CHAPTER 2

# Biome Redistribution Under Climate Change

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## Introduction/Background

General warming in the Northern Hemisphere has been recorded since the end of the 1800s following the Little Ice Age (Folland et al. 1990). Records of glacier retreat during the last 100 years over the entire globe (Oerlemans 1994) independently confirmed the recorded trend in global temperature rise. Several studies have illustrated various responses to this climate forcing, i.e., the recorded changes in temperature and precipitation concurrent with the increase in atmospheric $CO_2$ concentration, increases in density of tree populations (Morin and Payette 1984; Payette and Filion 1985; Scott et al. 1987), declines in tree populations (Hamburg and Cogbill 1988), treeline displacement (Lescop-Sinclair and Payette 1995) or lack thereof (MacDonald et al. 1998), lengthening of the growing season (Mynemi et al. 1997), and enhanced tree growth (Jacoby et al. 1996). It is critical that we identify the tools needed to estimate potential consequences of climate change on forest ecosystems (Joyce and Birdsey this volume) and develop management practices and policies adapted to projected drifts in the geographic distribution of ecosystems.

Emanuel et al. (1985), who used the Holdridge lifezone model (Holdridge 1947), and Box (1981) were among the first to use correlational models between average climate and vegetation distribution to predict the responses of vegetation to climate change using general circulation model (GCM) climate simulations. The Holdridge lifezone classification relates the distribution of major ecosystems to mean annual biotemperature, mean annual precipitation, and the ratio of potential evapotranspiration to precipitation (Holdridge 1947). It was used by several authors (Emanuel et al. 1985; Prentice and Fung 1990; Smith et al. 1992) to examine potential global shifts in major ecosystems with climate change (Dale 1997). Results from Smith et al. (1992) showed a global decrease in the extent of tundra and desert, with a concurrent increase in grassland area, under four different GCM climate change scenarios. Results also showed an increase in tropical forest area and the replacement of tundra by boreal forests. These static models offer simplicity and availability but: 1) they do not take into account seasonality; 2) they have strict climate boundaries which create problems for representing transitional vegetation; and 3) they cannot include any direct $CO_2$ effect or indicate changes in vegetation density, runoff, or nutrient fluxes.

Over 100 "gap" model studies have also been conducted to simulate the impacts of global change on forests (Smith and Shugart 1996; Dale and Rauscher 1994; Smith et al. 1992). These models predict the establishment, growth, and death of individual trees for all potential species on a site. They include a wide range of disturbances such as fire, blowdown, insect defoliation, and drought. Simple rules are used to simulate succession in most forests. Comparative studies showed that seemingly similar models could yield totally different projections of future forest composition (for example, Bugmann 1997), since there is considerable uncertainty about the appropriate formulation of environmental influences on demographic processes. Early versions of gap models had been developed for current climate. Their applicability to changing climate conditions and increasing $CO_2$ concentration was questionable (for example, Loehle and Leblanc 1996). However, a second generation of gap models was developed with improved formulations of key relationships, including physiological mechanisms, thus allowing more mechanistic calculations of environmental effects on tree growth. Functional types were used to reduce the numbers of site-specific parameters required to run the models (Friend et al. 1997). Unfortunately, there has not been enough time yet for results from climate change research with these newer models to be widely circulated and published.

Biogeography models such as DOLY (Woodward and Smith 1994), MAPSS (Neilson 1995), and BIOME2 or 3 (Haxeltine et al. 1996), which are based on ecophysiological constraints and resource limitations, have been considered the next generation of equilibrium spatial models (Monserud and Leemans 1992). They are capable of simulating impacts on natural vegetation at all scales from global to continental, regional, and local (Smith et al. 1994) and have been used in several global climate change studies (IPCC 1996; VEMAP Members 1995; Neilson et al. 1998).

The objective of this chapter is to address the following question: To what geographic extent will potential ecosystem types change or move across the United States, as measured in composition and boundary changes? To do so, we used results from three different studies (Neilson et al. 1998; VEMAP Members 1995; Neilson and Drapek 1998), which are summarized in table 2.1. Three different models (DOLY, MAPSS, BIOME2 and its later version BIOME3) were run at two spatial resolutions (half-degree latitude × half-degree longitude, and 10 km) for two geographic extents (North America and the conterminous United States). Older and newer GCM-generated climate scenarios were used to describe the impacts of

**Table 2.1—**Summarized description of the three studies used in this article to illustrate the impact of climate change on biome distribution. FAR = First Assessment Report (IPCC 1990) including climate change scenarios from GFDL-R30, GISS, OSU, UKMO; SAR = Second Assessment Report (IPCC 1996) including climate change scenarios from HADCM2SUL and HADCM2GHG (see table 3 for details on scenarios).

| Region of study (project) | Biogeography models | Resolution | Reference | Climate change scenario | Climate data source |
|---|---|---|---|---|---|
| North America | MAPSS<br>BIOME3 | 0.5° latitude × longitude | Neilson et al. 1998 | FAR and SAR | Leemans and Cramer 1991 |
| Conterminous USA (VEMAP) | MAPSS<br>DOLY<br>BIOME2 | 0.5° latitude × longitude | VEMAP Members 1995 | FAR | Kittel et al. 1995 |
| Regional USA | MAPSS | 10 km | Neilson and Drapek 1998; Borchers and Neilson 1998 | FAR and SAR | NOAA-EPA 1997 |

the improvements made in projecting future climates on ecological simulation results. The rationale for using this approach is that: 1) focusing on the entire North American continent enables us to include entire biomes regardless of political boundaries; 2) focusing on the U.S. enables us to address nationally relevant issues and to compare MAPSS results with other model projections; and 3) a 10 km resolution is a more adequate scale to focus on regional impacts. A different baseline climatic dataset was used for each of the three studies, which explains the differences between the North American study and VEMAP, both of which were performed at the same half-degree resolution. Using results from these studies increases the information gain about U.S. forests and also emphasizes the uncertainties associated with the results.

# Methodology

## Biogeography Models

### *Models*

Process-based biogeography models simulate the dominance of various plant lifeforms in different environments based on ecophysiological constraints, such as growing degree days and minimum winter temperatures, and resource limitations such as available soil water for plant uptake and available sunlight for the understory canopy (VEMAP Members 1995). These models simulate potential "climax" vegetation at steady state under any climate, past, present, or future (Neilson and Running 1996).

Most of the results presented in this chapter come from the MAPSS (Mapped Atmosphere Plant Soil System) model (Neilson 1995; Neilson and Marks 1994). It includes a water submodel that calculates plant available water and a rule-based submodel that determines the climatic zone, the lifeform, and the plant type as a function of temperature thresholds and water availability. The maximum potential leaf area index (LAI) a site can support is calculated iteratively. It uses an aerodynamic approach sensitive to canopy characteristics to calculate evapotranspiration. Grasses and trees have different rooting depths in a multi-layer soil and compete for available soil water, while shading by trees limits grass growth. Vegetation classification in MAPSS is based on the presence/absence and LAI values of three types of lifeforms—trees, shrubs, and grasses—with their leaf characteristics, thermal affinities, and seasonal phenology. The woody components, trees or shrubs, are assumed to be dominant and mutually exclusive. MAPSS includes a fire submodel that maintains transition zones such as the prairie peninsula. The model has been run at two different resolutions: 1) 10 km; and 2) half degree latitude-longitude resolution for VEMAP and the North American study.

BIOME2 and DOLY are two other biogeography models that have been compared to MAPSS in VEMAP (VEMAP Members 1995). The newer version of BIOME2, BIOME3, was later compared to MAPSS in the North American study (Neilson et al. 1998). BIOME3 builds upon BIOME2 but contains a more process-based canopy physiology, optimizing carbon gain through photosynthesis with radiation and water balance constraints on stomatal conductance. In BIOME2 and BIOME3 (Haxeltine and Prentice 1996; Haxeltine et al. 1996; Prentice et al. 1992), plant functional types (PFT) are calculated using a small set of ecophysiological constraints such as minimum temperature tolerance. Gross primary production (GPP) is calculated for each PFT as a function of photosynthetically active radiation (PAR) based on the Farquhar photosynthesis equation (Farquhar et al. 1980). GPP is then reduced by soil water availability and temperature lim-

itations. Foliar projected cover (or leaf area index, LAI, in the case of BIOME3) is calculated to maximize net primary production (NPP). Evapotranspiration is determined by available energy. Grass and woody vegetation compete for water as a function of their rooting depth in a hydrology submodel. Fire and light competition are empirically simulated in the model.

DOLY (Woodward and Smith 1994; Woodward et al. 1995) simulates photosynthesis using the Farquhar photosynthesis equation (Farquhar et al. 1980) and evapotranspiration using the Penman-Monteith equation (Monteith 1981). NPP is affected by temperature and nitrogen availability. N uptake is a function of soil carbon and nitrogen contents, temperature, and moisture. Maximum leaf area is constrained by radiation, water balance, and nitrogen.

DOLY, BIOME2, and MAPSS all incorporate some sort of direct response to changes in $CO_2$ concentration, but they differ in the specific mechanisms considered. In MAPSS, stomatal conductance is reduced by elevated $CO_2$ concentration, which leads to a reduction in evapotranspiration and—indirectly—increased LAI. The model, however, does not allow for any direct $CO_2$ effect on the competitive balance between C3 and C4 grasses. In BIOME2, the impact of $CO_2$ concentration is included in the photosynthesis algorithm where it can affect C3 vs. C4 competition, but does not directly affect water balance. DOLY includes $CO_2$ concentration in the calculation of photosynthesis and evapotranspiration, but does not include a direct $CO_2$ effect on the competitive balance between C3 and C4 grasses. Additional information on the models can be found in VEMAP Members (1995) where detailed comparison tables summarize their differences.

The models require latitude (BIOME), mean monthly or daily (DOLY model only) temperature, precipitation, humidity (DOLY and MAPSS), wind speed (DOLY and MAPSS), and solar radiation (BIOME and DOLY). MAPSS and BIOME3 were driven in the North American study by a baseline long term average monthly climate dataset, which corresponds to an improved version of that described in Leemans and Cramer (1991), and was obtained from the Cramer and Leemans database (W. Cramer, personal communication). In VEMAP, the three biogeography models (MAPSS, BIOME2, and DOLY) used a baseline dataset that was interpolated from a large number of U.S. weather stations (4613) and is described in Kittel et al. (1995). The method used to create the baseline climate dataset used by MAPSS at the 10 km-resolution is described in detail in Borchers and Neilson (1998). The dataset includes information between 1211 and 4613 stations (depending on the variable calculated) from the conterminous United States (NOAA/NGDC 1997).

The models also require soil texture (sand, silt, clay fraction) and soil characteristics such as depth and rock fragment content. U.S. soils data are based on the 10 km gridded National Soil Geographic (NATSGO) data base modified by Kern (1994, 1995). For the VEMAP project, cluster analysis grouped the 10 km subgrid elements into one to four dominant soil types for each half degree cell. Cell soil properties were then represented by one or more dominant soil profiles rather than by the average one that may not correspond to an actual soil in that region. For the runs over North America, the digital version of the FAO soils map of the world was used.

## *Vegetation Types*

MAPSS includes 45 vegetation types. In VEMAP, Küchler's (1964) map of potential vegetation was aggregated to 22 classes. To simplify result analysis in this chapter, we used a simplified classification aggregated into 10 vegetation categories. Table A1 in Appendix A illustrates the correspondence between our simplified categories, the MAPSS vegetation types, and the VEMAP classes. Table 2.2 summarizes the thresholds that MAPSS uses to distinguish the vegetation categories.

