Chapter 4

Forest canopies as sources and sinks of atmospheric trace gases (methods for scaling up, contributions of different ecosystems)

Scaling up to the ecosytem level

1. INTRODUCTION

The exchanges of solar energy, carbon dioxide, water vapor and trace gases between a forest and the atmosphere are among the most fundamental processes to be quantified when studying the physiological and ecological functioning of a forest and the chemistry and climate of its overlying atmosphere. A forest must attain energy to sustain the work that is needed to assimilate carbon dioxide, for biosynthesis, to evaporate water, and to transport nutrients from the soil to the plant. Concurrently, these activities require flows of substrate material, which are obtained from the atmosphere and soil.

The major trace gases that are exchanged between forests and the atmosphere are associated with chemical elements that are the principle constituents of organic matter. The Redfield ratio identifies these major elements and their relative importance to one another—for every unit of phosphorus in living organic matter, there are 80 units of carbon and 15 units of nitrogen. Reduced and oxidized forms of these elements, and micronutrients such as sulfur, constitute the bulk of trace gases that are evolved or assimilated by forests. Carbon dioxide, oxygen, ammonia, nitric oxide, sulfur dioxide, ozone and carbon monoxide are among the most notable trace gas compounds that are taken up by forests. Biological processes that cause the biosphere to be a sink for these trace gases respectively include carbon assimilation and respiration, ammonification, nitrification and denitrification and pollutant deposition. Ozone is included in this group of gases because its presence in the atmosphere is linked to the biogenic emission of nitric oxide and volatile organic hydrocarbons.

In converse, water vapor, carbon dioxide, oxygen, isoprene, and monoterpenes are among the most common gaseous compounds that are emitted by plants. The emission of these gases is linked, respectively, to transpiration and evaporation, respiration, assimilation, and volatilization.

The rates at which trace gases are transferred between forests and the atmosphere depend upon a complex interplay among physiological, ecological, biochemical, chemical and edaphic factors and meteorological conditions. Information on fluxes of trace gases between the biosphere and atmosphere is needed at a variety of time and space scales by models that predict ecosystem carbon water and nutrient balances, weather and climate and tropospheric chemistry. The time scale of processes that are associated with the transfer of trace gases between forests and the atmosphere can range from the hour and day to season, year and decade. The range of spatial information that is needed by a forest-scale model spans the dimension of needles and leaves to height and breadth of tree crowns and their placement across a landscape. How to model the processes that govern trace gas fluxes throughout the spectrum of biologically relevant time and space scales remains a challenge to forest ecologists, biometeorologists and biogeochemists (see Rastetter, 1996).

The goal of this chapter is to discuss the integration and scaling of information on trace gas fluxes from the leaf and soil to the canopy and landscape scales. Specific topics to be covered in this chapter include the theory of trace gas exchange, model design and complexity and temporal and spatial factors affecting model parameterization and implementation.

2. THEORY AND CONCEPTS

Any model of trace gas fluxes in the natural environment starts with the same fundamental principle, the conservation of mass. This equation states that the time rate of change of a gas' molar density (moles per unit volume, ρ_c) equals the difference between the molar flux in and out of the volume plus the rate of chemical production/destruction plus the rate of biological consumption or production. The time averaged equation for the conservation of mass at a point in space exposed to turbulent flow is expressed, using tensor notation, as:

$$\frac{\overline{d\rho_c(x,y,z,t)}}{dt} = \frac{\partial \overline{\rho_c}}{\partial t} + \overline{u_i}\frac{\partial \overline{\rho_c}}{\partial x_i} + \overline{\rho_c}\frac{\partial \overline{u_i}}{\partial x_i} = -\frac{\partial \overline{u_i'\rho_c'}}{\partial x_i} + S_B(t,x_i) + S_{ch}(t,x_i) \qquad (1$$

The space, x_i and velocity, u_i variables are incremented from 1 to 3. For the space dimensions, this corresponds to the longitudinal (x), lateral (y) and vertical (z) dimensions. For the velocity vectors, this incrementing corresponds with u, v and w, the longitudinal, lateral and vertical velocity vectors. The biological source/sink term is denoted as S_B and the production or destruction of a trace gas by chemical reactions is denoted by S_{ch}. The overbar represents time averaging.

