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Report: A Toy Terrestrial Carbon Flow Model

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Background

Simplified or toy models have been commonly used to test specific hypotheses about complex systems. During the 1990 Global Change Institute (GCI), we attempted to propose the structure of various toy models of different earth system components from which we can eventually test hypotheses relevant to global change. These toy models have been pared down to incorporate only essential attributes of key components and processes.

The value of these toy models is derived from their relatively transparent nature. That is, processes connecting various components are easily discerned, and responses of these models to perturbations to their parameter environment can be more readily determined. The development and testing of these simplified models will quicken the rate at which we are able to unravel specific interlinkages of the earth system. Thus, these toy models can be viewed as an important step in building more complex and intricate earth models.

Scientists presented several toy models in discussions during the 1990 GCI. These were: ocean biogeochemistry (W. Broecker), global nitrous oxide (N_2O) flux (I. Fung), biosphere interaction with climate (F. Bretherton), ocean carbon (B. Moore), terrestrial biogeochemistry (W. Parton), forest carbon and water flux (S. Running), and sea ice growth (A. Thorndike).

Carbon Flow Model

At the GCI, a conceptual framework was developed for a generalized carbon flow model for the major terrestrial ecosystems of the world. The model is a simplification of the Century model (Parton et al., 1987, this volume) and the Forest-Biogeochemical (BGC) model (Running and Coughlan, 1988). The C flow diagram (Figure 1) shows that live foliage, roots, and woody biomass are represented and that C flows from these compartments to the plant residue compartment. Plant residue then decomposes and forms soil organic matter. The soil organic matter is divided up into two compartments (slow and passive), with the slow pool having an approximate turnover time of 20 to 50 years and the passive pool having a long turnover time (1000 to 3000 years). The actual turnover times of these pools depend on abiotic decomposition factors (soil temperature and water), with shorter times in warm, humid environments and longer in cold, dry locations. This structure is a simplification of the Century soil organic matter model where the slow compartment of soil organic matter is further divided up into two boxes (active and slow with approximate turnover times of 2 and 20 years, respectively). The model also represents the dynamics of nutrients in the plants and soil. The nutrient flows are represented because either N or P limits plant production for most terrestrial ecosystems, and production can be constrained by the ratios of C:N or C:P in the various components. The nutrient flow model has the same structure as the C flow diagram and will represent the dynamics of the most limiting nutrient for plant production. Nitrogen limits most terrestrial systems; however, P limits production for many tropical forest systems.

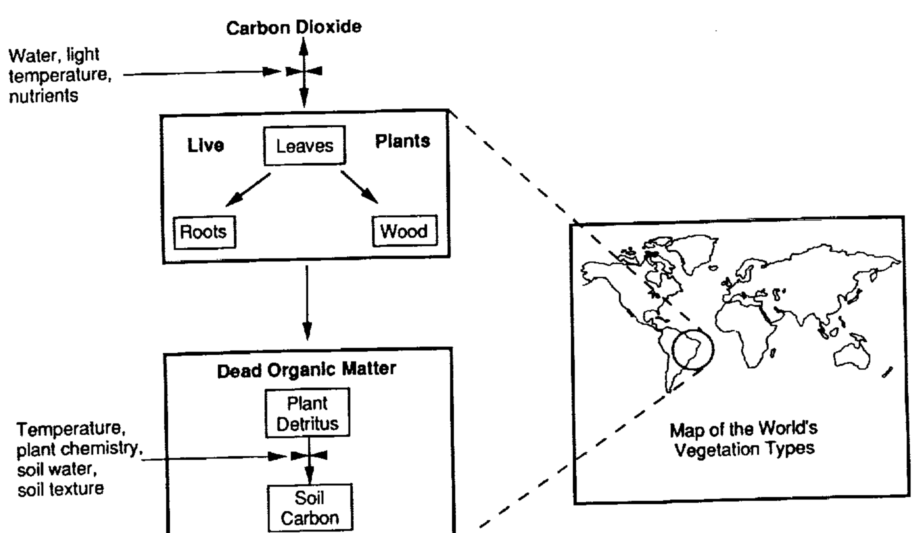

Figure 1. Conceptual framework for a global terrestrial C model.

