

MOVE -- Transient Model of Vegetation Migration Due to Climatic Change

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The analysis of global vegetation distributions is usually based on biogeographical models that assume a type of the vegetation cover in any location is determined by certain climatic parameters. Change in these parameters would produce instant changes in global vegetation distribution and carbon storage patterns. The application of these models to different climate change scenarios is generally limited to the presumption of 'dynamic equilibrium': the rate of climatic changes should be comparable with the rate of vegetation response. The projected scales and rates of hypothesized future global warming are now considered to be considerably faster than these vegetation response limits. A few models of climate-vegetation interactions include the parametrizations of the "transient" processes at finer hierarchical levels. These models of global vegetation can simulate the dynamic vegetation response to transient scenarios of climate changes, while omitting specific description of species interactions. Our model MOVES (Migration Of Vegetated Ecosystems-Stochastic) accounted for the time lag between climate variations and induced vegetation responses by incorporating rates of vegetation migration into the BIOME1.1 bioclimatic classification. We used the 1994 IPCC climate scenario data set of temperature and precipitation, based on results of three linked ocean-atmosphere transient GCMs to generate projections of new global vegetation distributions. We compared classifications which assume either deterministic or stochastic vegetation migration. The models showed the complex non-linear dynamics of vegetation zones. The stochastic version of the model predicts larger impacts of climatic change on forest vegetation types and leads to more gradual decline of carbon stored in live matter during the beginning 300 - 500 years of simulation. However, the simulated final distribution of vegetation comes close to the results of deterministic models 500-1000 years after climate ceases to change.

1. INTRODUCTION

Prediction of long-term vegetation response to climatic changes induced by increasing greenhouse gas (GHG) concentrations is an important scientific problem whose solution is required for evaluation of possible effects of mitigation and adaptation activity (IPCC, 1996). Changes in the amount of carbon in the atmosphere strongly depend on the carbon retained or released by wildland vegetation in response to climate change (IPCC, 1996). Estimating this quantity provides the greatest uncertainty in global carbon cycle budget studies.

A common approach to assess potential redistribution of terrestrial vegetation caused by a different climate uses bioclimatic classifications (Holdridge, 1947, Budyko, 1977, Prentice et al, 1992). The models based on bioclimatic classifications assume 'dynamic equilibrium' (Webb, 1986) between climate and the vegetation it controls (Emanuel, et al., 1985; Prentice, 1990; Prentice, et al., 1992; Smith, et al., 1992 a, b; Solomon, et al., 1993; Tchebakova et al., 1993). The rate of climatic changes that can be effectively used as a scenario in these models should be comparable with the rate of vegetation response triggered by these changes. Assuming the expected rates of climate changes in the next century, these models can only estimate biotic responses which

require little vegetation development time to sequester carbon, such as grasslands. For the forests in which 80% of the terrestrial carbon is stored (Dixon, et al., 1994), development time may involve hundreds of years (e.g., Solomon, 1986; IPCC, 1996).

Transient models of vegetation (King and Neilson, 1992, Smith and Shugart, 1993, Belotelov, et al., 1996) have included this lag time as a constant in time and space. Solomon and Kirilenko (1996) and Solomon (1996 a, b) used the BIOME1.1 (Prentice, et al., 1992) classification to project changes of vegetation during the period preceding the climate of a doubled GHG concentration. Two simulations were done: 'equilibrium,' with immediate response of biomes to changes in climate variables, and 'nonequilibrium,' which assumed instantaneous migration by shrub and grass vegetation but no migration of forest vegetation at all during the 70 years preceding imposition of a climate generated by a doubling of GHGs (thus, the nonequilibrium nature of the simulation). These two simulations differed significantly in the final distribution of their biomes and in their carbon content. Kirilenko and Solomon (1997) used deterministic migration rates characteristic of different plant functional types to simulate global vegetation redistribution in the model MOVE. This paper continues our examination of the potential for including

dynamic vegetation responses in static bioclimatic classifications, by comparing the results of deterministic and stochastic simulations of vegetation migration.

