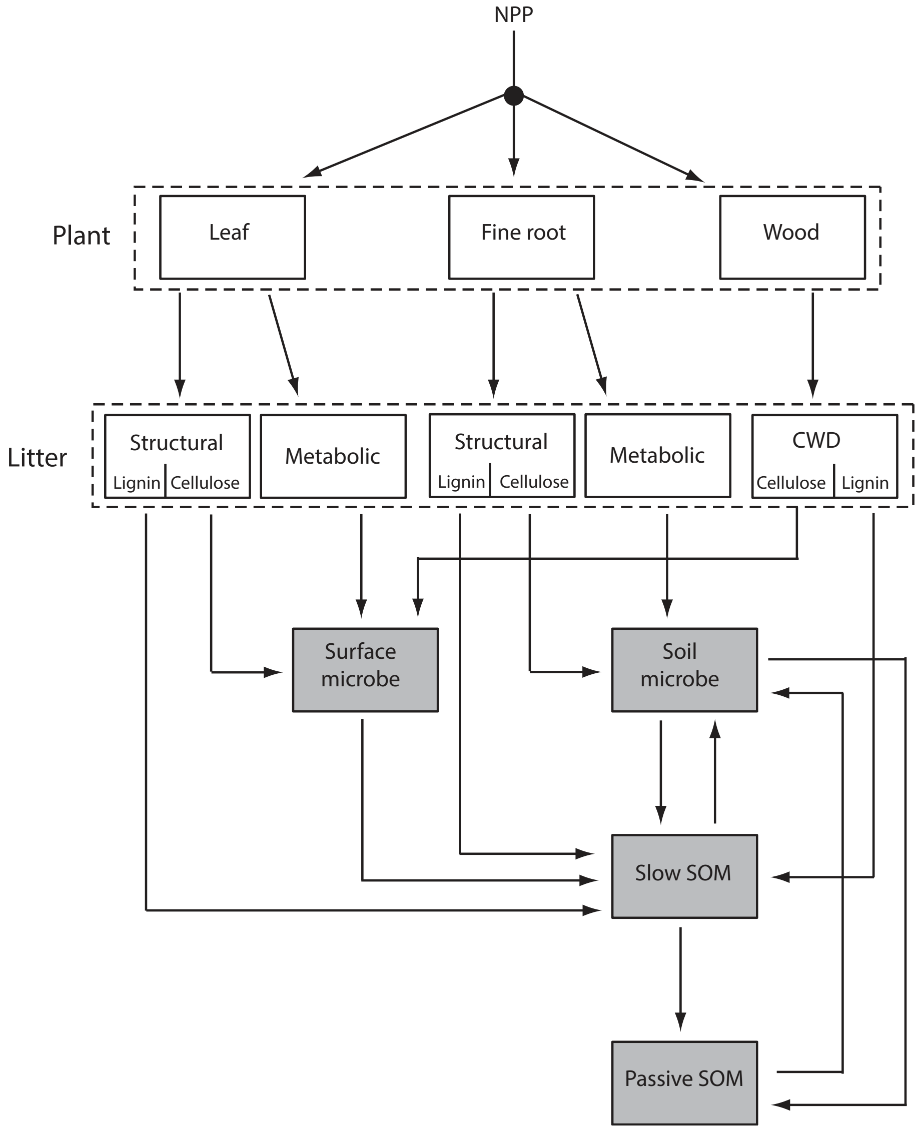

Figure 1.4 Carbon pools and associated transfers in CASA. Shown are the allocation of net primary production (NPP) to leaf, fine root, and wood plant compartments; turnover and litterfall to structural and metabolic litter pools for foliage and root and to coarse woody debris (CWD) for wood; and soil carbon pools consisting of microbes and soil organic matter (SOM). The litter and soil organic matter submodel is the same as in CENTURY. Redrawn from Randerson et al. (1996)

Ecosystem Model (TEM; Raich et al. 1991; McGuire et al. 1992; Melillo et al. 1993); and the Carnegie–Ames–Stanford Approach (CASA; Potter et al. 1993; Randerson et al. 1996). A more recent example of such models is CASA-CNP (Wang et al. 2010), which builds upon the CASA framework for carbon to include nitrogen and phosphorus. Many biogeochemical models focus on carbon and nutrient flows and represent the physical environment (evapotranspiration, soil water, temperature, plant canopies) in a simplified manner. BIOME-BGC is a notable exception and uses the concept of a big-leaf canopy to simulate the physical environment similar to the land surface models used in atmospheric models, albeit with a daily time step.