Plant Production

Plant production is calculated using two different submodels. The model developed by Running and Coughlan (1988) is used to calculate net daily photosynthesis as a function of soil water content, solar radiation, air temperature, and leaf area index. The calculated net photosynthesis rate is the maximum potential plant production rate for the day; the actual plant production rate will be lower than the maximum rate if there is insufficient available inorganic N or P. The C fixed each day is then allocated into the live shoot, root, and wood biomass. The allocation of C is primarily a function of the type of ecosystem being represented; however, the allocation pattern is also a function of the annual rainfall, grazing level, and atmospheric CO_2 level.

The second submodel uses a less mechanistic approach where the controls on potential plant production are monthly rainfall and soil temperature. This type of model is currently being used in the Century plant production model. The effect of rainfall on plant production (Figure 2a) is calculated as a function of the ratio of monthly rainfall to potential evapotranspiration (increases linearly as the ratio increases). The potential evapotranspiration rate is calculated as a function of the maximum and minimum air temperature using the equations developed by Linacer (1977). Production increases rapidly as surface soil temperature increases from 5° to 15°C, then increases relatively slowly up to 20°C, followed by a decline in production above this temperature (Figure 2b). For certain specified plant communities adapted to cooler climates, a curve similar to the C3 curve of the Century model can be used, or for warmer climates the C4 curve can be specified. The potential plant production rate is calculated by multiplying the temperature effect times the rainfall term times the maximum plant production rate for a month. The actual plant production will be less than the potential rate if sufficient nutrients are not available. The allocation of C into the different plant parts is calculated using the same approach as in the high-resolution plant production model.

The live wood, foliage, and root biomass grow as a result of inputs of carbon from the plant production model. The different plant parts have different lignin contents and nutrient concentrations, which are a function of the plant community. We have tentatively identified eight ecosystems that need to be represented in the worldwide application of the model:

- Desert
- Arid and semiarid savannas and shrublands
- Humid savannas and woodlands

