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Numerical models of the terrestrial biosphere

JONATHAN A. FOLEY *Climate, People and Environment Program (CPEP)—Institute for Environmental Studies and Department of Atmospheric and Oceanic Sciences, University of Wisconsin–Madison, 1225 West Dayton Street, Madison, WI 53706, U.S.A.*

Abstract. Many efforts have been made to develop numerical models of biospheric processes in recent years. Generally speaking, three classes of global terrestrial biosphere models have emerged: (1) soil–vegetation–atmosphere transfer (SVAT) models, (2) terrestrial biogeochemistry models (TBMs), and (3) potential vegetation models (PVMs). In this manuscript, I summarize the main characteristics of these models and discuss the need for a more fully integrated biosphere model, which would combine aspects of (1), (2) and (3) in a single modelling framework.

Key words. Terrestrial biosphere models, global vegetation models, biogeochemistry, SVAT models.

INTRODUCTION

In order to further our understanding of global environmental processes, it is necessary to consider the fundamental relationships between the physical, chemical and biological processes occurring on the planet. The terrestrial biosphere plays a central role in the Earth system, and interacts with other parts of the planet, including the atmosphere. Soils and vegetation, for example, are an integral part of the global water, carbon and energy cycles.

Exploring the relationships between the atmosphere and the terrestrial biosphere is difficult because of the large variety of spatial and temporal scales that are inherent to both systems. An additional difficulty in relating the atmosphere and the biosphere is that the atmosphere behaves as a continuous fluid, whereas the biosphere is free to be spatially discontinuous.

Despite the difficulty in achieving an elegant synthesis of the atmosphere and the biosphere, there are broad overlaps between the two. For example, the geographic distribution of vegetation communities is determined, to a large extent, by the climate. In addition, the characteristics of the vegetation and the land surfaces can, in turn, affect the climate through biogeophysical mechanisms. In addition, the terrestrial biosphere plays a key role in the global cycles of water vapour, carbon dioxide and methane and may influence the energy balance of the atmosphere, and hence climate, through biogeochemical processes.

MODELS OF THE TERRESTRIAL BIOSPHERE

While many different ecological models have been used on local and regional scales, three major categories of global biosphere models have emerged. They are:

- soil–vegetation–atmosphere transfer models (SVATs)
- terrestrial biogeochemistry models (TBMs)
- potential vegetation models (PVMs).

These three categories of biosphere models, while very different, all have similar boundary conditions: climate and soils. In addition, all three categories of models have been applied to climatic change scenarios. In fact, these models were built largely because of the importance of climate in ecological processes.

Below, I discuss the three categories of global biosphere models and how they are used to examine the interactions between climate and the terrestrial biosphere.

SOIL–VEGETATION–ATMOSPHERE TRANSFER MODELS

Atmospheric General Circulation Models (AGCMs) require, as surface boundary counditions, the flux of energy, water and momentum. Over the oceans, where sea surface temperatures are either modeled or fixed to climatological values, the calculation of these fluxes is relatively simple. However, over land it is considerably more difficult due to the highly variable nature of land surfaces. Additional complexities arise from the sensitivity of AGCMs to the specification of land surface properties. For example, numerical simulations have demonstrated the sensitivity of AGCMs to land surface albedo (Charney, Quirk & Kornfield, 1977; Thomas & Rowntree, 1992; Foley *et al.*, 1994), soil moisture (Shukla & Mintz, 1982) and surface roughness (Sud & Molod, 1986).

In the mid-1980s, two modelling groups (Dickinson *et al.*, 1986; Sellers *et al.*, 1986) independently developed models whereby the surface energy, water and momentum balance could be described within AGCMs. Now a wide variety of these land surface models (herein called SVATs) are available and many of them can be directly coupled to AGCMs to describe the behaviour of the soil–vegetation–atmosphere continuum. In the typical SVAT there are one or two layers of vegetation, where energy fluxes are computed for each layer using simplified radiative transfer equations. The diffusion of sensible heat, water and momentum through the boundary layer and vegetation canopies is also calculated. In addition, the interception of rain and snow by the vegetation is accounted for in most models. Nearly all SVATs also incorporate a multilayer thermodynamic snow and soil model to simulate subsurface heat and water storage.