Tundra and Taiga-Tundra exist beyond the climatic limit of the boreal forest. Beyond treeline, the cold-dominated landscapes with permanently frozen soils are characterized by tundra vegetation composed of shrubs, grasses, mosses, and lichens. Cryptogams are abundant. The boreal forest-tundra ecotone corresponds to the taiga-tundra zone, which can extend up to 235 km in width in central Canada and 300 km in Quebec. It corresponds to the limit beyond which the forest tree life cycle is interrupted and sexual regeneration is either irregular or unsuccessful (Lenihan and Neilson 1993). This vegetation category in MAPSS also includes the high-altitude alpine ecosystem located mostly in the western third of the United States. It is sometimes called "alpine tundra" because migrations of arctic plants during Pleistocene and Holocene resulted in alpine floras with a strong arctic component. However, the alpine flora can be much more diverse and richer than the arctic flora. Only low growing season temperatures are in common with the arctic tundra, and much variation exists in their physical environments (solar radiation, daylength, soil, snowpack, topography). It is located above the upper limits of forests and consists mostly of dwarf shrubs and short perennial herbaceous plants.

The boreal coniferous forest is constrained by cold temperatures to the north which limit forest stature and reproduction. The southern limits of the boreal coniferous forest are generally defined by their juxtaposition with temperate forests or with interior savanna woodlands and grasslands. Boreal tree species can generally grow further south but are outcompeted by temperate hardwoods and conifers, which are limited by cold temperatures from spreading further north (Lenihan and Neilson 1993; Starfield and Chapin 1996). As with tundra and taiga-tundra, there is a mid-latitude equivalent of

**Table 2.2—**Summary of the rules used to define the simplified vegetation classes in MAPSS. Under cold conditions, energy constraints are represented by the sum of growing degree days. For milder conditions, minimum monthly temperatures (or their equivalent), LAI, duration of the growing season, and associated available water are used to classify the vegetation. A monthly mean temperature of –16°C is approximately equivalent to an absolute minimum temperature of –40°C, the supercooled freezing point at water which limits the northward spread of most temperate deciduous trees. A monthly mean temperature of 13°C separates subtropical regions, where some frost occurs during the year, from tropical regions where no frost occurs during the year. Forests are assumed to have an LAI value greater than 3.75. Dry summers (mean summer precipitation below 40mm) characterize temperate evergreen forests. When there is enough rainfall in the summer but the growing season is too short, the vegetation is classified as short temperate mixed forests. We use the ratio of AT over LAI as an index of growing season productivity required to meet year-long respiration demand, to characterize the growing season length. GDD = growing degree days (base 0°C); MMT = monthly mean temperature; LAI = leaf area index with LAIg for grass LAI, LAIs for shrub LAI, and LAIt for tree LAI; MSR = minimum summer rainfall; AT = actual transpiration.

| Vegetation classes | GDD (°C) | MMT (°C) | LAI | MSR (mm) | AT/ LAI |
|---|---|---|---|---|---|
| Tundra | < 735* | | | | |
| Taiga - Tundra | 735* < GDD < 1330* | | | | |
| Boreal coniferous forest | > 1330* | < –16 | $LAI_t$ => 3.75 | | |
| Temperate evergreen forest | | –16 =< MMT < 14 | $LAI_t$ => 3.75 | < 40 | |
| Temperate mixed forest | | –16 =< MMT < 14 | $LAI_t$ => 3.75 | > 40 | < 10 |
| Tropical broadleaf forest | | > 14 | $LAI_t$ => 3.75 | | |
| Savanna woodland | | | 2 < $LAI_t$ < 3.75 | | |
| Shrub woodland | | | $LAI_s$ > 0.7 | | |
| Grasslands | | | $LAI_g$ > 0.1 | | |
| Arid lands | | | $LAI_g$ < 0.1 | | |

*For alpine rather than boreal environments, GDD thresholds used are 615 and 1165°C.

this vegetation type in high mountainous terrain. In the North American study, taiga, tundra and boreal forest vegetation types are mostly referred to as arctic types. In the VEMAP and 10 km-resolution study, the three types only correspond to their mid-latitudinal definitions.

Temperate evergreen forests, such as in the northeast U.S., tend to occur in areas that are warm enough for photosynthesis during the cool parts of the year, but that are often too cold for deciduous species to fix sufficient carbon during the frost-free season (Woodward 1987). Areas with dry summers, such as the Pacific Northwest, also tend to favor conifers or hardwoods with water conserving leaves (Waring and Schlesinger 1985; Neilson 1995). Summer drought and winter chilling required for seed set and to confer frost hardiness are critical climate factors rendering these forests sensitive to global warming (Franklin et al. 1991). Temperate mixed forests (mixed hardwood and conifer) are bound by cold temperatures to the north and the subtropical dry regions to the south (Caribbean coast in North America). They tend to occur in areas that are wet all year. The southeastern U.S. pines within this type are among the most important commercial species on the continent. Tropical broadleaf forests are currently confined to the subtropical regions of Central America.

Grasslands are the largest of the natural biomes in the United States, covering more than 125 million ha (Barbour and Billings 1988). Most of the productive arable lands in North America are former grasslands. They include the tall-grass, mixed-grass, and short-grass prairies of the central plains, the desert grasslands of the Southwest, the California grassland and the Palouse prairie in the Intermountain West. Their climates have distinct wet and dry seasons and are noted for temperature and precipitation extremes. Periodic drought and fire are important processes for limiting woody encroachment into grasslands. Arid **l**ands**,** or deserts, have warm to cool climates with low rainfall and high rates of evaporation. North American deserts are often thought of as semi-desert because of their relatively lush vegetation. Savanna **w**oodland is a broad class ranging from almost closed-canopy woodlands to very open grasslands with occasional trees. It includes pinyon-juniper woodlands, oak scrub, and the prairie peninsula region in Illinois and Indiana. Shrub **w**oodland includes the sagebrush steppe of the Intermountain West and the Southwestern chaparral and mesquite woodlands.

## Climate Change Scenarios

### *FAR Scenarios*

Most published climate change impact studies have been based on equilibrium experiments from a set of

Atmospheric General Circulation Models (GCM) with simple mixed-layer oceans and prescribed land-surface properties that were run with doubled $CO_2$ radiative forcing. Doubled $CO_2$ radiative forcing (2 x $CO_2$) includes about 50 percent actual $CO_2$ forcing, and other greenhouse gases account for the remainder. At the time of the First Assessment Report (FAR) of the IPCC (Intergovernmental Panel on Climate Change) (IPCC 1990), scenarios of future climate were produced by running those GCMs to equilibrium and producing an average climate for both current and doubled $CO_2$ conditions (Cubasch and Cess 1990). Simulations presented in this paper rely upon such scenarios generated by the UKMO (Mitchell and Warrilow 1987), GFDL-R30 (IPCC 1990), GISS (Hansen et al. 1988), and OSU (Schlesinger and Zhao 1989) models. FAR climate scenarios were supplied by the Data Support Section within the Scientific Computing Division of the National Center for Atmospheric Research (NCAR).

## SAR Scenarios

Recent climate change impact studies have been based on GCM transient $CO_2$ experiments with coupled atmosphere and ocean. By the Second Assessment Report (SAR) of the IPCC (Gates et al. 1996), the atmospheric-oceanic GCMs were simulating time series of climatic changes and some included sulfate aerosols that could regionally cool the climate. Some of the analyses presented in this chapter relied on such simulations from the Hadley Centre (Johns et al. 1997; Mitchell et al. 1995; IPCC 1996): HADCM2GHG scenario and HADCM2SUL scenario with sulfate aerosols. These scenarios were extracted from transient GCM simulations in which trace gases were allowed to increase gradually over a long period of years, allowing the climate to adjust while incorporating inherent lags in the ocean-atmosphere systems.

## Spatial and Temporal Resolution of the Scenarios

The coarse grid of the GCM scenarios was interpolated to a half degree latitude-longitude resolution or a 10 km Albers grid using a 4 point inverse distance squared algorithm in a raster-based Geographic Information System (U.S.A.-CERL 1993). Ratios ($(2 \times CO_2) / (1 \times CO_2)$) were applied to all climate variables (except temperature) from a baseline long-term average monthly climate dataset (Leemans and Cramer 1991). Ratios were used to avoid negative numbers, but were not allowed to exceed 5 to prevent unrealistic changes in regions with normally low rainfall. Temperatures were calculated as a difference $(2 \times CO_2) - (1 \times CO_2)$ and applied to the baseline climate dataset.

The control climate ($1 \times CO_2$) was extracted from transient GCM simulations as a 30-year model output average associated with present climate (1961–1990). The future climate ($2 \times CO_2$) scenario was extracted as a 30-year average from the time period approximating $2 \times CO_2$ forcing (2070–2099) when simulations had only attained about 64 percent to 68 percent of the eventual equilibrium temperature change, due to thermal lags in the oceans. Therefore, the two Hadley scenarios discussed here produced relatively modest warming compared to other SAR scenarios.

## Description of the Scenarios

FAR climate scenarios are described in detail in Cubasch and Cess (1990). Over the conterminous United States, the OSU scenario is the coolest with small increases in precipitation, the GISS is warm and relatively dry, the GFDL-R30 is warm and extremely wet, and the UKMO scenario is very warm and moderately wet (table 2.3). Over the land areas of the world, the OSU scenario is still the coolest but quite wet. Both GISS and GFDL-R30 are warm and wet, and UKMO is hot and drier than the three other scenarios.

The SAR climate scenarios from Hadley Centre are in general cooler scenarios (table 2.3) both over the North American land areas (Kattenberg et al. 1996) and over the United States. The sulfate aerosol scenario is very dry over the world but quite wet over the United States. Addi-

**Table 2.3—**Simulated changes in temperature (°C) and precipitation (percent) over the world land area and over the conterminous U.S. From the First Assessment Report (FAR) of the Intergovernmental Panel on Climate Change (IPCC), the atmospheric general circulation models (GCMs) used to simulate climate were: the Oregon State University model (OSU), the Goddard Institute of Space Studies (GISS) model, the Geophysical Fluid Dynamics Laboratory model (GFDL-R30), and the United Kingdom Meteorological Office model (UKMO). From the Second Assessment Report (SAR) of the IPCC, the atmospheric-oceanic GCM used to simulate climate was the Hadley Centre Transient general circulation model with (HADCM2SUL) and without (HADCM2GHG) sulfate aerosol forcing.

| | Temperature (°C) | | Precipitation (%) | |
|---|---|---|---|---|
| | World | U.S. | World | U.S. |
| FAR scenarios | | | | |
| OSU | 3.0 | 3.0 | 20.9 | 2.1 |
| GISS | 4.3 | 4.4 | 16.0 | 5.1 |
| GFDL-R30 | 3.9 | 4.2 | 18.7 | 18.9 |
| UKMO | 6.0 | 6.6 | 15.1 | 11.3 |
| SAR scenarios | | | | |
| HADCM2GHG | 4.3 | 3.7 | 13.2 | 30.7 |
| HADCM2SUL | 3.5 | 2.8 | 1.7 | 22.9 |

tional descriptions and comparisons of FAR and SAR scenarios can be found in Neilson and Drapek (1998).

# Results

## North American Impacts

### *Effects of $CO_2$: MAPSS Results With FAR Scenarios*

Results from running the equilibrium vegetation distribution model MAPSS for the North American region (half degree latitude-longitude resolution) with and without a $CO_2$ effect for three GCM scenarios are illustrated in table 2.4. Major agreements can be identified: 1) decreases in the area of both tundra and taiga-tundra (from 42 to 70 percent and from 39 to 56 percent respectively); 2) increases in the areal extent of savannas (from 14 percent with the $CO_2$ effect to 125 percent without); and 3) decreases in the area of shrublands (from 2 to 20 percent). When the $CO_2$ effect is included (35 percent decrease in stomatal conductance), temperate evergreen and temperate mixed forests are predicted to increase in area, with the largest increases predicted under the UKMO scenario (80 percent and 41 percent respectively).

### *Comparison Between BIOME3 and MAPSS Using SAR Scenarios*

MAPSS simulations using the Hadley Centre scenarios (HADCM2SUL and GHG) are compared to those of BIOME3 in table 2.5. The models predict opposite trends for both the boreal coniferous forest and the temperate evergreen forest. BIOME3 groups boreal forest and taiga-tundra into one vegetation type while MAPSS does not. MAPSS predicts large decreases in the taiga-tundra area (eastern Canada and Alaska, fig. 2.1), which matches BIOME3 simulations of boreal forest area increase, but MAPSS also simulates small increases in the boreal forest area proper. Thus, the two models are consistent with each other with respect to high-latitude ecosystems, with apparent differences only indicating different classification schemes. For all scenarios, both models agree on simulating: 1) large decreases in the area of pure tundra replaced by the warmer taiga-tundra; 2) large increases in the temperate mixed forest (table 2.5) moving westward in the United States and northward into Canada (fig. 2.1); and 3) large decreases in the area of arid lands (table 2.5) that are replaced by grasslands (fig. 2.1). When the $CO_2$ effect is not included in the models, both simulate increases in the extent of savannas and grasslands.