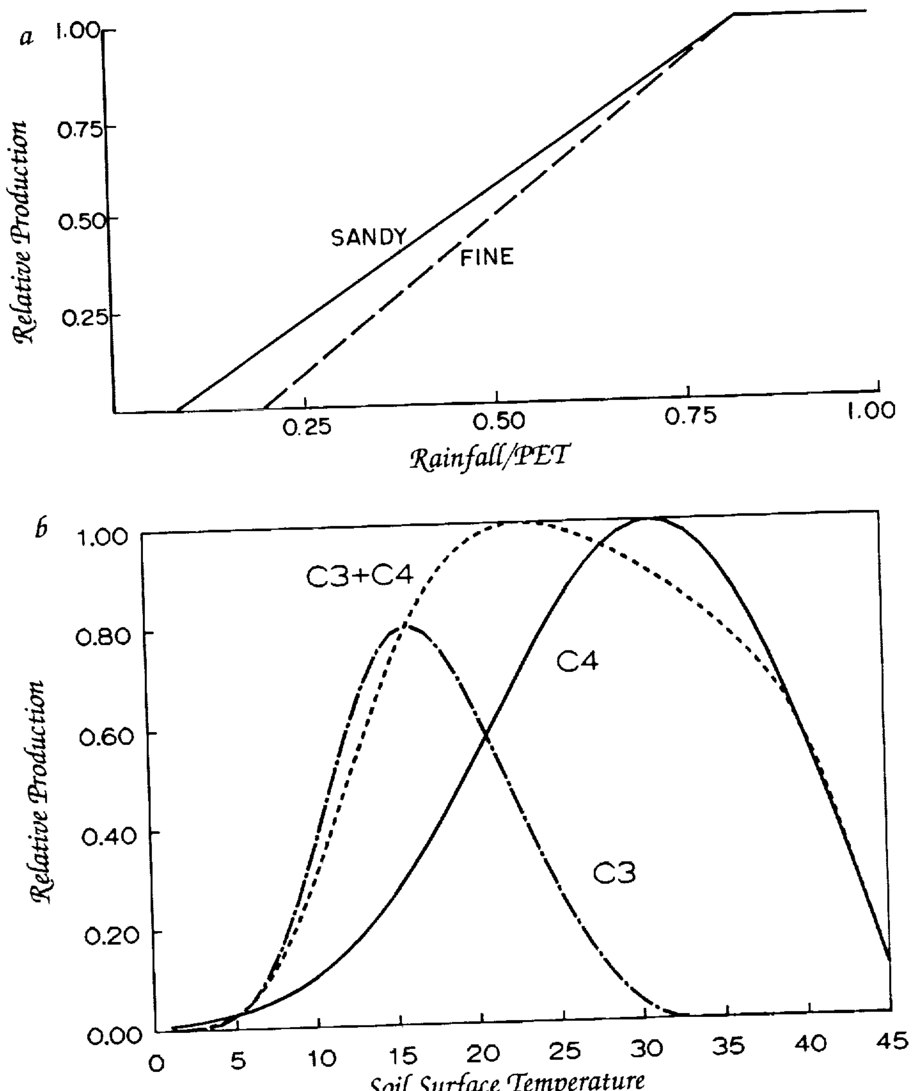

Figure 2. Climate controls on plant production. (a) Control of rainfall and potential ET on production as modified by soil texture. (b) Characteristic temperature response of terrestrial ecosystem dominated by C3, C4, or an even mixture of C3/C4 plants.

- Grasslands
- Temperate deciduous forests
- Temperate evergreen forests
- Arctic and subarctic tundra
- Tropical rainforests.

The live roots die at a constant rate that is a function of the ecosystem-specific annual fine root turnover rate. The large wood biomass includes the boles, large branches, and coarse roots. The model considers the effects of harvest and natural death of the live wood. Harvest of wood is an external driving variable, and wood death and decomposition are simulated. Wood death rates are ecosystem-specific and a function of the amount of wood biomass (higher for older and larger trees). Leaf death rates vary as function of the vegetation type, air temperature, and moisture stress. The ecosystem-specific patterns for leaf death (e.g., deciduous vs. coniferous) and the controls of air temperature and moisture stress are represented. Burning redistributes carbon and nutrients from live foliage and wood to litter and the atmosphere (as oxides of nitrogen and CO_2). The redistribution pattern needs to be modeled externally by a separate fire model, with the results being fed back into the carbon model.

Decomposition and Nutrient Cycling

Dead leaf and fine root material flow into the plant residue compartment (Figure 1), while dead wood goes into wood residue. Wood and plant residue decompose as a function of the lignin and N content of the material and the abiotic decomposition parameter. The abiotic decomposition rate is a function of soil temperature and rainfall, and the equations presented in the Century model are used for this model (Figure 3). The abiotic decomposition rate increases with increasing temperature and increasing values of the monthly ratio of rainfall to potential evapotranspiration rate. The effect of plant lignin and N content on decomposition is represented by the functions used in the Century model. Plant and wood residue decomposition rates decrease with increasing lignin content and decreasing N content. As plant residue decomposes, most (60 to 80%) of the C is lost to the atmosphere as respiration. The C lost as respiration is a function of soil texture and mineralogy and the plant lignin content of the vegetation. The effect of soil texture and lignin content on CO_2 respiration loss is represented using the equations presented in the Century model. CO_2 losses are higher for sandy soils and decrease as the lignin content of the vegetation decreases. Carbon not lost as CO_2 respiration flows into the two soil organic pools (slow and passive). The slow pool receives most of the carbon (98 to 99%). The fraction that goes to the passive pool is a function of the clay content of the soil, with higher values for clay soils. The slow and passive soil pools decompose at different rates (approximate turnover times of 20 and 1000 years) which are pool-specific and vary as a function of the abiotic decomposition rate (Figure 3).