2.1 Evaluating the Conservation Equation

2.1.1 Turbulence Closure Schemes for Computing Scalar Fields

The conservation budget equation for a scalar cannot be solved readily because it does not form a cbsed set of equations and unknowns. The equation defining the time rate of change in ρ_c contains an additional unknown, the covariance between vertical velocity (w) and scalar concentration fluctuations ($\overline{w'\rho_C'}$). To solve Equation 1, micrometeorologists use closure schemes to obtain an equal set of equations and unknowns.

Zero order closure is the simplest scheme used. It does not treat the prognostic equation for r_c directly. Instead, this closure scheme specifies the scalar fields in time and space. This approach is often adopted by ecosystem and ecophysiological models, which assume that temperature and humidity are constant within and above vegetation.

First order closure, called ‘K-theory’, is the next level of complexity. This closure level represents the flux covariance as the product of the scalar concentration gradient and a turbulent diffusivity (*K*):

$$F_c(z) = \overline{w' r_c'} = -K \frac{\partial \overline{r_c}}{\partial z} \qquad (2$$

‘K-theory’ is an appropriate concept in the surface boundary layer. On the other hand, it often fails to represent turbulent transfer inside forest canopies and within the roughness sublayer, where turbulent transport is dominated by large scale and intermittent eddies and turbulent diffusion is dominated by the distinct properties of ‘near field’ diffusion (Raupach, 1988). Near vegetative sources and sinks turbulent diffusion is linearly related to the time period that fluid parcels have traveled (Raupach, 1988). Only after a long travel distance is the time-independent, ‘far-field’ limit of turbulent diffusion reached, the process that K-theory represents.

Higher-order closure models have been proposed as a means of circumventing the inherent limitation of first order closure models (Meyers and Paw U, 1987). Higher order closure models rely on budget equations for mean horizontal wind velocity ($\overline{u}$) and higher order moments, such as the scalar-velocity covariance, tangential momentum stress ($\overline{w'u'}$) and the turbulent kinetic energy components ($\overline{u'u'}$, $\overline{v'v'}$, $\overline{w'w'}$). The appeal of a higher order closure model includes its mechanistic basis and its ability to simulate counter-gradient transport. Unfortunately, the budget equations for the second order moments include additional unknowns of the third order (e.g., $\overline{w'w'u'}$, $\overline{w'w'c'}$). Deriving additional budget equations for third order moments introduces more unknowns, consisting of the next order moment, and so on. Hence, an equal set of equations and unknowns can only be obtained through parameterizing the highest order moment with an 'effective' eddy exchange coefficient (Meyers and Paw U, 1987).

The Lagrangian framework circumvents the closure problem ailing Eulerian models. The Lagrangian approach analyzes the conservation equation by following parcels of fluid as they move with the wind, much like the trajectory of a neutrally-buoyant balloon. Thereby, Lagrangian models are able to explicitly differentiate between near and far field diffusion (Raupach, 1988). Lagrangian models, however, suffer from their own unique closure problem. The probability density function for the diffusion of fluid parcels depends only on the properties of the turbulent wind field, which must be prescribed or computed with a higher order turbulence closure model.

2.1.2 Quantifying Trace Gas Source-Sink Strengths

Functional relationships that quantify trace gas sources and sinks rates generally depend upon numerous micrometeorological and eco-physiological variables. To assess these functions, we must introduce micrometeorological modules that compute leaf and soil energy exchange, turbulent diffusion, scalar concentration profiles and radiative transfer through the canopy. Environmental variables, computed with the micrometeorological module, in turn, can be used to drive physiological modules that may compute leaf photosynthesis, stomatal conductance, transpiration and leaf, bole and soil/root respiration, gaseous deposition and emission rates. Products from a micrometeorological module are also needed to drive algorithms that compute trace gas fluxes from the soil.

3. MODEL DESIGN AND PARAMETERIZATION ISSUES

Forests may be tall or short, closed or open, and consist of shrubs or trees. The spatial distribution of leaves can be random or clumped and their shape can be needle-shaped or broad and planar. How much complexity to incorporate into a system of equations that quantifies trace gas fluxes between a forest and the atmosphere is a key issue to be considered when designing a model to quantify source/sink strengths. The complexity of the stand's physiognomy will dictate, in part, how complex the structure of a trace gas model needs to be. A simplified version of Equation 1, for example, can be used for the situation of horizontally homogeneous forests on level terrain. Full expansion of Equation 1 is needed to evaluate fluxes over forests that consist of patches of isolated trees on hill slopes. In the following sub-sections we discuss algorithms for computing source/sink strengths and issues relating to the parameterization of these algorithms.