With the HADCM2SUL scenario, MAPSS simulates large shifts of Northwest temperate evergreen forests to Alaska replacing the taiga-tundra area (fig. 2.1) but BIOME3 shows a much smaller expansion (not shown here, fig. C-4 and 5 in Neilson et al. 1998). They both simulate an expansion of the southeastern temperate mixed forest at its western edge.

## Conterminous U.S. Impacts

### *Comparison Between DOLY, BIOME2, and MAPSS Using FAR Scenarios*

Three biogeographical models (DOLY, BIOME2, and MAPSS) were used to simulate vegetation distribution for current climate conditions and future climate conditions under three different GCMs. The three biogeography models produce similar maps of current vegetation distribution. Whether the $CO_2$ effect is included or not, MAPSS and BIOME2 simulate a loss of alpine tundra and boreal coniferous forest area (table 2.6). DOLY simulates an increase in alpine tundra when the $CO_2$ effect is included for all climate change scenarios. DOLY only simulates an increase in the extent of the boreal coniferous forest under the OSU scenario when the $CO_2$ effect is included. When the $CO_2$ effect is not included, MAPSS simulates a decrease in temperate forests accompanied by an increase in savannas and grasslands; on the other hand, BIOME2 simulates an increase in temperate forests and tropical broadleaf forest areas at the expense of savannas, shrublands, and arid lands. Both DOLY and MAPSS simulate increases in arid land area. DOLY produces a greater expansion of forests into the Great Plains and produces little forest dieback under altered climate (not shown here). However, DOLY also produces far more dramatic increases in the extent of Southwest deserts than either MAPSS or BIOME2 (table 2.6). The only general agreements in VEMAP for all scenarios and all models are that shrubland area decreases when the effect of $CO_2$ is included, and when it is not, tundra and boreal forest areas decrease. A more detailed analysis of these results is presented in Neilson and Chaney (1997).

### *Effects of $CO_2$: MAPSS Results with FAR Scenarios*

There are large differences between MAPSS results whether the effect of $CO_2$ is included or not. For example, MAPSS simulated large decreases (40–80 percent) in the area of temperate mixed forest in the eastern United States for "warmer" scenarios such as the UKMO and GFDL when the $CO_2$ effect was not included. These decreases were greatly reduced (12–14 percent) when water use effi-

**Table 2.4—**Percentage of simulated area for each simplified vegetation type under current climate for North America at a half degree latitude-longitude resolution by the biogeography model MAPSS. Total area is 18,923 $10^3$ $km^2$. Percentage change in area for each vegetation type from current climate to future climate conditions with no $CO_2$ effect (A) and with $CO_2$ effect (B). Percentage change in vegetation type area is calculated as: (scenario – current)/current. The atmospheric general circulation models used to simulate climate (FAR scenarios) were: the Oregon State University model (OSU), the Geophysical Fluid Dynamics Laboratory model (GFDL-R30), and the United Kingdom Meteorological Office model (UKMO).

| | Current (% of total land area) | OSU (Δ %) | GFDL-R30 (Δ %) | UKMO (Δ %) |
|---|---|---|---|---|
| A. With no $CO_2$ effect: | | | | |
| Tundra | 16 | –42 | –58 | –70 |
| Taiga–Tundra | 16 | –39 | –39 | –56 |
| Boreal coniferous forest | 16 | +18 | +40 | –15 |
| Temperate evergreen forest | 7 | –3 | –6 | +8 |
| Temperate mixed forest | 16 | –18 | +49 | –28 |
| Savanna woodland | 12 | +71 | +104 | +125 |
| Shrub woodland | 7 | –4 | –2 | –10 |
| Grassland | 9 | +36 | +59 | +114 |
| Arid land | 2 | +100 | –3 | +113 |
| B. With $CO_2$ effect: | | | | |
| Tundra | 16 | –42 | –58 | –70 |
| Taiga–Tundra | 16 | –39 | –39 | –56 |
| Boreal coniferous forest | 16 | +35 | +50 | –13 |
| Temperate evergreen forest | 7 | +34 | +30 | +80 |
| Temperate mixed forest | 16 | +29 | +7 | +41 |
| Savanna woodland | 12 | +14 | +44 | +52 |
| Shrub woodland | 7 | –15 | –20 | –2 |
| Grassland | 9 | –<1 | +23 | +45 |
| Arid land | 2 | +5 | –64 | +17 |

ciency was increased (table 2.6). With a milder scenario like OSU, these forests could even increase in their extent by about 10 percent if stomatal conductance is reduced up to 35 percent by elevated $CO_2$ concentration as it is assumed in MAPSS (table 2.6). In the early stages of warming, when temperature increases are small, a $CO_2$-induced increase in water use efficiency could result in an expansion of temperate forests into neighboring drier areas, and a concurrent increase in forest density throughout much of the current forest distribution. However, as the $CO_2$ effects saturate and temperatures continue to increase, the elevated evaporative demand could then overwhelm the increased water use efficiency, and temperate forests could contract in area and undergo a drought-induced decline in vegetation density (Neilson and Drapek 1998). Complex responses of the vegetation to changes in their climatic environment and in the atmospheric $CO_2$ concentration are to be expected. Early responses to the $CO_2$ fertilization effect leading to a greening of the land may be followed by forest diebacks due to increased warming and drought stress.

## Regional Impacts

### *Results From MAPSS and Other Models Using FAR and SAR Scenarios*

MAPSS simulations at the 10 km resolution using the Hadley Centre sulfate aerosol scenario (fig. 2.1 and table 2.7) show that coniferous forests in northern Minnesota, Wisconsin, and Michigan (upper peninsula) are displaced by temperate mixed forests expanding from the east and south. For all FAR scenarios, MAPSS simulates large decreases in the temperate mixed forest and boreal forest area around the Great Lakes region, which are replaced by savannas and grasslands (figs. 2.1 and 2.2). With "warm" climate change scenarios such as the UKMO and, to a lesser extent, the GFDL-R30, MAPSS simulates the fragmentation of the southeastern temperate mixed forest, which is replaced by drier ecosystems such as savannas and grasslands (fig. 2.2). With cooler scenarios such as OSU, MAPSS simulates an increase in forested areas in and around the Willamette Valley in the Pacific North-

west and on the western edge of the southeastern forests (fig. 2.2). Mesquite-oak woodlands, currently in central Texas, would shift north into the Great Plains region while the grasslands would replace the semi-deserts of eastern Texas, southern New Mexico, western Arizona, and eastern California. Under the UKMO scenario (fig. 2.2 and table 2.7), southwestern warm-desert species could extend into cold-desert regions as far north as eastern Oregon and Washington, or in the case of the OSU scenario (fig. 2.2) remain about where they are today.

Mean annual temperatures have increased globally by 0.5°C per century, and by 1.2°C in the southwestern desert region of the United States between 1901 and 1987 (Lane et al. 1994). Emanuel et al. (1985) suggested a possible future increase of up to 17 percent in desert land area of North America. Predictions from VEMAP Members (1995) simulations (half degree latitude-longitude resolution), including both climate change and increased $CO_2$, show both decreases and increases in the areal extent of subtropical shrublands (southwestern deserts). Since thermal constraints have kept southwestern species from moving northward, an increase in temperature at higher latitude and sufficient available water should enable those desert species to reach the Great Basin area. In fact, MAPSS simulates a northern migration and expansion of subtropical mixed shrub savannas into the Great Basin region and as far north as eastern Washington. Yet, expansion of desert species does not necessarily imply increased desertification. In fact, MAPSS simulates up to a 200 percent increase in leaf area index (primarily grassland) in the southwestern desert region of the United States where grasses can outcompete shrubs under future wetter conditions.

Comparisons between MAPSS and the PnET model (Aber and Federer 1992) over the Southeast are consistent in terms of forest decline, but not in terms of runoff (Borchers and Neilson 1998). PnET simulated increases in annual runoff from 10 to 240 percent, as evapotranspiration was altered by climate change scenarios, and forest death was occurring without replacement (McNulty et al. 1994). PnET does not include an understory; thus when forests decline, no other vegetation types replace them and runoff increases. In MAPSS, when forests decline, shrubs and grasses increase and may use as much or more water, producing declines in runoff. PnET also simulated severe reductions in annual NPP on loblolly pine sites in Texas (–55 percent), Mississippi (–35 percent), Florida (–60 percent), and Virginia (–15 percent) with climate scenarios based on historical records from 1951 to 1984 (Aber et al. 1995; McNulty et al. 1994, 1996a and b).

Even in regions where the vegetation type would not change, it could either increase in density or decline. Where vegetation density, characterized in MAPSS by leaf area, is decreasing, some level of vegetation dieback (if forested) can be expected or at least a reduction in

**Table 2.5—**Percentage of simulated area for each simplified vegetation type under current climate (A) for North America at a half degree latitude-longitude resolution by the biogeography models MAPSS and BIOME3. Total area is 18,923 $10^3$ km$^2$. Percentage change in area for each vegetation type from current climate to future climate conditions with no $CO_2$ effect (B) and with $CO_2$ effect (C). Percentage change in vegetation type area was calculated as: (scenario – current)/current. The atmospheric general circulation model used to simulate climate (SAR) was the Hadley Centre model without aerosols (HADCM2GHG) and with sulfate aerosols (HADCM2SUL). BIOME3 groups together boreal forest and taiga-tundra. (+++ denotes a vegetation type that did not exist in current climate conditions. NA corresponds to a vegetation type that did not exist in either current or future climates.)

| A. Current climate: | MAPSS | BIOME3 |
|---|---|---|
| Tundra | 16 | 17 |
| Taiga–Tundra | 16 | |
| Boreal coniferous forest | 16 | 33 |
| Temperate evergreen forest | 7 | 6 |
| Temperate mixed forest | 16 | 20 |
| Tropical broadleaf forest | 0 | 0 |
| Savanna woodland | 12 | 6 |
| Shrub woodland | 7 | 8 |
| Grassland | 9 | 8 |
| Arid land | 2 | <0.1 |

| B. Future climate with no $CO_2$ effect: | No aerosols | | Sulfate aerosols | |
|---|---|---|---|---|
| | MAPSS | BIOME3 | MAPSS | BIOME3 |
| Tundra | –45 | –47 | –37 | –42 |
| Taiga–Tundra | –44 | NA | –41 | NA |
| Boreal coniferous forest | +10 | –32 | +12 | –24 |
| Temperate evergreen forest | +29 | –18 | +28 | –167 |
| Temperate mixed forest | +29 | +59 | +34 | +42 |
| Tropical broadleaf forest | NA | +++ | NA | +++ |
| Savanna woodland | +29 | +94 | +12 | +84 |
| Shrub woodland | –11 | +10 | +10 | +14 |
| Grassland | +46 | +19 | +15 | +23 |
| Arid land | –22 | –100 | –2 | –100 |
| C. Future climate with $CO_2$ effect: | | | | |
| Tundra | –45 | –47 | –37 | –42 |
| Taiga – Tundra | –44 | NA | –41 | NA |
| Boreal coniferous forest | +16 | –36 | +15 | –26 |
| Temperate evergreen forest | +82 | –22 | +82 | –15 |
| Temperate mixed forest | +57 | +98 | +52 | +79 |
| Tropical broadleaf forest | +++ | +++ | +++ | +++ |
| Savanna woodland | +2 | +20 | –1 | +11 |
| Shrub woodland | –22 | –<1 | +1 | +8 |
| Grassland | –3 | +6 | –30 | –5 |
| Arid land | –78 | –100 | –70 | –100 |