An alternative depiction of terrestrial ecosystems considers the behavior of an ecosystem as the

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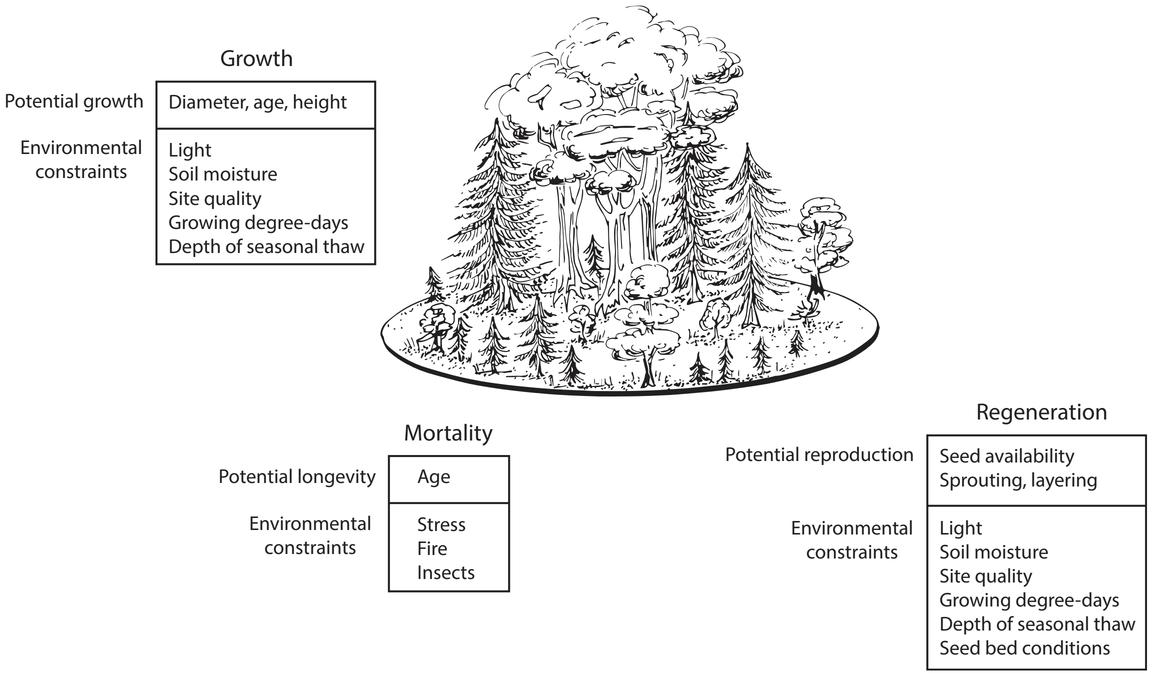

Figure 1.5 Depiction of a boreal forest gap model. The growth of an individual tree depends on its diameter, age, and height as modified by environmental constraints. Mortality depends on the age of the tree as modified by stress, wildfire, and insects. Regeneration depends on seed availability, the ability to sprout or layer, and site conditions. Redrawn from Bonan (1989)

outcome of individual plants competing for light and space (Figure 1.5). Such individual-based models were a response to the IBP box-and-arrow biogeochemical representation of ecosystems, and, indeed, the first individual-based models of forest dynamics were developed at about the same time as the IBP models. In contrast with biogeochemical models, however, individual-based models have their roots in population dynamics and the natural history and life cycle of species. A broad class of individual tree forest dynamics models called gap models simulate the dynamics of trees in an area of approximately 0.1 ha, which corresponds to the size of a gap in the canopy (Shugart 1984; Botkin 1993; Bugmann 2001). These models simulate size structure and community composition by directly representing demographic processes such as establishment, competition, and mortality. Ecosystem properties such as carbon storage and its distribution among foliage, stem, root, litter, and soil are the aggregate outcome of the interactions among and demography of individual plants. The first such model JABOWA (Botkin et al. 1972) was designed for northern hardwood forests in northeastern United States, followed by FORET (Shugart and West 1977) for the forests of eastern Tennessee. Forest dynamics, community composition, and size structure in these early models were primarily driven by light availability in the canopy. Later models added soil water and nutrient availability and were generalized to eastern North America (Pastor and Post 1986, 1996) or for boreal forests (Bonan 1989, 1990a,b). Forest gap models have been developed for numerous locations throughout the world (Shugart and Woodward 2011). They are still being developed and used, for example, in the forests of China (Yan and Shugart 2005) and Russia (Shuman et al. 2013, 2014, 2015). A newer class of model termed ecosystem demography (ED; Hurtt et al. 1998; Moorcroft et al. 2001; Medvigy et al. 2009; Fisher et al. 2010b, 2015, 2018) reduces the individual trees to cohorts of similar age and size so as to reduce the computational demands.