3.1 Model Design Attributes: Scaling or Integrating Trace Gas Fluxes from Leaf to Canopy Dimensions

A hierarchy of model algorithms exists for computing trace gas fluxes. The simplest models treat the canopy as a single layer, and are denoted 'big-leaf' models. This concept is followed, in order of increasing complexity, by dual-source models, one-dimensional multi-layer models and three-dimensional cube, ellipsoid or shell models.

3.1.1 Big-Leaf Models

Three types of 'big-leaf' trace gas models can be identified. The simplest 'big-leaf' model employs a series of multiplicative functions to a base flux rate.

$$F_c = S_{base} \cdot f(a) \cdot f(b) \cdot f(c)..... \quad (3)$$

where a, b, c represent governing variables such as light (I), temperature (T), humidity (q) and soil moisture (q). The isoprene emission model of Lamb et al. (1993) is a prime example of this model type. Technically Equation 3 is a scaling model, rather than integrative model (Jarvis, 1995). The appeal of Equation 3 is its dependence on a limited number of variables that have a linear dependence upon one another. A perceived weakness of a multiplicative, 'big-leaf' model revolves around its dependence upon parameters that do not relate to measurable physiological or physical quantities. Such models must be tuned against stand-level, eddy flux measurements. On the other hand, this method has practical appeal for gap filling data records and for constructing long term sums of trace gas fluxes, as driven by meteorological variables.

A second version of a 'big-leaf' model borrows its heritage from an electrical analog; current flow (mass or energy flux density) is equal to the ratio between a potential and the sum of the resistances to the flow.

$$F_c = \frac{C_a - C_0}{R_a + R_b + R_c} \quad (4$$

This approach is popular for computing gaseous deposition over forests (Meyers and Baldocchi, 1988) and canopy photosynthesis and evaporation (Amthor, 1994; dePury and Farquhar, 1997). In this case, C_a is the concentration of scalar in the atmosphere over the vegetation and C_0 is an 'internal' concentration. The major resistances are attributed to aerodynamics of the atmosphere (R_a), diffusion through quasi-laminar boundary layers (R_b) and resistances imposed by the vegetation and soil (R_c). The canopy resistance (R_c) is a function of the canopy stomatal resistance (R_{stom}), the canopy cuticle resistance ($R_{cuticle}$), and the soil resistance (R_{soil}). In turn, these plant and soil resistances are affected by leaf area, stomatal physiology, soil pH, and the presence and chemistry of liquid drops and films. The stomatal, leaf surface (cuticle) and soil resistances act in parallel.

A third type of a 'big leaf' model is an analytical one. It is derived by integrating environmentally-dependent, leaf-level functions for trace gas fluxes with respect to leaf area (*L*):

$$F_c = \int_0^L f(T(l), I(l), q(l))\,dl \quad (5$$

The Simple Biosphere (SIB) model of Sellers et al. (1986) is an example of this model class. A disadvantage of this model class is that compromising assumptions on the behavior of T, I and q with L may be needed to assemble a system of equations that can be integrated analytically.

Big-leaf' models are susceptible to criticisms from micrometeorologists on three principles. First, they rely on K-theory, which is invalid within canopies (Raupach and Finnigan, 1988).

Second, many ‘big-leaf’ models do not account for the impacts that environmental and physiological gradients have on the scaling of photosynthesis, stomatal conductance, transpiration and the leaf energy balance. And third, many parameters required by ‘big leaf’ models cannot be defined by mean leaf properties (Leuning et al., 1995; de Pury and Farquhar, 1997).

In practice, a ‘big-leaf model’ is most susceptible to failure when attempting to compute hour by hour fluxes of clumps of trees or isolated trees, as in savanna woodlands. Model performance is improved when 'dual source' or 'two-layer' models are applied to such complex circumstances. 'Dual source' models are able to account for differential fluxes associated with sunlit and shade leaves (Meyers and Baldocchi, 1998; dePury and Farquhar, 1997) or a mixture of herb and shrub (Huntingford et al, 1995). 'Two layer' models are able to account for strong differences in mass and energy exchange that occur the vegetation and highly exposed soil, as is experienced over sparse woodlands and savannas (Huntingford et al., 1995).