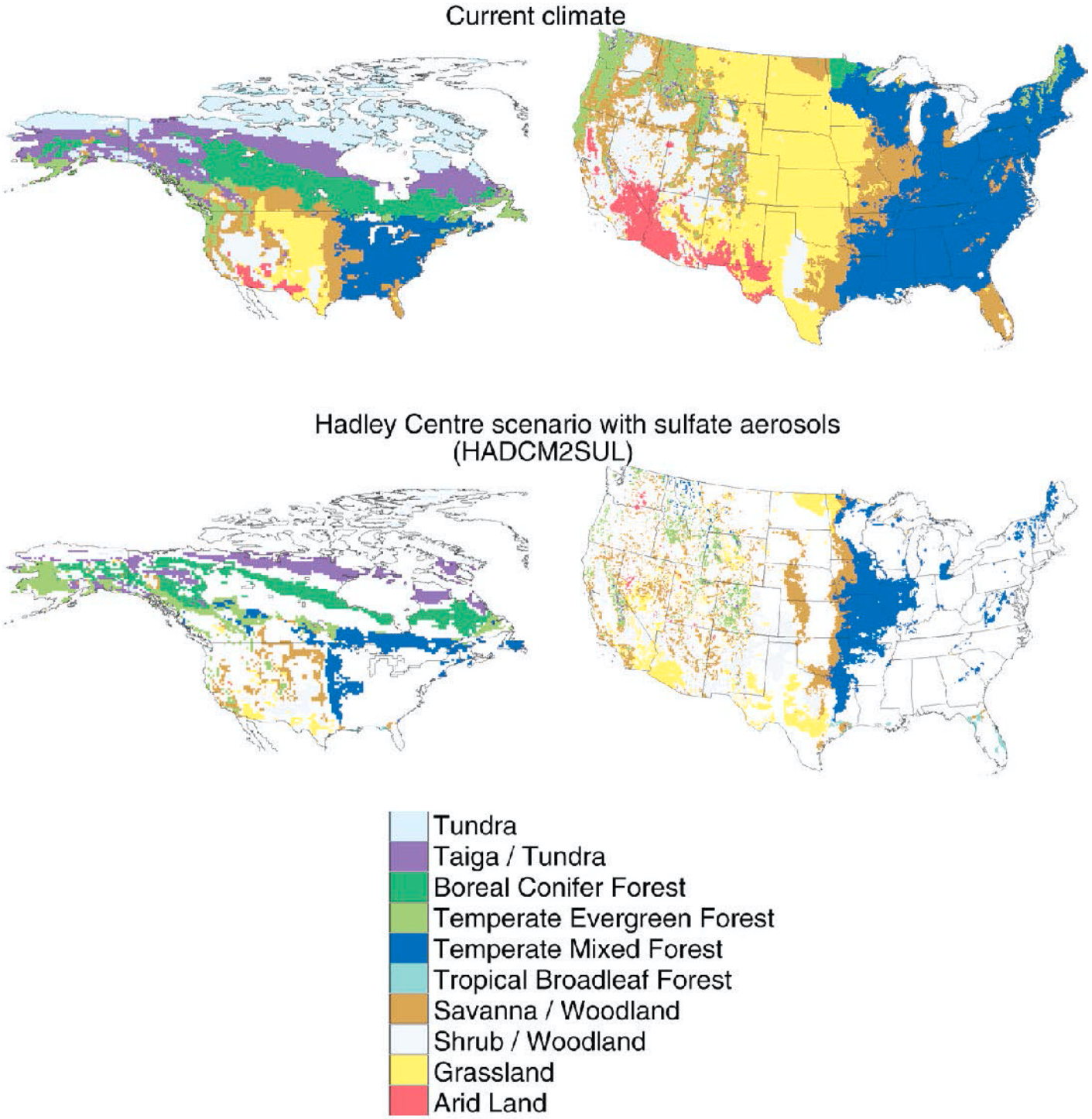


**Figure 2.1**–Top: Aggregated potential vegetation classes simulated for the North American region at a half degree latitude-longitude resolution and for the United States at a 10 km resolution for current climate conditions. Bottom: Areas where new vegetation classes are simulated in future climate conditions by the MAPSS model using the Hadley Centre climate change scenario including sulfate aerosols (HADCM2SUL). Areas where there is no change in vegetation type remain white.

the standing crop. Both FAR and SAR scenarios indicate that relatively large regions of the United States would undergo such reductions or increases (Neilson et al. 1998). However, "hotter," more severe scenarios, such as UKMO, indicate vegetation dieback or standing crop reduction over most of the U.S.

## *More Detailed Considerations About U.S. Forests With FAR and SAR Scenarios*

Neilson and Chaney (1997) translated the MAPSS vegetation types into forest type categories (MAPSS assess-

**Table 2.6—**Percentage of simulated area for each simplified vegetation type under current climate in the conterminous U.S. at a half degree latitude-longitude resolution for the VEMAP Project (A). Three biogeography models were used: MAPSS, BIOME2, and DOLY. Total area is 7,524 $10^3$ $km^2$. Percentage change in area for each vegetation type from current climate to future climate conditions with no $CO_2$ effect (B) and with $CO_2$ effect (C). Percentage change in vegetation type area is calculated as: (scenario – current)/current. The atmospheric general circulation models used to simulate climate (FAR) were: the Geophysical Fluid Dynamics Laboratory model (GFDL-R30), the Oregon State University model (OSU), and the United Kingdom Meteorological Office model (UKMO). (+++ denotes a vegetation type that did not exist in current climate conditions. NA corresponds to a vegetation type that did not exist in current climate conditions and does not exist either in future climate conditions.)

| Vegetation classes | MAPSS | BIOME2 | DOLY |
|---|---|---|---|
| A. Current climate: | | | |
| Tundra | <1 | 1 | <1 |
| Boreal coniferous forest | 2 | 2 | 3 |
| Temperate evergreen forest | 9 | 9 | 8 |
| Temperate mixed forest | 34 | 34 | 31 |
| Tropical broadleaf forest | 0 | <1 | 0 |
| Savanna woodland | 12 | 12 | 19 |
| Shrub woodland | 12 | 16 | 17 |
| Grassland | 27 | 19 | 17 |
| Arid land | 4 | 5 | 5 |

| | MAPSS | | | BIOME2 | | | DOLY | | |
|---|---|---|---|---|---|---|---|---|---|
| Vegetation classes | GFDL | OSU | UKMO | GFDL | OSU | UKMO | GFDL | OSU | UKMO |
| B. Future climate with no $CO_2$ effect: | | | | | | | | | |
| Tundra | –100 | –100 | –100 | –10 | –86 | –100 | –67 | –67 | –100 |
| Boreal coniferous forest | –100 | –87 | –100 | –81 | –63 | –94 | –79 | –33 | –83 |
| Temperate evergreen forest | –10 | –49 | –78 | +119 | +76 | +24 | –19 | –56 | –32 |
| Temperate mixed forest | –69 | –39 | –82 | +54 | +37 | +23 | +16 | –8 | +6 |
| Tropical broadleaf forest | NA | NA | NA | +113 | +167 | +533 | NA | NA | NA |
| Savanna woodland | +97 | +31 | +136 | –47 | –58 | –49 | +13 | –4 | –20 |
| Shrub woodland | +8 | +17 | –15 | –79 | –40 | –66 | –41 | –60 | –22 |
| Grassland | +48 | +39 | +71 | –25 | –16 | +45 | –7 | +62 | –24 |
| Arid land | +17 | +90 | +80 | –83 | –32 | –32 | +97 | +167 | +287 |
| C. Future climate with $CO_2$ effect: | | | | | | | | | |
| Tundra | –100 | –100 | –100 | –100 | –86 | –100 | +133 | +33 | +67 |
| Boreal coniferous forest | –100 | –87 | –100 | –81 | –63 | –94 | –54 | +25 | –63 |
| Temperate evergreen forest | +142 | +84 | +3 | +111 | +66 | +21 | –16 | –53 | –30 |
| Temperate mixed forest | –12 | +9 | –14 | +59 | +45 | +40 | +24 | +<1 | +16 |
| Tropical broadleaf forest | NA | NA | NA | +133 | +167 | +533 | NA | NA | NA |
| Savanna woodland | +15 | –23 | +29 | –48 | –57 | –58 | –4 | –17 | –30 |
| Shrub woodland | –25 | –20 | –10 | –77 | –37 | –59 | –25 | –40 | 0 |
| Grassland | –17 | –17 | +21 | –33 | –32 | +12 | –8 | +49 | –30 |
| Arid land | –57 | +3 | –40 | –76 | –22 | –22 | +28 | +95 | +182 |

**Table 2.7—**Percentage of simulated area for each vegetation type under current climate in the conterminous U.S. at a 10 km resolution by the biogeography model MAPSS and percentage change in area for each vegetation type from current climate to future climate conditions with no $CO_2$ effect (A) and with $CO_2$ effect (B). Total area is 7,706 $10^3$ $km^2$. The atmospheric general circulation models used to simulate climate were: the Goddard Institute for Space Studies (GISS), the Geophysical Fluid Dynamics Laboratory model (GFDL-R30), the Oregon State University model (OSU), the United Kingdom Meteorological Office model (UKMO), and the Hadley Centre model without aerosols (HADCM2GHG) and with sulfate aerosols (HADCM2SUL). Note: in B, Current (climate) is without $CO_2$ effect. Percentage change in vegetation type area is calculated as: (scenario – current)/current.

| | Current (%) | GISS | GFDL | OSU | UKMO | CM2GHG | CM2SUL |
|---|---|---|---|---|---|---|---|
| A. No $CO_2$ effect: | | | | | | | |
| Tundra | <1 | –92 | –96 | –81 | –100 | –96 | –92 |
| Taiga – Tundra | <1 | –89 | –87 | –67 | –96 | –89 | –83 |
| Boreal coniferous forest | <1 | –100 | –90 | –75 | –100 | –94 | –99 |
| Temperate evergreen forest | 6 | –36 | –42 | –33 | –76 | –31 | –31 |
| Temperate mixed forest | 30 | –42 | –88 | –55 | –94 | –5 | +5 |
| Savanna woodland | 16 | +31 | +122 | +35 | +79 | +9 | –8 |
| Shrub woodland | 14 | –9 | –9 | +<1 | –<1 | –12 | +14 |
| Grassland | 28 | +30 | +39 | +38 | +56 | +19 | +4 |
| Arid land | 5 | +90 | +21 | +72 | +118 | –3 | +1 |
| B. With $CO_2$ effect: | | | | | | | |
| Tundra | <1 | –92 | –96 | –81 | –100 | –96 | –92 |
| Taiga – Tundra | <1 | –89 | –87 | –67 | –96 | –89 | –83 |
| Boreal coniferous forest | <1 | –100 | –90 | –73 | –100 | –94 | –99 |
| Temperate evergreen forest | 6 | +9 | +49 | +14 | –43 | +23 | +23 |
| Temperate mixed forest | 30 | +1 | –36 | –15 | –45 | +26 | +28 |
| Savanna woodland | 16 | +11 | +77 | +16 | +58 | +2 | –2 |
| Shrub woodland | 14 | –8 | –20 | –8 | +2 | –26 | +2 |
| Grassland | 28 | –5 | +5 | +7 | +25 | –4 | –18 |
| Arid land | 5 | +0 | –47 | +1 | +19 | –69 | –66 |

ment classes) corresponding to an aggregation of the RPA forest types. We use the same approach (table A2 in Appendix A) to present some of our results with more details about specific forest types.

With SAR scenarios, GISS, and GFDL-R30, MAPSS (at the 10 km resolution) simulates an overall increase in total forest area and small decreases (1 to 12 percent) with OSU and UKMO scenarios (table 2.8). Using either FAR or SAR scenarios, the model simulates decreases (14 to 100 percent) in northeast mixed forest area, especially mixed woodlands (100 percent), which are replaced by southeast mixed pines and hardwood forest type that are moving northward and expanding in area (by 25 to 57 percent, table 2.8). With FAR scenarios, MAPSS simulates a decrease in eastern hardwood forests (11 to 99 percent); with SAR scenarios, it simulates an increase except in the case of the oak-hickory forests, which are predicted to decrease by 16 percent when the HADCM2SUL scenario is used.