Many AGCMs are now coupled to SVATs to simulate the biophysical interactions between land surfaces and the atmosphere. However, these models require a specification of the geographic distribution of vegetation types and their associated physical characteristics (e.g. leaf area index, vegetation height). Because the distribution of vegetation types (and their associated physical characteristics) are fixed, and not allowed to change by any predictive means, it is possible that two fundamental problems may arise. First, the prescribed vegetation type of a given gridcell may be incompatible with the simulated climate of that gridcell, thus giving erroneous descriptions of ecosystem and climatic processes. Secondly, the fixed patterns of vegetation types are of limited use in climatic change simulations, where the distribution and structure of biomes is likely to respond to the changing patterns of climate.

A useful analogy for understanding this issue is the atmosphere-ocean interface in AGCMs. An AGCM can either fix sea surface temperatures (SSTs) to some climatological value or allow them to respond to changing atmospheric conditions. Typically, a coupled, or interactive ocean is described with a simple thermodynamic mixed layer model, where the SSTs are simulated as being driven by atmospheric heating. Using a land surface package with geographically fixed vegetation types is similar, in many ways, to running a climate model with fixed SSTs. Clearly the SSTs and vegetation distributions can change with the climate, albeit over different timescales, and therefore should be modeled as interactive boundary conditions within AGCMs.

Very preliminary attempts at simulating vegetation cover within AGCMs have been made. For example, Henderson-Sellers (1993) used the NCAR CCM1 and BATS (Dickinson *et al.*, 1986) together with the Holdridge (1947) potential vegetation model. In these coupled runs, the simulated climate was used to predict the distribution of vegetation types, which in turn were used to change the physical properties of the land surface. This study found that the interactions between the AGCM and the Holdridge vegetation model were stable, with no noticeable global trends during the 5-year integration. However, there were substantial regional-scale differences in simulated climatic parameters that were beyond the realm of observation. Henderson-Sellers concluded that it may be necessary to apply a correction to the AGCM output in order to remove a possible bias in the model's climatology. This preliminary study illustrated some key issues and caveats related to coupling potential vegetation, SVAT and climate models.

TERRESTRIAL BIOGEOCHEMISTRY MODELS

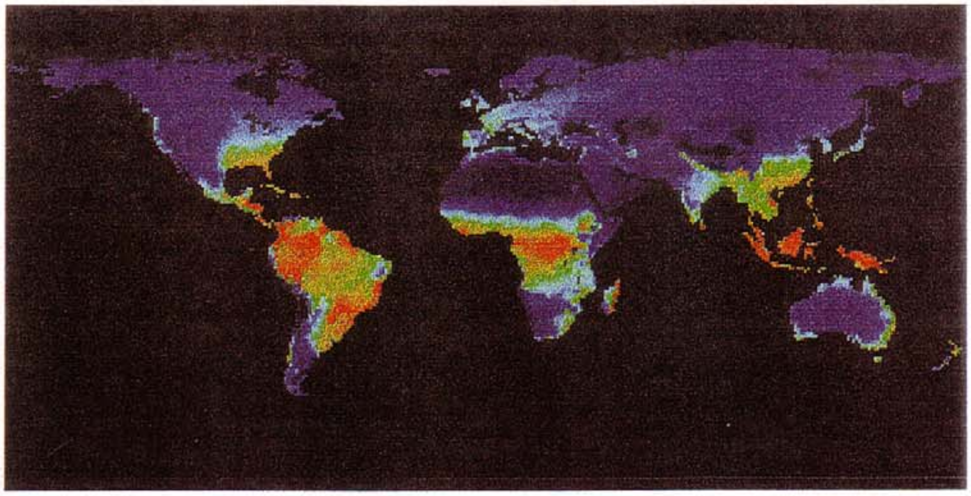
Several global-scale models of the biogeochemistry of carbon and nitrogen in terrestrial ecosystems have been developed. Typically, these models simulate the biogeochemical dynamics of a small number of pools: vegetation biomass, litter, and soil organic matter. One of the most important and fundamental process simulated by the terrestrial biogeochemistry models is net primary productivity (NPP).

Since the International Biosphere Program (IBP) of the 1960s and 1970s, a wide variety of NPP measurements have been compiled and tabulated (Whittaker & Likens, 1973; Lieth & Whittaker, 1975; Atjay, Ketner & Duvingneaud, 1979). Estimates of the global net primary productivity from these data range from 45 to 75 Gt-C yr^{-1} (e.g. Lieth & Whittaker, 1975; Atjay *et al.*, 1979). Lieth (1975) carried these observations a step further and formulated the Miami Model of primary productivity, which correlates observed NPP to values of annual mean temperature and precipitation. More recently, a number of process-based global NPP models have been developed, including TEM (Raich *et al.*, 1991; McGuire *et al.*, 1992; Melillo *et al.*, 1993), CASA (Potter *et al.*, 1993), and CARAIB (Warnant *et al.*, 1994).