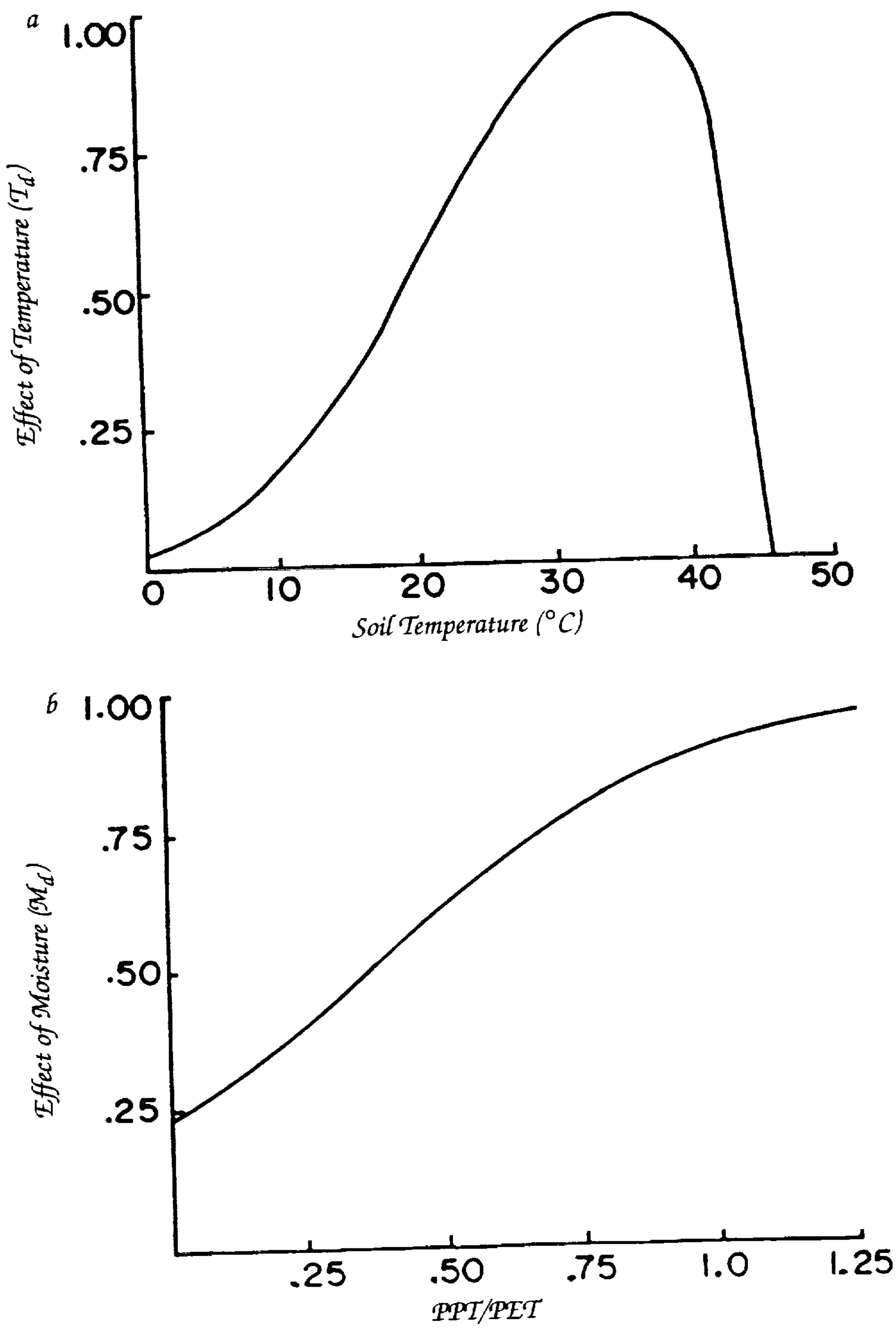

Figure 3. (a) The effect of soil temperature (T_d) on monthly deposition rates. (b) The effect of moisture (M_d) on monthly deposition rates.

When the soil organic pools decompose, the carbon is returned to the atmosphere as CO_2.

Nutrient cycling is modeled by using the same flow diagram as in the carbon model. The nutrient content of the vegetation is an ecosystem-specific input variable, and the plant nutrients flow along with the carbon. When soil C pools decompose they release C to the atmosphere, and nutrients associated with the decomposing soil C are assumed to be mineralized and flow into available mineral pools (nitrate, ammonium, and phosphate: NO_3^-, NH_4^+, and $PO_4^{\equiv}$).

When plant residue decomposes it immobilizes nutrients from the mineral pools at a rate that is a function of the nutrient and lignin content of the vegetation. The immobilization rate is higher for vegetation containing high lignin and low nutrients. The soil nutrient mineralization model uses the equations developed in the Century soil organic matter model. The nutrients remaining after immobilization into decomposing plant residue are then available for uptake into new plant production. Nutrients will be lost from the system by leaching, by erosion, and through gaseous emissions. Nutrient input to the system comes from the atmosphere and N fixation by the plants. Simple equations for these inputs and losses are included in the model.