Another type of vegetation dynamics model is known as dynamic global vegetation models (DGVM; Prentice et al. 2007). These models also simulate changes in community composition, biomass, productivity, and nutrient cycling. Because the models are applied globally, they do not recognize individual species. Rather, they employ plant functional types, typically distinguished by woody or herbaceous biomass, broadleaves or needleleaves, and evergreen or deciduous leaf longevity. Most models do not formally simulate individual plants as in gap models. Instead, they represent cohorts of individuals based on similar size distribution, or the model may represent separately an average individual plant and the density of plants. One such model is the Lund–Potsdam–Jena (LPJ) model (Sitch et al. 2003). This model characterizes vegetation as patches of plant functional types within a model grid cell. Each plant functional type is represented by an individual plant with the average biomass, crown area, height, and stem diameter of its population, by the number of individuals in the population, and by the fractional cover in the grid cell. Vegetation is updated in response to resource competition, allocation, mortality, biomass turnover, litterfall, establishment, and fire. There are many such models, as described by Fisher et al. (2014). Other examples include the Sheffield DGVM (SDGVM; Woodward et al. 1995; Woodward and Lomas 2004), LPJ-GUESS (Smith et al. 2001, 2014), and the Spatially Explicit Individual-Based DGVM (SEIB-DGVM; Sato et al. 2007).

1.3 The Atmospheric Ecosystem

Deardorff (1978) outlined the basic equations needed to represent energy and water fluxes from vegetation and soil, and this approach was adopted for use in climate models with the Biosphere–Atmosphere Transfer Scheme (BATS; Dickinson et al. 1986, 1993) and the Simple Biosphere model (SiB; Sellers et al. 1986). Figure 1.6 illustrates this framework for SiB. The canopy is treated as a single exchange surface without any vertical structure (known as a big-leaf