3.1.2 Multi-Layer Models

A multi-layered model is an ideal means for computing trace gas fluxes to or from vertically inhomogeneous forests. The multi-layer model scheme is derived from Equation 1 by assuming steady state conditions, horizontal homogeneity and no chemical reactions. This assumptions yields an equality between the change, with height, of the vertical turbulent flux and the diffusive source/sink strength, $S_B(c,z)$:

$$\frac{\partial F(c,z)}{\partial z} = S_B(c,z) \qquad (6$$

In practice, the net forest-atmosphere flux is computed by integrating Equation 6 with respect to height. The diffusive source strength is typically expressed in the form of a resistance-analog relationship:

$$S_B(c,z) = - r_a \; a(z) \; \frac{(c(z) - c_i)}{r_{bc}(z) + r_{sc}(z)} \qquad (7$$

where *a(z)* is the leaf area density, $(c(z) - c_i)$ is the concentration difference between air outside the laminar boundary layer of leaves and the air within the stomatal cavity, r_{bc} is the boundary layer resistance to molecular diffusion, r_{sc} is the stomatal resistance and r_a is air density. Normally, Equation 7 is evaluated by treating and weighting the sunlit and shaded portions of the canopy layer separately (Norman, 1979). This activity requires the application of a radiative transfer model.

Chemical reactions are important when the time scale of the reactions are shorter than the turbulence time scale that determines the residence time of a parcel of air (Gao et al., 1993). In this case Eq. 7 is expanded to include chemical production and destruction (S_{ch}):

$$\frac{\partial F(c,z)}{\partial z} = S_B(c,z) + S_{ch}(c,z) \qquad (8$$

In the simplest circumstance, S_{ch} is parameterized using chemical kinetics, where the rate of reaction is proportional to the local concentration:

$$S_{ch} = -kc(z) \qquad (9$$

The introduction of chemistry into a canopy trace gas exchange model increases the need to compute scalar profiles accurately. This is because errors attributed to the parameterization of turbulence and scalar profiles will translate directly into errors in the evaluation of chemical kinetics. The other issue associated with the evaluation of Equation 9 involves what suite of chemical compounds to consider. Photochemical models tend to involve hundreds of reactions, which can be reduced to a suite of 20 to 40 key reactions (Gao et al., 1993).

Three-dimensional 'cubed' or ‘shell’ models (Wang and Jarvis, 1990) treats trace gas fluxes to and from heteorogeneous and open stands most realistically. In practice, the approach is be very difficult to parameterize and implement with fidelity.

3.2 Model Parameterization Issues

In ecological sciences, the philosophy dictated by Ocam's razor is often invoked as a guiding principle for designing a model. In other words, the simplest of competing theories is preferred to explain a phenomenon. One obvious question that is often raised, when modeling trace gas fluxes, is: do we need to worry about the attributes of every species in a forest or can we parameterize the system as a functional unit? In many cases, as with CO_2, energy and water vapor exchange, functional attributes of the forest stand (e.g. leaf area index, canopy conductance) are more important than the unique attributes of each species and tree in a stand (Valentini et al., 1999). On the other hand, if we desire to predict hydrocarbon emissions from a forest we must know its species composition and their spatial distribution (Baldocchi et al., 1999).

Some model simplification can be achieved by restricting the span of time and space scales that are considered. Based on hierarchy theory, one generally uses information from adjacent time and space scales to design and implement a model (O'Neill, 1989). Typically, the mechanics and the dynamics of the operational-scale is described at the smallest and fastest scales. For the case of a forest, this corresponds to the scale of leaves and how they respond to second by second variations in light and wind. Information at the operational-scale, i.e. the forest, is obtained by integrating reductionist-scale information in both time and space. For our case, this would correspond to hourly averages of stand-scale fluxes. The state variables that drive the operational-scale are imposed from the higher or macro-scale. In this case, a canopy-scale trace gas flux model would use weather and leaf area information as external inputs, rather than predicting the weather and forest growth.

As a model is applied for longer time-periods, other information on the structural and nutrient status of the plant canopy will be needed. Many trace gas model parameters, for example, vary significantly over the course of the year, as leaves age and resources change. Yet often this temporal dynamics is ignored.

Leaf area index is a prominent characteristic that experiences great variability over a year (Figure 1). Deciduous broad-leaved forests, for instance, are leafless and dormant during the winter. In spring, they experience a rapid expansion of leaves and attain full-leaf within a month. The date of leaf initiation at a given site can vary by 20 days on a year to year basis and over a month along a north-south latitudinal gradient. Evergreen tropical and conifer forests exhibit seasonal variations in leaf area, too, though the changes are less dramatic. Over longer time scales, leaf area and leaf area profiles will be affected by disturbance history of the stand (Parker, 1995; Hurtt et al., 1998). Physiological and structural characteristics that govern trace gas fluxes will depend on whether a forest is in the invading, aggrading or old growth stages.