A representative description of soils for the present modeling effort and for interactions with atmospheric models will need to specify both hydrologic and fertility parameters. These will likely include depth, texture, presence or absence of an impedance layer (for water or root penetration), active carbon content, sum of exchangeable bases, and an additional description of topography.

A combination of basic soil attributes such as parent material (from surface geological maps) and soil age, together with plant functional groups that grow on these soils (see below), may allow us to deduce both fertility and the hydrological cycle in an ecosystem without complex and detailed mapping of soil texture depth, infiltration, interflow, and runoff.

Biomes

The ability to model different processes in the carbon and nutrient cycles of terrestrial ecosystems needs to be tested in different biomes. On a precipitation and temperature plot, eight major biomes can be distinguished, as listed in the previous section. Within each of these, on a regional basis (i.e., by general circulation model grid cell), it is necessary to define the proportion that has been converted to dryland or irrigated arable land. Feasible land use systems can be superimposed upon these biomes, and the model should be tested under these combinations.

Since the C model describes productivity in several key plant components, and also allows for the incorporation of nutrient fluxes, it can be used with only minor additional algorithms to predict other important ecosystem variables such as leaf area index, albedo, and to some extent moisture.

A critical gap in this, as in most other models, is the inadequate representation of water use and storage within the ecosystem. Incoming precipitation controls primary production, but soil moisture storage and water uptake by roots from different soil layers at different times are not represented. The redistribution of precipitation into evaporation, soil moisture storage, transpiration, and drainage depends on such factors as relief, soil type, texture, rooting depth, and plant type. In sandy and loamy soils water will gradually penetrate the soil as successive layers become saturated. Water extraction (and loss to the atmosphere) subsequently depend on surface evaporation and root distribution. This is relatively simple to represent in a model. In heavier soils, cracks permit the rapid infiltration of incoming rainwater to depth without the complete saturation of upper soil layers. Subsequent water uptake and transpiration by plants from lower soil layers is an important factor for plant survival in dry climates, but is difficult to represent with simple models. The complex redistribution patterns of water on the individual ecosystem level will have to be simplified to provide water balances at a resolution appropriate at the general circulation model (GCM) grid scale. No satisfactory solution to this problem is yet available.

Scenarios

The utility of the carbon flow model for predicting C dynamics under global change depends on whether it can be applied to different scenarios of global change around the globe. The scenarios include different conditions and changes in atmospheric CO_2 levels; temperature; precipitation; atmospheric deposition of N, S, and others; land use, such as fertilization, irrigation, and cultivation; deforestation/afforestation; extraction of selected ecosystem products; grazing; and fire.

CO_2 levels are covered in the plant production portion of the model structure. In Running's model, photosynthesis depends on CO_2 gradients that inherently depend on atmospheric CO_2 levels. In the Century model, the slope of the relationship between available water and productivity is modified by atmospheric CO_2 levels.

Temperature and precipitation are controlling factors for both production and decomposition functions of the simplified Century models. In addition, the allocation of production to root and shoot is controlled by moisture availability. Irrigation will have similar effects on production and decomposition through improved moisture availability.

Atmospheric deposition may affect the availabilities of nutrients for plant production. Productivity is modeled depending on C:nutrient ratios, which allows for the effects of such atmospheric deposition. Atmospheric deposition may also change acidity levels in the soil depending on the soil's buffering capacity. The potential productivity depression will lower the slope of the curve relating productivity to moisture availability of the simplified Century.

Levels of inorganic nutrients in the soil as affected by atmospheric deposition or land management (including fertilization) may need to be modeled separately from the C:nutrient function. Phosphorus, for instance, has several inorganic forms of differing solubility and availability, which interact with organic P forms and plant uptake. Transformations between these forms need to be modeled separately. This has been done successfully in the complete version of Century.

The effect of cultivation is to mix residues into the soil and speed up decomposition processes. This is successfully modeled by Century, and adequately represented in the present model.

The processes of deforestation and afforestation involve depletion and buildup of leaf, wood, and root components, which can be adequately modeled.