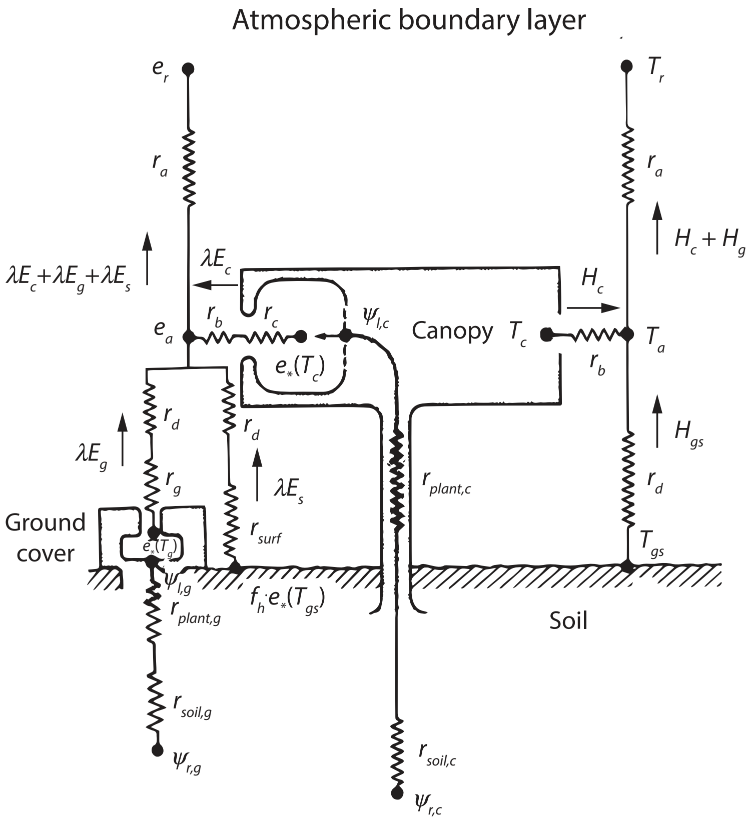

Figure 1.6 Latent heat fluxes (left) and sensible heat fluxes (right) in SiB. These fluxes are modeled as a network of resistances. The sensible heat flux consists of a ground flux H_{gs} that depends on the ground T_{gs} and canopy air T_a temperatures and a within-canopy aerodynamic resistance r_d, a vegetation flux H_c from the canopy with temperature T_c and bulk boundary layer resistance r_b, and the total flux to the reference height with temperature T_r and aerodynamic resistance r_a. Plant water uptake occurs from the soil with matric potential $\psi_{r,c}$ to the canopy with leaf water potential $\psi_{l,c}$ in relation to soil $r_{soil,c}$ and plant $r_{plant,c}$ resistances acting in series. Transpiration is from the stomatal cavity with vapor pressure $e_*(T_c)$ to the canopy air with vapor pressure e_a in relation to the bulk stomatal r_c and boundary layer r_b resistances acting in series. Similar fluxes occur in ground cover. Soil evaporation is a separate water flux and depends on the vapor pressure of the surface soil layer $f_h e_*(T_{gs})$ and a soil surface resistance r_{surf}. Additional processes include radiative transfer and intercepted water, but they are omitted for clarity. Redrawn from Sellers et al. (1986)

canopy), but with separate fluxes for soil. Processes in the models include radiative transfer in the plant canopy; momentum transfer arising from vegetated canopies, including turbulence within the canopy; sensible heat exchange from foliage and soil; latent heat exchange from evaporation of intercepted water, soil evaporation, and transpiration; the control of transpiration by stomata; and heat transfer in soil. Associated with the energy fluxes is the hydrologic cycle consisting of interception, throughfall, stemflow, infiltration, runoff, snowmelt, soil water, evaporation, and transpiration. BATS and SiB were pioneering in showing that vegetation is essential to model climate. The second version of SiB was particularly groundbreaking in its linkage of canopy physiology (including leaf photosynthesis), canopy fluxes, and remote sensing (Sellers et al. 1996a). The computational framework was quickly adopted by the major climate modeling centers and remains the standard in the current generation of models (Table 1.2). The same approach is used in numerical weather prediction models and air quality models (Chen and Dudhia 2001; Ek et al. 2003; Niu et al. 2011; Pleim and Ran 2011; Ran et al. 2017).

With the advent of global biogeochemical models and DGVMs, climate modelers readily adapted their models of the land surface to allow for simulation of the carbon cycle and biogeography and their feedbacks with climate change. The coupling with these models was enabled by the ability of land surface models to simulate photosynthesis in conjunction with stomatal conductance. This carbon input to the ecosystem is then tracked in ecological submodels. In contrast with their ecological counterparts, the models are specifically designed for coupling with atmospheric models and link biogeophysical, hydrologic, physiological, demographic, and biogeochemical processes into a unified representation of surface energy fluxes, hydrology, photosynthesis, respiration, allocation, and the cycling of carbon and nutrients within ecosystems. One of the first such models to include a DGVM was the Integrated Biosphere Simulator (IBIS; Foley et al. 1996; Kucharik et al. 2000), and most climate modeling centers now include either a biogeochemical or DGVM submodel (Table 1.2).

Land surface models with a DGVM simulate ecosystem processes at multiple timescales (Figure 1.7). The land and atmosphere exchange energy, water, momentum, and CO_2 over periods of minutes to hours through short timescale biogeophysical, biogeochemical, physiological, and hydrologic processes. Leaf phenology includes the timing of budburst, senescence, and leaf abscission in response to temperature and soil water over periods of days to weeks. Changes in community composition, vegetation structure, and soil carbon occur over periods of years or longer in relation to gross primary production and respiration; allocation of net primary production to grow foliage, stem, and root biomass; and mortality as a result of low growth rate or fire. The growth and success of particular plant functional types are dependent on life history patterns such as evergreen and deciduous phenology, needleleaf and broadleaf foliage, C_3 and C_4 photosynthetic pathway, and temperature and precipitation preferences for biogeography. Plant growth is linked to soil biogeochemistry through litterfall, decomposition, and nitrogen availability. Research frontiers include representing managed croplands, pastures, and forests; chemistry–climate interactions from biogenic volatile organic compounds (BVOCs), reactive nitrogen, methane, ozone, secondary organic aerosols, dust, and wildfires; and nitrogen and phosphorus biogeochemistry.