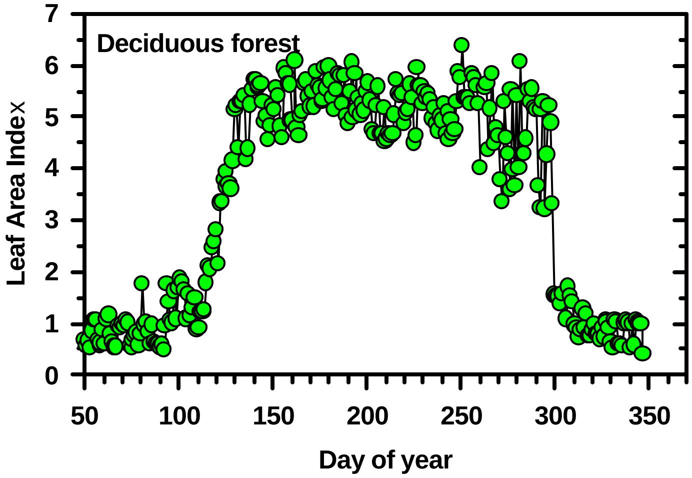

Figure 1. Seasonal variation of leaf area index of a temperate, broad-leaved deciduous forest growing near Oak Ridge, TN, USA.

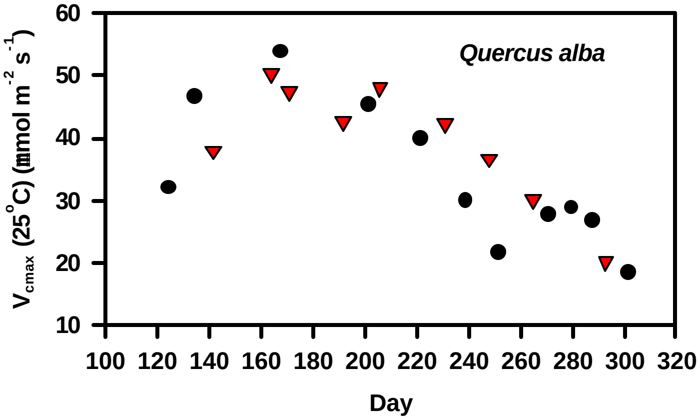

Figure 2. Seasonal variation of the maximum carboxylation velocity (V_{cmax}), a measure of photoysnthetic capacity, of a temperate broad-leaved deciduous forest.

Photosynthetic capacity is another model parameter that will vary over the course of the growing season (Figure 2). Photosynthetic capacity increases in harmony with leaf expansion, during the spring. Exposure to frost, in the spring or fall will diminish it, as will subjection to drought and soil moisture deficits, during the growing season. Seasonal variation of photosynthetic capacity is attributed to changes in the amount and fraction of leaf nitrogen that is allocated to rubisco. For instance, leaf nitrogen is re-mobilized into the stem of trees before senescence and leaf abscission. Maximum stomatal conductance experiences a similar seasonal pattern as photosynthesis since these two variables are well-correlated with one another. Isoprene emission, on the other hand, is not initiated until the period when maximal is achieved.

The spatial variation of certain model parameters can be pronounced within a forest. Measurements on leaf nitrogen content and photosynthetic capacity, for example, vary by a factor of three between the top and bottom of a forest canopy (Ellsworth and Reich, 1993; Harley and Baldocchi, 1995). This adaptation of leaves to sun and shade causes the variation of photosynthetic capacity to be as great as what can be experienced across the globe, between tropical and boreal forest biomes (Schulze et al., 1994).

3.3 Validation and verification

Due to the multiplicity of time and space scales and processes that are associated with modeling trace gas fluxes, model testing is a necessary, but non-trivial, exercise. In practice, no will trace gas exchange model will pass the falsification criteria, which has been advocated by Popper (1959). For example, Rastetter (1996) shows that the Farquhar photosynthesis model, a key component of a coupled trace gas model, is capable of estimating photosynthesis responses to light and CO_2 correctly on hour to day time-scales. But the model fails to mimic seasonal and multi-year time-scales responses to CO_2, as plants acclimate or down-regulate. To correctly validate a canopy-scale trace gas model, the time and space scale of the model and validation data must match. It is unfair to test a model for conditions it was not intended for using (Rastetter, 1996).