Extraction of selected products such as firewood, fruit, or animals in grazed systems without wholesale modification of the ecosystem can be represented by loss functions on the leaf or wood components. The partial return of materials through feces of grazing animals or accelerated litter production in extractive use may require additional simple models that provide new parameters to the simplified Century.

Similarly, fire causes a redistribution of model components, export of C and N, and generation of inorganic forms of nutrients in ashes that will need to be modeled in a separate fire model, which should account for the differential effects of burn intensities, fuel availability, and vegetation state.

Vegetation Change

The eight biomes listed above may be exchanged for a more appropriate classification of vegetation functional types once these have been developed using plant functional types (PFTs) and soil properties. The PFTs will be defined in terms of characteristics that determine their interaction with the atmosphere and other ecosystem components.

Thus far the terrestrial carbon model discussed here is applicable to a fixed vegetation cover within each of the eight biomes. As climate and atmospheric CO_2 change, however, the functioning of the terrestrial ecosystem will change, and this will eventually lead to global changes in the state of the ecosystem. To take these changes into account, fine-scale models of detailed changes in species composition are inappropriate. What is needed are a broad-scale data base of geo-referenced characteristics of the earth's vegetation cover and a model that predicts changes that are significant in terms of their consequences for GCMs and atmospheric chemistry (i.e., carbon).

We propose the development of two complementary models for the changing ecosystem: a state-and-transition model and an environmentally driven global vegetation model.

State-and-Transition Model

This model should be based on a present-day land cover map of the world, classified into the eight biome types, with local and regional differences represented by:

- Separate descriptions of the vegetation functional types (woodland, grassland, etc.), with each vegetation type being defined by its proportional composition of plant functional types (evergreen vs. deciduous, annual vs. perennial, etc.)
- Differences in the amounts of the variables in the carbon model
- The proportion of the biome that has been converted to cultivated land.

The first requirement is that the model must apply to the entire land surface of the globe, and this puts a constraint on the scale. A grid cell or polygon size of about 100 x 100 km is tentatively proposed. For each grid (polygon) cell, the proportion of each biome type should be determined. It is necessary to determine the possible states in which each biome type can exist. The definition of these states should be guided by the interaction of the ecosystem with the atmosphere. Minor differences in species composition should not be considered as differences in state. Large differences in the proportions of different functional types of species (e.g., from evergreen to deciduous trees, or from trees to grass), which will lead to measurable differences in the atmosphere/climate models, are significant.

Transition from one state to another is driven by both endogenous (community) processes and exogenous (disturbance) effects. Both need to be taken into account. Change due to endogenous processes will be determined mostly as a function of the changes in levels of the C boxes and fluxes in the C model, but may also be based on known successional processes in that type of ecosystem. In terms of environmental (precipitation and temperature) changes, present-day correlations between vegetation state and environment may be used to guide the degree of change in environment required to induce a "significant" change in state (with due recognition given to the various lag effects). In addition, there should be an attempt to derive relationships (within each biome) between the levels of C in each box of the model and the "state" of the vegetation. These relationships could then be used to drive the vegetation change model.

For ecosystems where change is predominantly a function of disturbance regime, the combinations and sequences of conditions for each transition need to be explicitly stated, based on what is currently known about the ecology of that region.

The two types of processes are then amalgamated into a set of rules which determines each transition.

Environmentally Driven Global Vegetation Model

We envisage this model as based on first principles, using fundamental processes of vegetation development, and having no recourse to existing maps. It is based on a set of plant functional types with defined environmental responses, and the proportional composition of the vegetation is determined by the individual and interactive dynamics of these PFTs in response to given climatic scenarios. The proposed model is a simplified FORET-type model (Shugart, 1984) of plant-by-plant replacement, with globally defined plant functional types replacing individual species.

Validation

Given our present understanding of global vegetation dynamics, and the existing data (or lack thereof), it will be particularly valuable to develop both of these vegetation change models. Discrepancies between them will focus attention on high-priority areas for reducing uncertainty. The vegetation model will be particularly valuable in setting bounds for the state-and-transition model and for checking on climate-driven changes to vegetation/environment combinations for which there are no current analogs. Other means of validation will include the use of advanced very high resolution radiometer (AVHRR) data and existing data sets on vegetation, soil, and climate for various regions within each biome.

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