With both FAR and SAR scenarios, MAPSS simulates a large decrease in the area of western fir and spruce forests (71 to 98 percent), an increase in coastal spruce, hemlock, and redwood forests (11 to 503 percent), and an increase in western hardwoods (6 to 681 percent). With SAR scenarios, the model simulates increases in the area of other types of western forests while with FAR scenarios results are less clear. With all scenarios, the model simulates increases in tropical forest areas replacing the southeast mixed pines and hardwood forest. MAPSS also simulates decreases in arid woodland areas and increases in Mediterranean shrublands with SAR scenarios and GISS.

## Implications of Biome Redistribution Results on Ecosystem Processes

### *Carbon Pools: Sources and Sinks*

Climate change affects temperature- and moisture-controlled processes such as production and litter decomposition. Lifeform changes due to shifts in climate also affect carbon inputs. An important impact of future climate change is the projected reduction of tundra and taiga ecosystems, which may be reduced by as much as 40 to 50 percent of their present size in North America (table 2.5). The impact on the regional storage of carbon in the higher latitudes of North America may result in a shift from a net

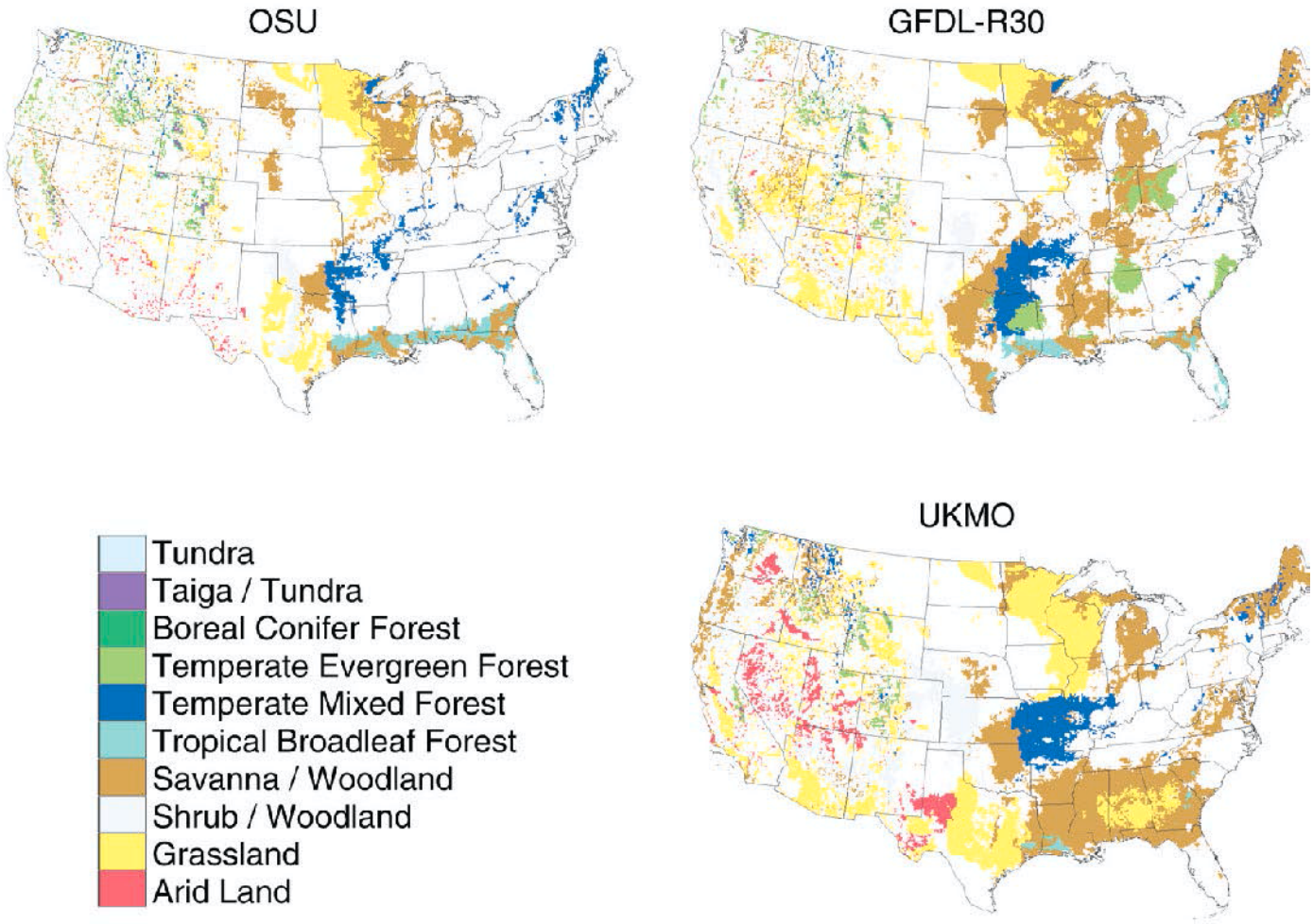


**Figure 2.2—**Areas where new vegetation classes are simulated in future climate conditions by MAPSS using 3 FAR climate change scenarios: OSU, GFDL-R30, and UKMO, in the conterminous United States at a 10 km resolution. Areas where there is no change in vegetation type remain white.

sink (sequestration of carbon) to a net source (release of carbon) of $CO_2$ (Anderson 1991; Oechel et al. 1993). Soil warming would also affect methane fluxes from tundra plant communities directly affected by drier soil surfaces and the resulting increased surface oxidation. The frozen soils of boreal forests contain one of the largest pools of carbon (Dixon et al. 1994; Gorham 1991) in the terrestrial biosphere: 200–500 Gt of carbon (1Gt = $10^9$ metric tons). Goulden et al. (1998) used eddy correlation, chamber, and laboratory techniques to measure carbon balance in a typical black-spruce boreal forest site in Canada. They concluded that the deep soil carbon pool was not in equilibrium and discussed the possibility that soil C losses might be due to climate warming since Oechel et al. (1993) already reported such findings. Projected shifts in vegetation types due to climate warming would probably accentuate soil carbon losses.

Also see Heath and Smith (this volume), Smith and Heath (this volume), Birdsey (this volume), and Skog and Nicholson (this volume) for additional discussions of carbon sequestration in forests and wood products.

## *$CO_2$ Impacts on Physiological Processes*

Elevated $CO_2$ has been documented to increase productivity, nitrogen efficiency, and water-use efficiency (IPCC 1996; Bazzaz et al. 1996). Wullschleger et al. (1995) reviewed 58 studies where a doubling of atmospheric $CO_2$ concentration resulted in a 32 percent average increase in plant dry mass. Norby (1996) studied seven broadleaf species under a doubling of atmospheric $CO_2$ concentration over a wide range of conditions, and recorded a 29 percent increase in annual growth per unit leaf area. Eamus (1991) reported reductions of leaf conductance to

**Table 2.8—**Forest area (in 1,000 km$^2$) as described by assessment classes (Neilson and Chaney 1997) under current and future climate conditions. The atmospheric general circulation models used to simulate climate were: the Goddard Institute for Space Studies (GISS), the Geophysical Fluid Dynamics Laboratory model (GFDL-R30), the Oregon State University model (OSU), the United Kingdom Meteorological Office model (UKMO), and the Hadley Centre model without aerosols (HADCM2GHG) and with sulfate aerosols (HADCM2SUL). "Current" corresponds to current climate conditions.

| Assessment classes | Current | GISS | GFDL-R30 | OSU | UKMO | CM2GHG | CM2SUL |
|---|---|---|---|---|---|---|---|
| NE mixed conifers and hardwoods | 536 | 181 | 18 | 99 | 29 | 302 | 462 |
| NE mixed woodlands | 52 | 0 | 0 | 0 | 0 | 0 | 0 |
| Maple-beech-birch | 210 | 184 | 18 | 187 | 3 | 488 | 723 |
| Oak hickory forest | 602 | 467 | 238 | 333 | 51 | 756 | 506 |
| SE mixed pines and hardwoods | 946 | 1487 | 1184 | 1333 | 1184 | 1343 | 1252 |
| Western fir-spruce | 113 | 5 | 13 | 33 | 2 | 9 | 9 |
| Douglas fir | 401 | 371 | 429 | 441 | 209 | 443 | 448 |
| Coastal spruce-hemlock-redwood | 37 | 104 | 223 | 58 | 41 | 98 | 92 |
| Western pines | 307 | 308 | 426 | 305 | 215 | 367 | 373 |
| Western hardwoods | 32 | 119 | 250 | 34 | 147 | 165 | 156 |
| Moist tropical forest | 0 | 130 | 77 | 118 | 19 | 55 | 24 |
| Dry tropical forest | 75 | 153 | 244 | 217 | 453 | 155 | 102 |
| Oak hickory woodland | 338 | 308 | 634 | 352 | 148 | 148 | 124 |
| SE mixed woodland | 188 | 113 | 366 | 214 | 770 | 72 | 91 |
| Chaparral | 39 | 80 | 40 | 30 | 143 | 42 | 73 |
| Pinyon juniper | 250 | 381 | 286 | 326 | 231 | 356 | 370 |
| Total forest area | 4126 | 4391 | 4446 | 4080 | 3645 | 4799 | 4805 |
| Non-forest area | 3579 | 3314 | 3259 | 3627 | 4061 | 2910 | 2904 |

water vapor leading to increases in water use efficiency of 30 to 40 percent. However, some species have been documented to acclimate to elevated $CO_2$ concentration by downregulating their photosynthesis (Bazzaz 1990; Gunderson and Wullschleger 1994; Wullschleger et al. 1997; Teskey 1997). On the other hand, most of the early research on effects of $CO_2$ was done on juvenile trees in pots and growth chambers. Evidence now shows that acclimation may not be as prevalent when roots are unconstrained (Eamus 1996; Curtis 1996). Moreover, limiting supplies of nutrients and water tend to only slightly restrict the growth response of trees to elevated $CO_2$ concentrations (Wullschleger et al. 1997).

While results from controlled exposure studies on seedlings and young trees are useful in describing the response of individual trees, they can only provide guidance on how such data can be extrapolated to the scale of mature trees, forest stands, and ecosystems. Simulating natural forest response to elevated $CO_2$ concentrations remains a challenge to the scientific community (Wullschleger et al. 1997). There are no data from which to assess the effect of elevated $CO_2$ on stand-level questions of LAI, and few data sets on tree responses can support a detailed analysis of growth per unit leaf area (Wullschleger et al. 1997). Forests could produce more leaf area under elevated $CO_2$ concentration, but this would increase transpiration and stand water use. Elevated temperatures would increase transpiration even further, possibly inducing a drought effect on the system by drying up the soil (Eamus 1996). This negative feedback would then reduce leaf area. These complex interactions are difficult to implement in the models, and each biogeography model includes its own simplified view of how the system might behave (for example, Neilson and Drapek 1998).

McGuire and Joyce (1995) summarized $CO_2$ effects on trees and therefore incorporated increased gross primary production in a biogeochemistry model used to evaluate the implication of climate change on U.S. temperate forests. In MAPSS, a decrease in stomatal conductance is assumed under elevated $CO_2$, which leads to enhanced water use efficiency and results in an LAI adjustment. Several studies have documented this enhancement for many tree species (Norby et al. 1986; Norby and O'Neill 1989; Oberhauer et al. 1985; Rogers et al. 1983a and b; Teskey and Shrestha 1985; Hollinger 1987). This effect is particularly important in regions where trees are more limited by moisture than nutrient availability (Conroy et al. 1986; Gifford 1979; Hollinger 1987; Idso 1989; Kimball and Idso 1983; McGuire et al. 1993; Polley et al. 1993; Sionit et al. 1980; Tolley and Strain 1984, 1985). It explains why temperate mixed forests in the eastern United States, for example, subject to a warmer and drier environment, are projected to decrease by 40 to 82 percent when stomatal conductance is left unchanged. They are only sup-

posed to decrease by 12 to 14 percent or even increase by up to 9 percent, in the case of OSU scenario, when stomatal conductance is decreased by 35 percent (table 2.6). Because of the different ways models implement $CO_2$ effects, they can produce widely different simulations for the same climate change scenarios. Because MAPSS is very sensitive to changes in stomatal conductance and LAI, it predicts the most dramatic changes in moisture availability for all scenarios. Similarly, since BIOME2 includes an effect of $CO_2$ on the competitive balance between C3 and C4 plants, it simulates an expansion of C3 over C4 grasslands under milder climate change scenarios predicting only small increases in temperature (not shown here, VEMAP Members 1995).