2. THE MODEL

The MOVES (Migration of Vegetation with Stochasticity) model is based on model MOVE by Kirilenko and Solomon (1997) and simulates dynamics of global vegetation cover, based on properties of 18 plant functional types (PFTs) distinguished by Prentice et al. (1992) in the BIOME bioclimatic classification. Two basic processes are included in MOVES. The first is vegetation "migration," which consists of climate-driven replacement of dominant vegetation, modulated by different maximum rates of forest development following seed transport and establishment. The second process is the flux of carbon stored in live vegetation and soil, derived from new vegetation cover established during the previous time step.

The rate of vegetation migration, measured in km/century, determines the potential of vegetation to move into newly available niches, provided that climatic conditions stay within existing tolerances of migrating PFTs, and no competition from other vegetation modifies the process. Testing different approaches, we included two basic modifications of the migration submodel. The first one supposes that the migration is a continuous process with constant (but different for different PFTs) speed. In this case, the rate of migration was assumed from natural histories (seed transport modes; seed mass and productivity; life-cycle rates; etc.) of species characteristic of each PFT, based on multiple literature sources (Harlow, et al., 1979; Burns and Honkala, 1990; Ellenberg, 1988; Shugart, et al., 1992; Chabot and Mooney, 1985; Franklin and Dyrness, 1973; van der Pijl, 1969). This approach is "deterministic migration," and the "average rate" of migration is the rate measured in paleoecological data (e.g., Davis, 1976, 1983; Huntley and Birks, 1983; Gear and Huntley, 1991; King and Herstrom, 1996) and synthesized by Kirilenko and Solomon (1997). These values were 10 - 35 km per century, varying with each PFT.

The second approach, in contrast, accounts for temporal variation in migration success. Such variations in migration would be induced by variations in annual weather events, which suppress seedlings some years and permits their survival other years; by differences in annual seed transport distances by wind, animals and running water; by variations in soils and established vegetation which require differing amounts of time for establishment and growth of invading species; and by human land-use activities which vary from place to place, and which reduce or encourage seed transport and plant establishment. Here, we assumed that the rate of migration (under the same conditions as above) is described by a stationary stochastic process with a mean migration rate equal to that of the deterministic model. Because we lacked a means to estimate the migration variance about the mean, we used a "first approximation"

in which migration rates were uniformly distributed between zero and two times the average rate.

We simulated vegetation migration on a geographical grid of 0.5 degrees of latitude and longitude and a time step of 10 years. Typical model experiments consisted of fifty 5000-year model runs, in which all runs were made with a vegetation migration rate randomly selected within the range of 0 to 2 times the mean for specific plant functional types. The initial vegetation distribution and the carbon flux are assumed to be in equilibrium. Model dynamics are driven by the climate changes occurring within the initial 80 simulated years, and thereafter carbon stored in vegetation and soil attain a new equilibrium at the rate permitted by residual tree migration.

2.1 Deterministic Model

The model is based on the following principles. (1) The form of relationship between the equilibrium distribution of vegetation and climate will not change in future. (2) Change of climate forces the vegetation to immigrate toward the new equilibrium state (as incorporated in the bioclimatic classification), but this response is moderated by delays, which are long for forest and short for non-forest vegetation. (3) Two types of delays determine the rate of migration: first, delays are induced by elimination from a cell, termed emigration (mortality) of PFTs, after imposition of unsuitable climate conditions. Second, delays are induced by PFT invasion and establishment in a cell, termed immigration, into available sites with newly suitable climate. Emigration and immigration of each PFT proceeds at different rates. The model represents vegetation migration as shifts to new PFT and biome distributions. It then simulates the resulting changes of stored carbon.

We modified the BIOME 1.1 bioclimatic classification (Prentice, et al., 1992, 1993 a). The BIOME classification includes two levels of vegetation: PFTs, which form in different combinations, a limited number of biomes (see table 1). Any number of PFTs can co-exist in one location, constrained by climate, competition and in the modified version, by seed availability. The five climate parameters that affect PFT distribution include mean coldest-month and warmest-month temperature, accumulated heat units (growing-degree days) above 0 °C and 5 °C thresholds, and, the "Priestley - Taylor" ratio of actual to equilibrium evapotranspiration (Table 1 of Prentice, et al., 1992). Competition between PFTs suppresses certain PFTs in the presence of other, more dominant PFTs. After the subordinate PFTs are suppressed, the remaining dominant PFTs are combined into biomes.