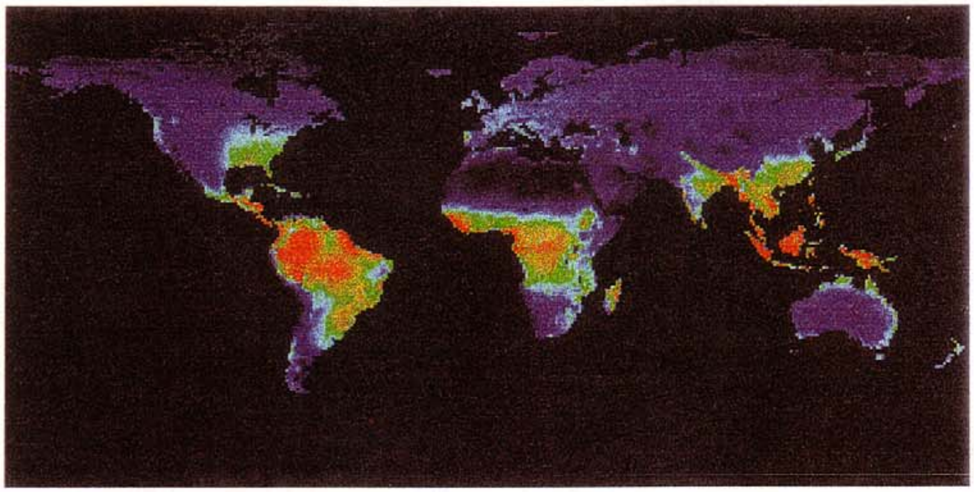
These process-based terrestrial biogeochemistry models (TBMs) simulate ecosystem processes in relation to prescribed boundary conditions: vegetation cover, soil texture and climate. Typically, TBMs operate on a monthly or weekly timestep. CARAIB is the exception: it has a diurnal cycle. While these models represent a significant improvement over the empirically-based models (e.g. the Miami Model), they have several limitations. First, most terrestrial biogeochemistry models prescribe fixed geographic distributions of vegetation cover and therefore cannot easily be used for studies of climate change. Also, many of these models are particularly concerned with the interacting dynamics of carbon and nitrogen in the ecosystem and, as a consequence, may be difficult to parameterize at the global scale. Finally, these models often have fairly simple parameterizations of the surface energy and water balance, which may not be altogether compatible with the simulations of AGCM land surface packages.

POTENTIAL VEGETATION MODELS

'Potential vegetation' is often defined as the vegetation cover that would exist in a given geographic location if the role of land use, natural disturbances, and nutrient limitation is ignored. Classical models of potential vegetation cover (e.g. Holdridge, 1947) classify vegetation into whole ecological units, each independently responding to climatic



DEMETER-1 NPP



Miami Model NPP

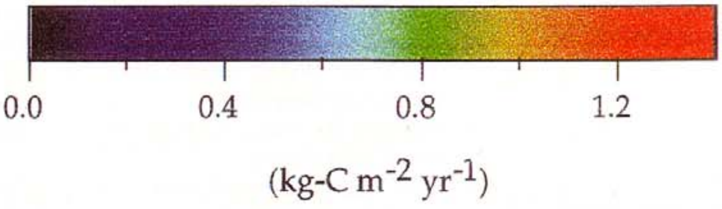


FIG. 1. Net primary productivity (NPP) for the modern climate as simulated by DEMETER (Foley, 1994a) and the Miami Model (Lieth, 1975).

variables. However, a more recent approach, developed by Box (1981), defines vegetation cover in terms of unique combinations of plant functional types.

Several potential vegetation models have adopted the plant functional type classification methodology of Box: these include BIOME-1 (Prentice *et al.*, 1992), MAPSS (Neilson, King & Koerper, 1992) and EVE (Bergengren & Thompson, 1995). BIOME and MAPSS, in particular, have included explicit climatic, physiological, and ecological constraints on the distribution of plant functional types (Woodward, 1987). These potential vegetation models have been successful at reproducing the observed patterns of global vegetation cover. In addition, these models have been applied to paleoclimatic and $2 \times CO_2$ climate scenarios (e.g. Neilson, 1993; Foley, 1995; Bergengren & Thompson, 1995).