### *Water Budget*

Water use by vegetation is a complex interaction between lifeform water use efficiency, soil characteristics, snow dynamics, and climate (Dale 1997). It is thus difficult to predict a general response of how it will be affected by climate change. With increased temperatures and longer growing seasons, vegetation will transpire more water, thus making less water available in the form of runoff for irrigation or domestic uses. Thus, it is not surprising that in large areas of the conterminous United States, MAPSS simulates a decrease in runoff under all climate change scenarios, and in some regions quite drastically (Neilson and Marks 1994). For example, at the 10 km resolution in the tundra and taiga-tundra area, MAPSS simulates large decreases in runoff (60–86 percent of the total area undergoes a decrease in runoff) under both the GFDL-R30 and the Hadley Centre HADCM2SUL scenarios (tables A3 and A4 in Appendix A) that correspond to large increases in LAI (tables A5 and A6). Similarly, in grasslands, the decrease in runoff (61 percent of the total area) is due to an increase in LAI (80 percent of the total area) (tables A3, A4, A5, A6). MAPSS simulates significant areas (30–60 percent of the total area) of decreased runoff for temperate mixed forests (eastern United States), which are very sensitive to water losses. MAPSS also simulates large areas (80–100 percent of the total area) of increased runoff for temperate evergreen forests.

## Simulation Uncertainties

### Current Climate Source

The Cramer and Leemans dataset, derived from Leemans and Cramer (1991), used fewer U.S. stations and a different precipitation interpolation than the VEMAP dataset. As a result, the North American vegetation simulations do not capture mountainous vegetation as well as simulations using the VEMAP or VEMAP-derived 10 km datasets. Moreover, some distortion of vegetation boundaries also result from the different climatology.

### Climate Scenario

Considerable uncertainty remains in the differences among the GCM climate scenarios (IPCC 1996; Ciret and Henderson-Sellers 1997). However, the capabilities of GCMs have improved significantly from the older (IPCC 1990) to the newer (IPCC 1996) scenarios, resulting in lower estimates of climate sensitivity. Nevertheless, some of the improvements—such as the inclusion of a cooling effect by aerosols—may prove to be less important than assumed by the climate modelers (Taylor and Penner 1994). Scientists generally agree on the likely rise in the average global temperatures over the next century, and that annual worldwide precipitation and evaporation will increase a few percent for every degree of warming. However, projections of climate change in specific areas are not forecasts but are reasonable examples of how the climate might change. By analyzing different scenarios from several different GCMs, the objective is to include a wide range of scientific uncertainty. But it is important to remember that climatic inputs derived from the GCMs have been interpolated to the higher resolution and may not correspond to realistic regional simulations.

Atmospheric circulation is strongly affected by fluxes of energy and water from the land surface. These fluxes depend on vegetation characteristics such as albedo, LAI, and vegetation height. Changes to land surface characteristics eventually feed back to the atmosphere. The current generation of climate models include the biophysical interactions between land surface and atmosphere in a "land surface module." Sensitivity studies have now shown the importance of the feedback processes (for example, Bonan et al. 1992; Xue and Shukla 1993; Betts et al. 1997; Foley et al. 1998) and that using a fixed geographic distribution of vegetation types limits their use in global change studies. Unfortunately, all the assessments to date have been using ecosystem models that simulate changes in vegetation structure, with no feedback to climate models that produce the climate change scenarios they are so dependent upon. Results to date must thus be taken with caution since the atmosphere is totally decoupled from the land surface changes. Current research is now focusing on coupling fully dynamic representations of terrestrial ecosystems with climate models. Some of the new generation of biogeography models - dynamic global vegetation models or DGVMs - have already been designed to be fully coupled with climate models (for example, Foley et al. 1998).

**Table 2.9—**Predicted percent of the total area of North America and of the conterminous United States occupied by the various simplified vegetation types and percentage change when the GFDL-R30 scenario is applied and the $CO_2$ effect is included in MAPSS. Results correspond to three projects: 1) the North American project, from the Mexican border to northern Canada, at a half degree latitude-longitude resolution; 2) the VEMAP project at the same resolution as the North American project but concentrating on the continental U.S.; 3) the last project concentrating on the conterminous U.S. at a 10 km resolution. Percentage change in vegetation type area is calculated as: (scenario – current)/current. (*: in VEMAP the category taiga-tundra was not used since the BIOME model did not separate it from the boreal forest component.)

| | Current climate | | | GFDL-R30 | | |
|---|---|---|---|---|---|---|
| Model resolution | half degree - North America | half degree - VEMAP (U.S.) | 10 km - U.S. | half degree - North America | half degree - VEMAP (U.S.) | 10 km - U.S. |
| Vegetation classes | | | | | | |
| Tundra | 16 | <1 | <1 | –58 | –100 | –96 |
| Taiga – Tundra | 16 | * | 1 | –39 | * | –87 |
| Boreal coniferous forest | 16 | 2 | 1 | +50 | –100 | –90 |
| Temperate evergreen forest | 7 | 9 | 6 | +30 | +142 | +49 |
| Temperate mixed forest | 16 | 34 | 30 | +7 | –12 | –36 |
| Savanna woodland | 12 | 12 | 16 | +44 | +15 | +77 |
| Shrub woodland | 7 | 12 | 14 | –20 | –25 | –20 |
| Grassland | 9 | 27 | 28 | +23 | –17 | +5 |
| Arid land | 2 | 4 | 5 | –64 | –57 | –47 |

## Spatial Resolution

We compared simulation results from MAPSS at two different scales (10 km and half degree latitude-longitude resolution) and for two regions (North America and the continental United States). First, we compared results from 10 km resolution runs and results from VEMAP at approximately 50 km resolution (table 2.9 and fig. 2.3) for the continental United States using the GFDL-R30 scenario. The $CO_2$ effect was included in MAPSS. A small area increase (5 percent) in grasslands is simulated at the 10 km scale while a decrease of 17 percent is simulated at the VEMAP scale. Larger changes in the extent of temperate evergreen forests are simulated at the VEMAP scale with smaller changes in the extent of savannas. Simulation results agree in the direction of change for runoff pattern in the United States, with the exception of tundra areas, and anticipate increases in runoff in forest areas, savannas, and shrublands (table A3). Decreases in runoff are simulated in grasslands and arid lands. The model also simulates an increase in LAI (index of vegetation density) in tundra areas, savannas, shrublands, and arid lands, but a decrease in LAI in temperate mixed forests (table A5).

Secondly, we compared results obtained for the North American region (including Canada and the United States) and for the continental U.S. (VEMAP), both at a half degree latitude-longitude resolution. Changes due to the climate change scenarios are generally consistent both for runoff and LAI estimates (tables 2.9, A3, and A5).

Finally we compared results obtained for the North American region at a half-degree latitude-longitude resolution with those obtained for the continental United States at a 10 km resolution. There is good agreement between simulations except for the tundra area since coarse resolution results reflect large changes occurring in Canada but not in the United States (table 2.10). Tables A4 and A6 illustrate the agreement between simulations of LAI and runoff changes. The only disagreement occurs in the tundra and the boreal forest areas.

In summary, results from climate change impact simulations have to be carefully analyzed, the area of interest must be well delineated, and the scale of resolution specified. Trends in the expansion or reduction of certain systems can change dramatically between regions. Small changes that can be captured at high resolution can collectively modify the direction of trends. Caution is needed when analyzing model results for coarser resolution regional simulations.

## Temporal Resolution Uncertainty

Current climate conditions used to run the models correspond to long-term average climate data that ignore extreme events and year-to-year variability. In reality, this variability greatly affects vegetation dynamics. Similarly, GCM-generated future climate scenarios for an "average" year are only snapshots of future climate at equilibrium with a doubled atmospheric $CO_2$ content. They do not

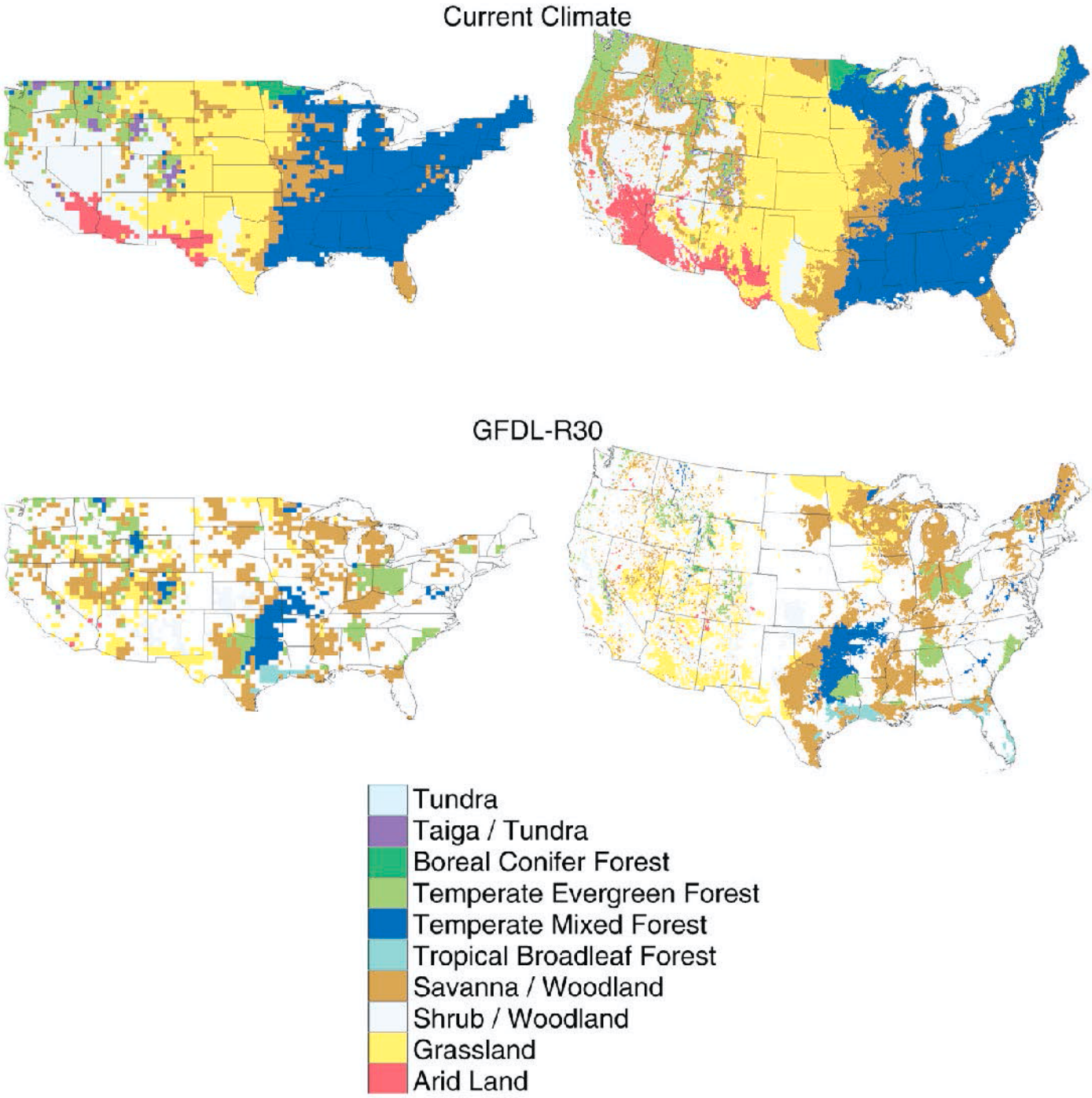


**Figure 2.3**—Aggregated potential vegetation classes simulated by MAPSS for current conditions (top) and areas where new vegetation classes are simulated by MAPSS using the GFDL-R30 climate change scenario (bottom) at a 10 km resolution (right) and at a half-degree resolution (VEMAP) (left) in the conterminous United States. Areas where there is no change in vegetation type remain white.

accurately represent the constantly evolving interactions between atmosphere, ocean, and land. In reality, there is no "average" year and thus equilibrium models such as MAPSS simulate vegetation distributions that do not and will not have an exact analog in nature (Borchers and Neilson 1998). The value of equilibrium projections, however, is that they depict theoretical equilibrium states or potential natural "climax" that the vegetation might evolve toward, a concept that has guided decision-making in forest management and silviculture for many years.