Bioclimatic classifications define new equilibrium spatial distributions of vegetation due to changed climate. However, the substitution of one vegetation type by another will not be instantaneous: some time is necessary for new tree seedlings to establish and grow to maturity. Also, the succession of species culminating in dominance by the most shade-tolerant ones requires several

generations of trees. Seed availability also constrains the rate of migration into otherwise available places. Estimates of this transition time have been based on paleoecological records of radiocarbon dates of species appearances at spatial sequences of specific locations (e.g., Davis, 1976, 1983; Huntley and Birks, 1983; Gear and Huntley, 1991; King and Herstrom, 1996). Other investigations included only the time required for forest succession to proceed from the presence of pioneer trees to slow-growing shade-tolerant late-successional tree species (e.g. Solomon, 1986; Overpeck and Bartlein, 1989; Prentice, et al., 1993 b).

In addition to lags of PFT migration into new cells, we modeled the more rapid elimination of PFTs in a grid cell due to new inappropriate climate conditions or competition with vegetation that recently appeared. Trees undergoing the most rapid climate changes near the limits of their distribution, and in stressed habitats, may die in only a few years, while others may just begin to respond to stress by the time GHGs have doubled. Following mortality, release of carbon from dead trees may require additional decades. The processes of PFT migration on one side, and of elimination, on the other, were parameterized for MOVES (table 1).

Plant functional types	in- dex	hie- rarchy	mortality delay, yr.	migration yr/km	Biomes
Tropical evergreen	1	1	20	10	Tropical rain forest
Tropical evergreen	1	1	20	10	Tropical seasonal forest
Tropical deciduous	2	1	20	10	
Tropical deciduous	2	1	20	10	Tropical dry forest/savanna
Warm-temperate evergreen	4	2	40	5	Broad-leaved evergreen/warm mixed forest
Temperate decid.	5	3	40	5	
Cool-temp. evergr.	14	3	40	3.3	Temperate deciduous forest
Boreal deciduous	8	3	30	3.3	
Temperate decid.	5	3	40	5	
Cool-temp. evergr.	14	3	40	3.3	Cool mixed forest
Boreal deciduous	8	3	30	3.3	
Boreal evergreen	7	3	30	3.3	
Cool-temp. evergr.	14	3	40	3.3	Cool conifer forest (southern taiga)
Boreal deciduous	8	3	30	3.3	
Boreal evergreen	7	3	30	3.3	Taiga and northern taiga
Boreal deciduous	8	3	30	3.3	
Cool-temp. evergr.	14	3	40	3.3	Cold mixed forest
Boreal deciduous	8	3	30	3.3	
Boreal deciduous	8	3	30	3.3	Cold deciduous forest
Sclerophyll/succulent	13	5	5	1	Xerophytic woods/shrub
Warm grass/shrub	3	6	10	0.1	Warm grass/shrub
Cool grass/shrub	6	7	10	0.1	Cool grass/shrub
Cold grass/shrub	9	7	5	0.1	
Cold grass/shrub	9	7	5	0.1	Tundra, wooded tundra
Hot desert shrub	10	9	-	0.01	Hot desert
Cool desert shrub	11	10	-	0.01	Semidesert
Dummy type	12	11	-	-	Ice/polar desert

Table 1. Names of plant functional types and of the biomes they compose (in the stochastic model). Rates of mortality for plant functional types from Esser, 1991 and Lieberman and Lieberman, 1987. Rates of migration from multiple sources, cited in text. The original model MOVE also included the "northern" sub-types for PFTs 7, 8, and 9, which have hierarchy of 4, 4, and 8, and "agriculture" type.

2.2 Carbon Module

The dynamics of carbon exchange in MOVES are driven by delayed plant migration, succession, tree mortality, and soil carbon fluxes. We used initial carbon densities of vegetation and soils in each biome assigned by Prentice, et al. (1993 a). Transients in carbon quantities were calculated for the same functions considered by Smith and Shugart (1993). That latter work provided constant vegetation and soil carbon pulses at all points on the globe for several processes: loss of life zones because of climate changes (tree mortality), competition between established life zones (forest succession), and replacement of established life zones by more appropriate life zones from other sites (migration) at any distance.

We used the variable carbon flux rates of 0.004 yr^{-1} to 0.02 yr^{-1} (Smith and Shugart, 1993). The carbon increment changes if a PFT is eliminated from the site due to climate changes. Also, carbon increment shifts when the composition of PFTs changes because new PFTs migrated from a neighboring cell. Finally, the increment declines to zero when the amount of stored carbon reaches its equilibrium state.