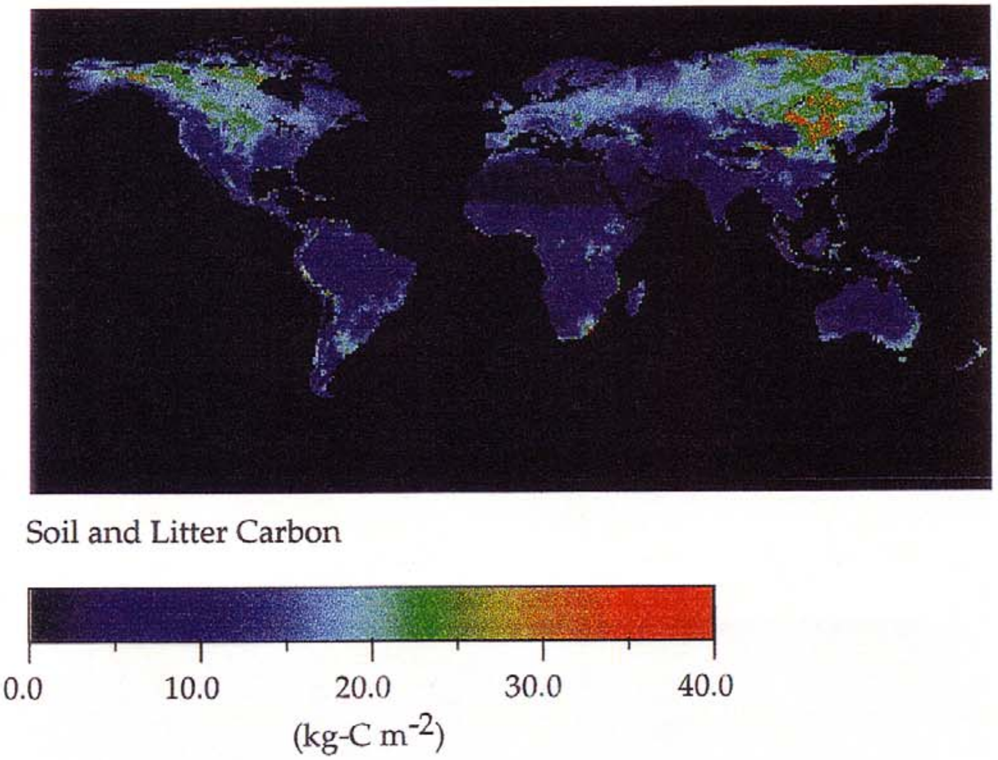


FIG. 2. Carbon storage in litter and soil organic matter as simulated by DEMETER.

DEMETER: A SIMPLE POTENTIAL VEGETATION AND TERRESTRIAL BIOGEOCHEMISTRY MODEL

DEMETER (Foley, 1994a, b, 1995) is a highly simplified global biosphere model that combines elements of the terrestrial biogeochemistry models and potential vegetation models. As a very preliminary attempt at linking TBMs and PVMs, the model employs some several simplifying assumptions. For example, the terrestrial biogeochemistry submodel differs from many other TBMs because it is mainly concerned with carbon and does not consider mineral nutrients. The potential vegetation submodel of DEMETER is based on the BIOME-1 model of Prentice *et al.* (1992). DEMETER has been forced with climatic data to simulate aspects of the contemporary terrestrial biosphere (Figs 1 and 2).

DISCUSSION

With these three categories of global biosphere models, addressing the impact of climatic change on global vegetation and terrestrial biogeochemical cycles would require the following chain of simulations.

1. An AGCM (coupled to a SVAT) is used to simulate changes in climate.
2. The climate change scenario is used to drive a potential vegetation model.
3. Climate and potential vegetation change scenarios are used to drive a terrestrial biogeochemistry model.

While this is a commonly used approach, inconsistencies between the models may affect the final outcome. For example, this chain of simulations has three totally different treatments of the surface energy and water balance. In addition, there are large differences in spatial and temporal resolution among the three models.