**Table 2.10—**Predicted percent of total area of either the North American region or the conterminous United States occupied by the various simplified vegetation types and percentage change in area when the Hadley Centre sulfate aerosol scenario (HADCM2SUL) is applied and the $CO_2$ effect is included in MAPSS. Results correspond to two projects using the MAPSS equilibrium biogeography model: one concentrating on the North American region from the Mexican border to northern Canada at a half degree latitude-longitude resolution, the other concentrating on the conterminous U.S. at a 10 km resolution. (+++ denotes a vegetation type that did not exist in the current climate scenario. NA corresponds to a vegetation type that did not exist in either current or future climates.) Percentage change in vegetation type area is calculated as: (scenario – current)/current.

| | Current climate | | HADCM2SUL | |
|---|---|---|---|---|
| Model resolution | half degree – North America | 10 km - U.S. | half degree – North America | 10 km - U.S. |
| Vegetation classes | | | | |
| Tundra | 16 | <1 | –37 | –92 |
| Taiga – Tundra | 16 | 1 | –41 | –83 |
| Boreal coniferous forest | 16 | 1 | +15 | –99 |
| Temperate evergreen forest | 7 | 6 | +82 | +23 |
| Temperate mixed forest | 16 | 30 | +52 | +28 |
| Tropical broadleaf forest | 0 | 0 | +++ | NA |
| Savanna woodland | 12 | 16 | –1 | –2 |
| Shrub woodland | 7 | 14 | +1 | +2 |
| Grassland | 9 | 28 | –30 | –18 |
| Arid land | 2 | 5 | –70 | –66 |

A new generation of models—the dynamic global vegetation models, or DGVM—is now emerging. These models couple vegetation structure and biogeochemical fluxes and simulate their dynamic changes as a response to changes in climate and disturbance regimes (Neilson and Running 1996; Foley et al. 1996; Friend et al. 1997; Lenihan et al. 1998). However, other constraints to the transient response of vegetation are still missing, such as soil development and seed dispersal. These models are being developed and should soon become the essential tools of future assessments.

# Model Limitations

## Nitrogen Budget

Nitrogen limitation is thought to moderate long-term responses to elevated $CO_2$ (Kirschbaum et al. 1994; McGuire et al. 1995; Eamus 1996). Climate change affects temperature- and moisture-controlled processes such as nutrient uptake, mineralization, and volatilization. Unless $CO_2$ stimulates an increase in nitrogen mineralization (Curtis et al. 1995; VEMAP Members 1995), productivity gains with high $CO_2$ concentration will be constrained by the available nitrogen (Körner 1995). Nitrogen limitations may constrain carbon gains to structural tissue rather than leaves (Curtis et al. 1995). Lifeform changes due to shifts in climate will also affect nutrient inputs (Pastor and Post 1988). Nitrogen fixation has been poorly quantified and has yet to be simulated accurately. Anthropogenic nitrogen fixation far exceeds natural nitrogen fixation (Vitousek 1994). In areas receiving large amounts of nitrogen deposition, a direct $CO_2$ response could result in large increases in leaf area. This increased LAI could increase transpiration and possibly provoke rapid soil water depletion, thus increasing the system sensitivity to drought. Nitrogen deposition has likely caused considerable accumulation of carbon in the biosphere since the last century (Vitousek 1994; Townsend et al. 1996). However, nitrogen saturation in soils can also be deleterious and possibly cause forest dieback in some systems (Foster et al. 1997). This effect is not included in MAPSS.

## Disturbance

Disturbance intensity, frequency, and duration are likely to change with climate (Overpeck et al. 1990; Dale 1997). Natural fire frequency, duration, and intensity are closely tied to storm occurrences and precipitation regimes, which will be affected by global climate change (Dale 1997). Future climate coincident with changes in fire management practices and possible forest decline or dieback could bring longer fire seasons and potentially more frequent and larger fires in all forest zones (even those that do not currently support fire) (Fosberg 1990; Flannigan and Van Wagner 1991; King and Neilson 1992; Wotton and Flannigan 1993; Price and Rind 1994; Fos-

berg at al. 1996). Fire suppression during much of the 20th century has allowed biomass in many interior forests to increase considerably over historic levels (Agee 1990). With increased biomass, forests transpire almost all available soil water and become very sensitive to even small variations in drought stress. Forests are then highly susceptible to catastrophic fires even without global warming (Neilson et al. 1992; Stocks 1993; Stocks et al. 1996). Forests in the interior of North America are experiencing increased frequencies of drought stress, pest infestations, and catastrophic stand-replacing fires (Agee 1990). This sequence of events is a reasonable analog for what could happen to forests over much larger areas in the zones indicated by the biogeography models to undergo a loss of biomass or leaf area due to temperature-induced transpiration increases and drought stress (Overpeck et al. 1990; King and Neilson 1992). Because fire mediates rapid change, vegetation change could be significantly affected by changes in fire frequency.

The ability to predict changes in the frequency or intensity of extreme weather events such as drought, flooding, hail, hurricanes, and tornadoes using global and regional models is limited by their lack of small scale spatial and temporal resolution and uncertainties about representation of processes (IPCC 1996).

## Conclusions

Current published assessments of biospheric responses to climate change are based on equilibrium models of the terrestrial biosphere such as MAPSS, BIOME2 or 3, and DOLY. These models simulate the combination of plant lifeforms that are in steady state with a given climate given a particular soil environment. These models, when run with various scenarios of climate change, show a series of strong responses:

1) Boreal forest and taiga-tundra regions are predicted to move northward or upward in elevation at the expense of the Canadian or alpine tundra (boreal forests are also simulated to experience diebacks of various degrees along the southern or lower elevational limits under all climate change scenarios). The boreal forest simulated in Minnesota for current climatic conditions totally disappears with even mild climate change scenarios such as the HADCM2SUL. Upper elevational or northern boundaries are predicted to shift upslope or northward.
2) Warmer scenarios produce the largest impacts on the boreal forest, but are also responsible for forest dieback in the conterminous United States.
3) Northwest and southeast forests might initially expand, then later contract in area. For the warmer climate change scenarios, MAPSS simulated extensive fragmentation of the eastern temperate mixed forests, which are very sensitive to changes in available water and thus to any positive effect of elevated $CO_2$.
4) Southwestern desert species may move into the Great Basin region given adequate thermal and hydrologic conditions.

The treatment of $CO_2$ effects in each of the three biogeography models strongly influences their simulations and explains some of the differences among them. Results from these equilibrium models also clearly depend on the climate change scenario that was used for the assessment. Although there is a growing consensus about the increase in future global average temperature, there is little agreement on the magnitude and timing of the changes in the hydrological cycle in various regions of the world. Moreover, large uncertainties remain about the regional changes of the various climate variables (Kattenberg et al. 1996). Therefore, assessments of future vegetation distribution carry the uncertainty intrinsic to the climate change scenarios and should not be considered as solid predictions. Equilibrium models, by definition, do not simulate dynamic or transient changes in vegetation assemblages. The rate of change predicted by the climate models may exceed historical rates of change (Kirschbaum et al. 1996). Simulation results may thus be used to indicate the direction of possible change, but not to estimate the time it might take a particular plant type to reach a new site (Cramer and Steffen 1997).

Movement of the various ecosystems may also be constrained after their initially rapid expansion by various factors such as lack of seed dispersal or establishment, lack of seasonal thermal requirements for establishment, poor soils, or unfavorable land use such as urbanization or cultivation. For example, the extent of the temperate mixed forest zone near the Great Lakes increases or declines depending, in part, on soil properties (Post and Pastor 1996). Moreover, vegetation types will probably not be displaced homogeneously. Different assemblages may appear and disappear over long periods of time (Huntley et al. 1997; Lenihan and Neilson 1995) and their composition will be strongly affected by changes in disturbance regimes.

Changes in boundaries limited by water balance are difficult to predict because of the complex interactions between changes in temperature, precipitation, and $CO_2$ concentration. Increases in rainfall are in some cases sufficient to balance increases in evaporative demand, and in other cases they are not. $CO_2$-induced changes in water use efficiency could reverse a potential drought response for certain plants. Northern states such as Minnesota, Michigan, and Wisconsin would endure displacement of forests by

grasslands under all scenarios (figs. 2.2 and 2.3), a transition that would be mediated by drought and fire. Future climate changes coincident with changes in fire management practices and possible forest decline or dieback could bring longer fire seasons and potentially more frequent and larger fires in all forest zones. Drought and forest dieback could increase the fuel load and trigger more frequent and larger fires, while increased growth, given climatic oscillations, would also increase the fuel load. The importance of fire on vegetation change could increase and mediate rapid changes. Moreover, in the early stages of warming, when temperature increases are small, a $CO_2$-induced increase in water use efficiency could result in an expansion of temperate forests into neighboring drier areas and a concurrent increase in forest density throughout much of the current forest distribution. For example, MAPSS simulates the expansion of the temperate evergreen forest into Canada, where it replaces the taiga-tundra. It also simulates the expansion of the eastern temperate mixed forest westward into the central United States at the expense of savannas. A similar shift of northwestern forests into drier areas is simulated under the moderate warming scenarios. As the $CO_2$ effect saturates and temperatures continue to increase, however, the elevated evaporative demand could overwhelm the increased water use efficiency. Temperate forests could then contract in area and undergo a drought-induced decline in vegetation density (Neilson and Drapek 1998).

Comparing the "warmer" climate change scenarios with cooler ones illustrates what might happen to the southeastern mixed forest, where extensive fragmentation is simulated to occur with higher temperatures. The beneficial effects of elevated $CO_2$ could make a large difference in the response of the southeastern forests to the warming.

Finally, we want to emphasize that important factors, such as grazing by herbivores, invasions by weeds, diseases, and pests, and changes in land use due to human development, could drastically alter the responses of vegetation to climatic changes. There is currently no model that incorporates all these factors, and adding such complexity to currently existing models would also increase the margin of uncertainty in the resulting predictions. Climate change assessments should thus include these factors but new methods need to be developed to retain the usefulness of model simulations by keeping the uncertainty manageable.