Although the big-leaf concept with its vertically unstructured canopy is the prevailing paradigm in land surface models, multilayer models that vertically resolve physiological and microclimatic gradients within the canopy have been developed for many years. An early example is the model of Waggoner and Reifsnyder (1968) and Waggoner et al. (1969), which considered radiative transfer and leaf energy fluxes in a multilayer canopy. Goudriaan (1977) extended this type of model to include leaf physiology and gas exchange (photosynthesis, stomatal conductance). The current generation of such models provides a comprehensive depiction of the soil–plant–atmosphere system. The models simulate canopy processes by linking radiative transfer, mechanistic parameterizations of leaf energy fluxes, photosynthesis, and stomatal conductance, and parameterization of turbulent processes within and above the plant canopy. They depict a canopy based on the physiology of leaves, leaf gas exchange, and canopy architecture (the vertical distribution of leaf and stem area, leaf angle distribution, foliage clumping). They account for vertical structure but, similar to big-leaf models, treat the canopy as spatially homogenous layers of phytoelements

Table 1.2 Models of the land surface and biogeochemistry or vegetation dynamics used in Earth system models

Center	Land	Ecosystem	Reference
Beijing Climate Center	BCC-AVIM	same	Ji (1995); Wu et al. (2013)
Canadian Center for Climate Modelling and Analysis	CLASS	CTEM	Verseghy (1991); Verseghy et al. (1993); Arora et al. (2009)
Centre National de Recherches Météorologiques (France)	ISBA	same	Noilhan and Planton (1989); Séférian et al. (2016); Boone et al. (2017)
Commonwealth Scientific and Industrial Research Organization (Australia)	CABLE	CASA-CNP	Kowalczyk et al. (2006, 2013); Wang et al. (2010, 2011)
European Center for Medium-Range Weather Forecasts	H-TESSEL	–	van den Hurk et al. (2000); Balsamo et al. (2015)
Geophysical Fluid Dynamics Laboratory (USA)	LM2	–	Milly and Shmakin (2002); Anderson et al. (2004)
	LM3	same	Shevliakova et al. (2009); Milly et al. (2014)
Goddard Institute for Space Studies (USA)	ModelE2	–	Rosenzweig and Abramopoulos (1997); Friend and Kiang (2005); Schmidt et al. (2014)
Hadley Center (UK)	MOSES	TRIFFID	Cox et al. (1999); Cox (2001); Essery et al. (2001)
	JULES	TRIFFID	Best et al. (2011); Clark et al. (2011a)
Institut Pierre Simon Laplace (France)	SECHIBA	ORCHIDEE	Ducoudré et al. (1993); Krinner et al. (2005)
Japan Agency for Marine-Earth Science and Technology	MATSIRO	SEIB-DGVM	Takata et al. (2003); Sato et al. (2007)
Max Planck Institute for Meteorology (Germany)	JSBACH	same	Raddatz et al. (2007); Reick et al. (2013)
National Center for Atmospheric Research (USA)	BATS	same	Dickinson et al. (1986, 1993, 1998, 2002)
	LSX	IBIS	Pollard and Thompson (1995); Foley et al. (1996)
	NCAR LSM	DGVM	Bonan (1996); Bonan et al. (2003)
	NCAR LSM	CASA'	Fung et al. (2005)
	CLM3	DGVM	Oleson et al. (2004); Levis et al. (2004)
	CLM4	CN	Oleson et al. (2010b); Thornton et al. (2009)
	CLM4.5	BGC	Oleson et al. (2013); Koven et al. (2013)
	CLM4.5	ED	Fisher et al. (2015)
	CLM5	FATES	Lawrence et al. (2018)

without regard to individual plants or mixtures of species. They have mostly been applied at the local scale to simulate a single stand of vegetation. Examples include CUPID (Norman 1979, 1982, 1989; Norman and Campbell 1983; Kustas et al. 2007) and CANOAK (Baldocchi and Harley 1995; Baldocchi and Meyers 1998; Baldocchi and Wilson 2001; Baldocchi et al. 2002). The latter model was