2.3 General Model Algorithm

The first step of the model simulation is to input climate and vegetation data and to compute the initial biome distribution and carbon pools in soil and vegetation. Each successive 10-year time step of the model produces a new combination of PFTs on the surface of the earth and therefore a new distribution of biomes. This simulation process consists of the following stages:

New climate parameters are generated;

The bioclimatic scheme is applied to generate available PFTs which would appear in an equilibrium environment;

PFTs disappear in cells where they have become climatically obsolete (i.e., the new climate parameters exceed the climate boundaries for a PFT) for a predefined number of consecutive years, according to the results of the previous step;

PFTs migrate from neighboring cells to those made available by changed climate, if climate change persists long enough. This period of time varies and is determined from multiplying PFT migration rates by distances between cells.

The hierarchy definition is applied to the new set of PFTs to suppress PFTs lower in the hierarchy;

The type of biome is determined based on the new set of PFTs;

Carbon accumulation in soil and live matter in each cell is recalculated based on the new biomes.

2.4 Stochastic Model

Migration of vegetation into the newly available space occurs at a constant rate in the deterministic model MOVE. In the stochastic model MOVES, we asked whether significant changes in the model results would result from including nondirectional variation in the rate of vegetation migration. We modified the model by including a stochastic component to the migration rate. As the simplest way to introduce stochasticity, we assumed that migration rates are represented by random values, uniformly distributed between zero and double the average rate. To analyze the results, we averaged the results of 50 5000-year runs and compared changes in the areas occupied by PFTs with changes calculated in the absence of migration variance.

2.5 Data

The model uses the climate parameters listed in section 2.1. All values of those parameters were derived from the IIASA climate database (Leemans and Cramer, 1991) and the IPCC climate change scenarios (Greco, et al. 1994) and distributed on a geographic grid of 0.5 x 0.5 degrees of latitude and longitude. For each of the 5 climate parameters we generated a time course by linear interpolation using the values at the three times selected by Greco, et al. (1994) for simulation decades 0, 6, and 8. We assumed that after the 8th decade climate does not change. This supposition enables us to estimate the relaxation time for model variables in a steady-state environment and therefore to evaluate the aftereffects of the lagged variables. The migration rates of vegetation used in the model are based on the mean tree migration rates documented in the paleoecological literature (e.g., Davis, 1976, 1983; Huntley and Birks, 1983; Gear and Huntley, 1991; King and Herstrom, 1996). These were 10 - 35 km per century, varying with each PFT.

3. RESULTS AND DISCUSSION

The deterministic model generated the greatest changes in simulated vegetation during the initial 500 years (see Kirilenko and Solomon, 1997, for details). During the first 50 years, wooded tundra, steppe and desert vegetation begin to migrate. Then, during years 50 - 100, while migration of those biomes intensifies, changes in forest biomes also begin to emerge. Many of these changes appear to be associated with species withdrawal rather than with invasion.

Figure 1 illustrates the effects on biome area of deterministic migration. Here, we combined all tropical forest biomes into "hot forests", temperate and cool mixed forests into "temperate forests", and taiga and cold forests - into "cold forests". The climate scenario was generated from the MPI model. In addition to the processes of forest withdrawal from current areas and of migration into newly available areas, we also found that significant areas of the earth (up to $3 \times 10^6 \text{ km}^2$) become occupied by unique non-analog temperate forest biomes in western Europe, eastern Asia and southeastern North America. These unique biomes are transitory but exist for

a considerable amount of time. They are important primarily during the intermediate stages of migration (i.e., between 100 and 300 years). Actual immigration of forest vegetation produces the most significant changes in biome geography between the years 200 and 500. Tropical forest immigration into newly available moist areas does not occur until after the year 500.