Data from a network of long term eddy flux measurements sites (FLUXNET, http://www-eosdis.ornl.gov/FLUXNET) is now available to test a hierarchy of trace gas flux models across a spectrum of forest types, on time scales from hours to years. In Figure 3, we show an example of a comparison between model calculations and measurements of carbon dioxide and water vapor exchange over a broad-leaved deciduous forest for the duration of a year. Overall, the agreement between measurement and theory is good, as much of the data over lap. How well a model should agree with data is a matter of debate. A 1 μmol m^{-2} s^{-1} difference between calculated and measured carbon flux densities falls within expected measurement and modeling errors. Yet, a bias of this magnitude can cause annual sums of net carbon exchange to differ by 400 g C m^{-2}. There is also the issue relating to the accuracy of the test data, as eddy flux data suffer from bias errors at night and over complex terrain (Baldocchi and Meyers, 1998).

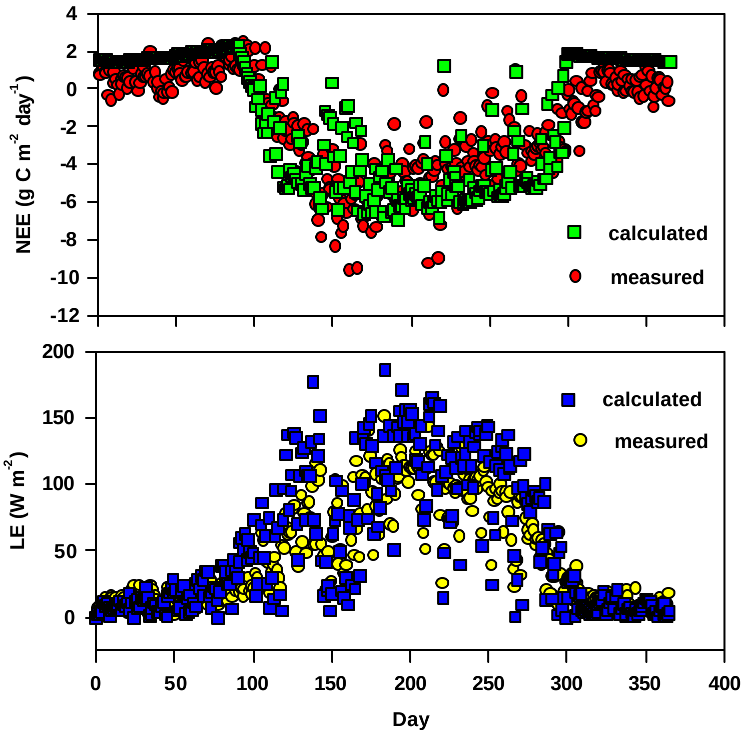

Figure 3. A comparison between measured and calculated fluxes of net ecosystem CO_2 exchange (NEE) and latent heat flux densities (LE). The calculations were derived from the CANOAK model (Baldocchi et al., 1999). The measurements were derived from the eddy covariance method. The data are from a temperate broad-leaved deciduous forest growing near Oak Ridge, TN.

4. CONCLUSIONS

We, as a community, possess a hierarchy of models for evaluating trace gas fluxes to and from forest canopies. The theory has matured enough that these models can simulate trace gas fluxes with reasonable fidelity, under ideal conditions. Into the future, we need to make use of network of long-term flux measurement sites to validate a hierarchy of models over heterogeneous forests and over long time scales. To implement such models correctly, we will need better information on the seasonal and spatial variation of canopy model scaling parameters, i.e. leaf area index, photosynthetic capacity etc.

If we expect to model how trace gas fluxes of a forest will respond to future environmental perturbations, we will need to consider how a forest responds to disturbance (e.g. fire, insects) and how new genetic material is able to invade the stand and alter the genetic composition, and the functionality of the stand (see Hurtt et al., 1998). In the future, forest trace gas flux models should evolve toward a system that links micrometeorological, soil, ecophysiological, ecosystem, atmospheric chemistry and biogeochemical cycling models. A canopy micrometeorology model is needed to assess the light, temperature, humidity, CO_2, wind speed and the scalar trace gas environment within and above vegetation, which drives physiological functions described above. The soil model will be needed to compute information on soil temperature and moisture and on gas diffusion. The ecosystem and biogeochemical models will be needed to predict changes in leaf area index, canopy height, stand species composition and photosynthetic capacity of the stand. The chemistry modules are needed to compute rates of chemical reactions that are occurring within a forest and in its surface boundary layer. The most capable models will need to be able to simulate trace gas fluxes of open forests, growing on complex terrain that are subject to water deficits.

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