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# Appendix A

**Table A1**—Equivalence between VEMAP (VEMAP Members 1995) and MAPSS (Neilson 1995) vegetation categories and our simplified vegetation categories. E: evergreen, D: deciduous, B: broadleaf, N: needleleaf, PJ: pinyon juniper. C3 and C4 refer to the photosynthetic pathway of the plants.

| VEMAP classes | Simplified categories | MAPSS categories |
|---|---|---|
| 1. Tundra | 1. Tundra | 601. Tundra |
| 2. Boreal coniferous forest | 2. Taiga – Tundra | 600. Taiga – Tundra |
| | 3. Boreal coniferous forest | 107. Forest EN taiga |
| 3. Maritime temperate coniferous forest | 4. Temperate evergreen forest | 112. Forest EN maritime |
| 4. Continental temperate coniferous forest | 4. Temperate evergreen forest | 108. Forest mixed warm EN |
| | | 113. Forest EN continental |
| 5. Cool temperate mixed forest | 5. Temperate mixed forest | 102. Forest mixed cool |
| 6. Warm temperate – subtropical mixed forest | 5. Temperate mixed forest | 101. Forest mixed warm DEB |
| 7. Temperate deciduous forest | 5. Temperate mixed forest | 100. Forest deciduous broadleaf |
| | | 111. Forest hardwood cool |
| 8. Tropical deciduous forest | 7. Savanna woodland | |
| 9. Tropical evergreen forest | 6. Tropical broadleaf forest | 105. Forest EB tropical |
| 10. Temperate mixed xeromorphic woodland | 7. Savanna woodland | 210. Tree savanna PJ maritime |
| | | 109. Forest seasonal tropical ED |
| | | 110. Forest savanna dry tropical ED |
| | | 205. Tree savanna mixed cool EN |
| | | 206. Tree savanna mixed warm EN |
| | | 207. Tree savanna EN maritime |
| | | 208. Tree savanna EN continental |
| 11. Temperate coniferous xeromorphic woodland | 7. Savanna woodland | 209. Tree savanna PJ continental |
| 12. Tropical thorn woodland | 10. Arid lands | 305. Shrub savanna tropical EB |
| | | 309. Shrub savanna mixed warm EN |
| | | 404. Grass semi-desert |
| | | 425. Grass semi-desert C4 |
| | | 500. Desert boreal |
| | | 501. Desert temperate |
| 13. Temperate – subtropical savanna | 7. Savanna woodland | 200. Tree savanna DB |
| | | 201. Tree savanna mixed warm DEB |
| 14. Warm temperate subtropical mixed savanna | 8. Shrub woodland | 310. Shrub savanna subtropical mixed |
| | | 303. Shrub savanna mixed warm DEB |
| | | 307. Shrub savanna mixed cool EN |
| | | 311. Shrubland subtropical xeromorphic |
| | | 313. Shrubland temperate conifer |
| | | 314. Shrubland temperate xeromorphic conifer |
| | | 423. Grass semi-desert C3 |
| | | 424. Grass semi-desert C3-C4 |
| 15. Temperate coniferous savanna | 7. Savanna woodland | 211. Tree savanna PJ xeric continental |
| 17. C3 Grasslands | 9. Grasslands | 414. Grass tall C3 |
| | | 415. Grass mid C3 |
| | | 416. Grass short C3 |
| | | 418. Grass mid C3 C4 |
| | | 419. Grass short C3 C4 |

*continued*

**Table A1 (continued).**

| VEMAP classes | Simplified categories | MAPSS categories |
|---|---|---|
| 18. C4 Grasslands | 9. Grasslands | 417. Grass tall C3 C4 |
| | | 420. Grass tall C4 |
| | | 421. Grass mid C4 |
| | | 422. Grass short C4 |
| 19. Mediterranean shrubland | 8. Shrub woodland | 312. Shrubland subtropical mediterranean |
| 20. Temperate arid shrubland | 8. Shrub woodland | 301. Open shrubland – no grass |
| | | 302. Shrub savanna DB |
| | | 308. Shrub savanna EN |
| 21. Subtropical arid shrubland | 10. Arid lands | 502. Desert subtropical |
| | | 503. Desert tropical |
| | | 504. Desert extreme |

**Table A2—**Equivalence between MAPSS assessment classes (Neilson and Chaney 1996), MAPSS (Neilson 1995) vegetation classes, VEMAP (VEMAP members 1995) classes, and our simplified vegetation classes. E: evergreen, D: deciduous, B: broadleaf, N: needleleaf, PJ: pinyon juniper.

| Assessment classes | MAPSS classes | VEMAP classes | Simplified classes |
|---|---|---|---|
| **Eastern forests** | | | |
| 1. NE mixed conifers and hardwoods | 102. Forest mixed cool | 5. Cool temperate mixed forest | 5. Temperate mixed forest |
| 2. NE mixed woodlands | 205. Tree savanna mixed cool EN | 10. Temperate mixed xeromorphic woodland | 7. Savanna woodland |
| 3. Maple-beech-birch | 111. Forest hardwood cool | 7. Temperate deciduous forest | 5. Temperate mixed forest |
| 4. Oak hickory forest | 100. Forest deciduous broadleaf | 7. Temperate deciduous forest | 5. Temperate mixed forest |
| 5. SE mixed pines and hardwoods | 101. Forest mixed warm DEB | 6. Warm temperate – subtropic mixed forest | 5. Temperate mixed forest |
| **Western forests** | | | |
| 6. Western fir - spruce | 600. Taiga - Tundra | 2. Boreal coniferous forest | 2. Taiga – Tundra |
| | 107. Forest EN taiga | | 3. Boreal coniferous forest |
| 7. Douglas fir | 112. Forest EN maritime | 3. Maritime temperate coniferous forest | 4. Temperate evergreen forest |
| | 113. Forest EN continental | 4. Continental temperate coniferous forest | |
| 8. Coastal spruce - hemlock redwood | 108. Forest mixed warm EN | 4. Continental temperate coniferous forest | 4. Temperate evergreen forest |
| 9. Western pines | 207. Tree savanna EN maritime | 10. Temperate mixed xeromorphic woodland | 7. Savanna woodland |
| | 208. Tree savanna EN continental | | |
| 10. Western hardwoods | 206. Tree savanna mixed warm EN | 10. Temperate mixed xeromorphic woodland | 7. Savanna woodland |
| **Tropical** | | | |
| 11. Moist tropical forest | 105. Forest EB tropical | 9. Tropical evergreen forest | 6. Tropical broadleaf forest |
| 12. Dry tropical forest | 109. Forest seasonal tropical ED | 10. Temperate mixed xeromorphic woodland | 7. Savanna woodland |
| | 110. Forest savanna dry tropical ED | | |
| **Arid woodlands** | | | |
| 13. Oak hickory woodland | 200. Tree savanna DB | 13. Temperate - subtropical savanna | 7. Savanna woodland |
| 14. SE mixed woodland | 201. Tree savanna mixed warm DEB | 13. Temperate - subtropical savanna | 7. Savanna woodland |
| **Mediterranean** | | | |
| 15. Chaparral | 312. Shrubland subtropical mediterranean | 19. Mediterranean shrubland | 8. Mediterranean fraction of shrub woodland |
| 16. Pinyon juniper | 209. Tree savanna PJ continental | 11. Temperate xeromorphic coniferous forest | 7. Savanna woodland |
| | | | 7. Savanna woodland |
| | 210. Tree savanna PJ maritime | 10. Temperate mixed xeromorphic woodland | |
| | | | 7. Savanna woodland |
| | 211. Tree savanna PJ xeric continental | 15. Temperate coniferous savanna | |
| **Non forests** | | | |
| 17. Non forests | see Table A1 | see Table A1 | 8. (Rest of) shrub woodland |
| | | | 9. Grasslands |
| | | | 10. Arid lands (see Table A1) |

**Table A3—**Predicted percent area of increased or decreased runoff either in the North American region or the conterminous United States for the various simplified vegetation types when the GFDL-R30 scenario is applied and the $CO_2$ effect is included in MAPSS. Results correspond to three projects using the MAPSS equilibrium biogeography model: 1) the North American project, from the Mexican border to northern Canada, at a half degree latitude-longitude resolution; 2) the VEMAP project at the same resolution as the North American project but concentrating on the conterminous U.S.; 3) the last project concentrating on the conterminous U.S. at a 10 km resolution. Decrease corresponds to the areas where runoff decreases while Increase corresponds to areas where runoff increases.

| | half degree – North America | | half degree – VEMAP (U.S.) | | 10 km – U.S. | |
|---|---|---|---|---|---|---|
| Model resolution | Decrease | Increase | Decrease | Increase | Decrease | Increase |
| Vegetation classes | | | | | | |
| Tundra | 11 | 89 | 51 | 49 | 70 | 30 |
| Taiga – Tundra | 89 | 11 | 22 | 78 | 80 | 19 |
| Boreal coniferous forest | 0 | 100 | 0 | 100 | 0 | 100 |
| Temperate evergreen forest | 3 | 97 | 0 | 100 | 1 | 99 |
| Temperate mixed forest | 40 | 60 | 39 | 61 | 39 | 61 |
| Savanna woodland | 27 | 72 | 16 | 83 | 2 | 79 |
| Shrub woodland | 29 | 65 | 30 | 67 | 2 | 69 |
| Grassland | 61 | 35 | 69 | 30 | 69 | 30 |
| Arid land | 69 | 15 | 63 | 27 | 67 | 15 |

**Table A4—**Predicted percentage in area of increased or decreased runoff when the Hadley Centre sulfate aerosol scenario (HADCM2SUL) is applied and the $CO_2$ effect is included in MAPSS. Results correspond to two projects using the MAPSS equilibrium biogeography model: one concentrating on the North American region, from the Mexican border to northern Canada, at a half degree latitude-longitude resolution, the other concentrating on the conterminous U.S. at a 10 km resolution. Decrease corresponds to the areas where runoff decreases while Increase corresponds to areas where runoff increases.

| | half degree – North America | | 10 km – U.S. | |
|---|---|---|---|---|
| Model resolution | Decrease | Increase | Decrease | Increase |
| Vegetation classes | | | | |
| Tundra | 18 | 80 | 60 | 40 |
| Taiga - Tundra | 76 | 24 | 86 | 14 |
| Boreal coniferous forest | 4 | 93 | 0 | 100 |
| Temperate evergreen forest | 17 | 81 | 1 | 99 |
| Temperate mixed forest | 44 | 56 | 32 | 67 |
| Savanna woodland | 37 | 58 | 37 | 60 |
| Shrub woodland | 17 | 81 | 13 | 85 |
| Grassland | 66 | 30 | 61 | 37 |
| Arid land | 43 | 42 | 36 | 51 |

**Table A5—**Predicted percent area of increased or decreased LAI either in the North American region or the conterminous United States for the various simplified vegetation types when the GFDL-R30 scenario is applied and the $CO_2$ effect is included in MAPSS. Results correspond to three projects using the MAPSS equilibrium biogeography model: 1) the North American project from the Mexican border to northern Canada at a half degree latitude-longitude resolution; 2) the VEMAP project at the same resolution as the North American project but concentrating on the conterminous U.S.; 3) the last project concentrating on the conterminous U.S. at a 10 km resolution. Decrease corresponds to the areas where LAI decreases while Increase corresponds to areas where LAI increases.

| | half degree – North America | | half degree – VEMAP (U.S.) | | 10 km – U.S. | |
|---|---|---|---|---|---|---|
| Model resolution | Decrease | Increase | Decrease | Increase | Decrease | Increase |
| Vegetation classes | | | | | | |
| Tundra | 0 | 62 | 13 | 87 | 11 | 88 |
| Taiga – Tundra | 1 | 97 | 0 | 100 | 0 | 100 |
| Boreal coniferous forest | 37 | 42 | 100 | 0 | 90 | 9 |
| Temperate evergreen forest | 20 | 47 | 31 | 67 | 49 | 41 |
| Temperate mixed forest | 88 | 10 | 66 | 32 | 85 | 13 |
| Savanna woodland | 19 | 73 | 14 | 81 | 15 | 80 |
| Shrub woodland | 17 | 76 | 6 | 90 | 11 | 83 |
| Grassland | 45 | 42 | 28 | 61 | 45 | 45 |
| Arid land | 2 | 92 | 0 | 94 | 0 | 91 |

**Table A6—**Predicted percent area of increased or decreased LAI when the Hadley Centre sulfate aerosol scenario (HADCM2SUL) is applied and the $CO_2$ effect is included in MAPSS. Results correspond to two projects using the MAPSS equilibrium biogeography model: one concentrating on the North American region, from the Mexican border to northern Canada, at a half degree latitude-longitude resolution, the other concentrating on the conterminous U.S. at a 10 km resolution. Decrease corresponds to the areas where LAI decreases while Increase corresponds to areas where LAI increases.

| | half degree – North America | | 10 km – U.S. | |
|---|---|---|---|---|
| Model resolution | Decrease | Increase | Decrease | Increase |
| Vegetation classes | | | | |
| Tundra | 0 | 38 | 8 | 88 |
| Taiga - Tundra | 0 | 93 | 0 | 100 |
| Boreal coniferous forest | 14 | 54 | 61 | 35 |
| Temperate evergreen forest | 13 | 55 | 17 | 62 |
| Temperate mixed forest | 3 | 95 | 8 | 79 |
| Savanna woodland | 10 | 89 | 3 | 95 |
| Shrub woodland | 13 | 84 | 6 | 91 |
| Grassland | 3 | 93 | 14 | 80 |
| Arid land | 1 | 94 | 0 | 95 |