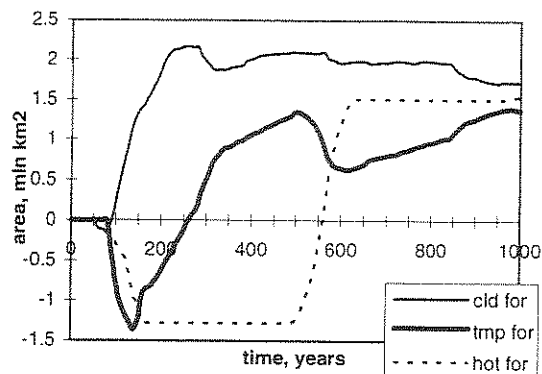


Figure 1. Deterministic simulation of area (in 10^6 km^2) occupied by forest biomes under the MPI scenario, which generated the weakest total carbon influx into the atmosphere due to changing vegetation geography. An initial carbon pulse of up to 65 Pg of carbon for MPI model (42 and 29 for GFDL and UKMO, respectively) peaked somewhere between years 100 and 200. After this initial period of carbon release of about 350 years, natural vegetation becomes a carbon sink. By year 1000, stored carbon gains about 20 Pg over the initial level.

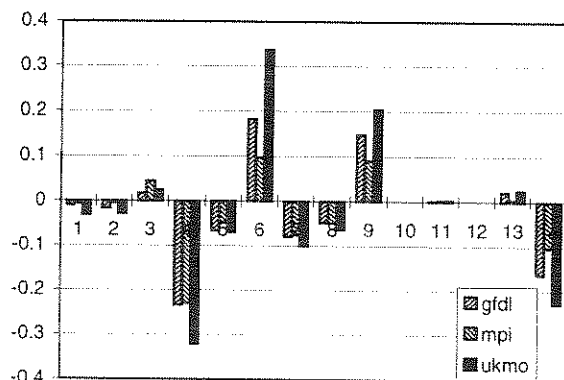


Figure 2. Areas (in 10^6 km^2) occupied by PFTs as projected by the stochastic model minus areas occupied by PFTs as projected by the deterministic model for three climate change scenarios.

However, stochasticity in migration rates changes the above results considerably. Figure 2 shows the difference between areas occupied by plant functional types calculated by the stochastic model, minus those from the deterministic models. The reaction of PFTs to "migration variation" can be separated into three classes: those reacting to "variation" by gaining area (above the abscissa), those losing area (below the abscissa), and those with neutral reactions. The first group is composed of forest vegetation (PFTs 1, 2, 4, 5, 7, 8, 14) with less reaction in tropical forests (1 and 2) and more effect in temperate forests (PFTs 4, 5, and 14). The second group

of vegetation is represented by shrubs and grasses (PFTs 3, 5, 9, and 13) with the similar pattern: less reaction in tropical (PFT 3) and Mediterranean (PFT 13) vegetation and more in temperate zone (PFT 6). Finally, the third group with neutral reaction to migration is desert vegetation (PFTs 10, 11, 12).

The changes in shrub and grass PFTs are probably controlled by differences in tree PFTs because in the absence of trees but with benign climate, shrubs and grasses assume dominance in the model, as they do in the real world. The reason for reduction of tree PFTs, however, is not so obvious. Possibly, the irregular but frequent absence of one or more related tree PFTs needed to comprise a forest biome precluded as rapid a biome appearance in newly-invaded cells, permitting grasses and shrubs to persist. The fact that most of the unique depauperate biomes (i.e., biomes missing one or more PFTs) appear in temperate forest areas (Kirilenko and Solomon, 1997) where most of the tree PFTs are least successful under stochastic migration (Fig. 2) supports this idea.

Those changes persist from the beginning to the end of the simulation, though they can be considered insignificant before year 50 and after the year 1000. The maximum difference between deterministic and stochastic models can be observed between years 100 and 500, varying between vegetation types. This difference decreases with time. However, it still exists at the end of simulation period. We can explain this effect with the fact that vegetation in the model could never reach its new equilibrium state, defined by climate.

Rapid climate change should gradually widen the distance between areas where climates suitable for each species exist and areas where growth occurs, as controlled by slower migration of those species (Solomon and Bartlein, 1992). This gap is likely to grow as long as the climate continues to change. As a result of these processes, carbon now sequestered in trees must be transferred either to the atmosphere, or to the soil for subsequent eventual release to the atmosphere (Harmon, et al., 1986). The changes in vegetation geography being discussed will certainly affect anticipated carbon release and, later, the sequestration of additional atmospheric carbon into vegetation. The simulations with stochastic migration of vegetation generally project a more significant role of forest vegetation as a transient source of carbon during the next few centuries, and, correspondingly, a greater feed-back effect from forest vegetation to anticipated global climate change, than were projected under constant migration rates.

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