To better address the role of the terrestrial biosphere in the Earth system, it will become necessary to develop a fully *integrated terrestrial biosphere model*. This model would include elements of the existing models, and should be designed to facilitate coupling to AGCMs and other Earth system models. Ideally, such a model would:

- operate on an AGCM timestep (~ 10 to ~ 60 minutes);
- operate on a variety of spatial resolutions (e.g. from ~ 0.5° for climate impact simulations and up to ~ 5° for AGCM coupling);
- represent the diurnal cycle of water, energy, carbon and momentum fluxes;
- have biophysical parameterizations that are based on sound physical, physiological and ecological principles;
- be able to simulate the carbon and nutrient budgets of vegetation, detritus and soil organic matter pools;
- be able to predict potential vegetation and the seasonal phenology of the vegetation cover.

Such a model would remove the inconsistencies that are found when coupling various global biosphere models. In addition, it could be directly coupled to AGCMs to fully examine climate and biosphere interactions. This modelling framework could eventually be extended to include some

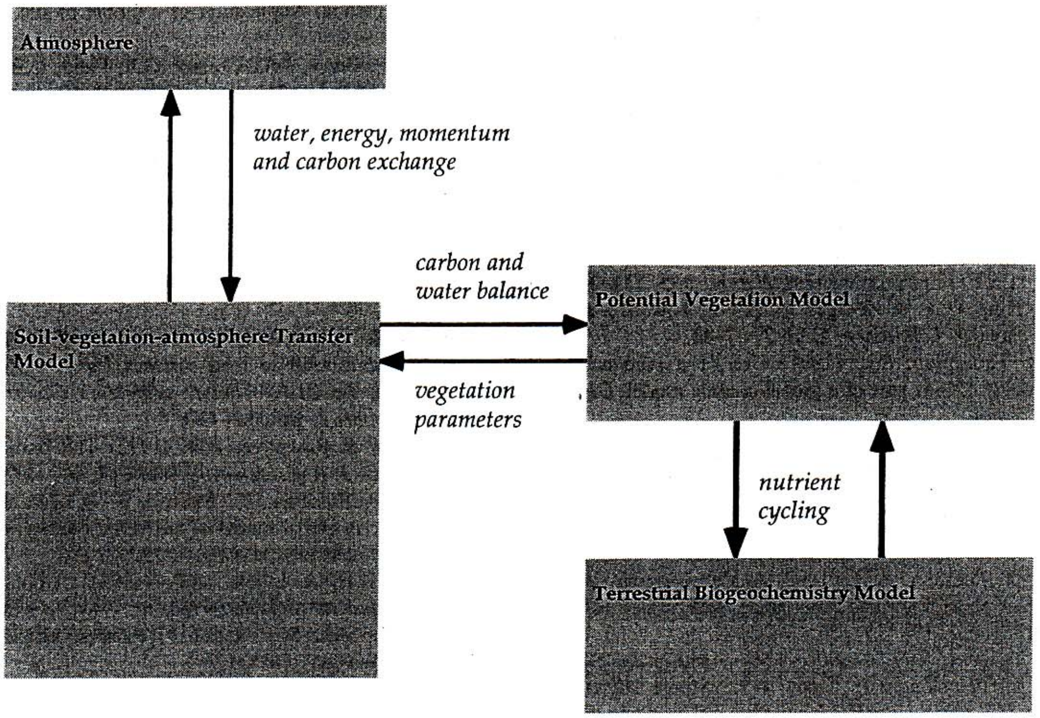


FIG. 3. A schematic illustration of a proposed 'integrated biosphere model'.

description of vegetation dynamics and the effect of disturbances, which are likely to be of importance in addressing the response of the biosphere to transient climatic change. Fig. 3 presents a proposed integrated biosphere modelling framework.

A significant step towards a more integrated approach to biosphere modelling has been made by Sellers *et al.* (1992) and Bonan (1994), who have constructed SVATs that simulate photosynthesis, canopy conductance and respiration from an ecophysiological perspective. These models, which have been coupled to AGCMs, can be used to examine the short-term biophysical and biogeochemical interactions between the atmosphere and terrestrial biosphere.

A fully integrated biosphere model could be based upon the same parameterizations of these SVATs (to be compatible with AGCM physics), and include explicit simulations of terrestrial biogeochemistry and vegetation cover. Potential vegetation cover could be predicted by several means, including: (1) a simple rule-based approach; (2) an iterative approach which converges on the vegetation cover that best meets a specified ecophysiological criterion, or (3) an explicit model of global vegetation dynamics. Such a tool would have enormous utility in the study of global change and terrestrial ecosystems.

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