CHAPTER 2

VEGETATION AND BIOGEOCHEMICAL SCENARIOS

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CHAPTER SUMMARY

Ecosystems are communities of plants and animals and the physical environment in which they exist. Ecologists often categorize ecosystems by their dominant vegetation – the deciduous broad-leafed forest ecosystems of New England,the short-grass prairie ecosystems of the Great Plains,the desert ecosystems of the Southwest. Concerns for continued ecosystem health and performance stem from two primary issues. Ecosystems of all types,from the most natural to the most extensively managed, produce a variety of goods and services that benefit humans. Examples of ecosystem services include modification of local climate,air and water purification,landscape stabilization against erosion, flood control,and carbon storage. Ecosystems are also valued for recreational and aesthetic reasons. Climate change has the potential to affect the structure, function,and regional distribution of ecosystems, and thereby affect the goods and services they provide.

For this Assessment,the Vegetation/Ecosystem Modeling and Analysis Project (VEMAP) was used to generate future ecosystem scenarios for the conterminous United States based on model-simulated responses to the Canadian and Hadley scenarios of climate change. The ecosystem scenarios were then shared with Assessment participants to assist them in their evaluations of the potential sensitivities of ecosystems and ecosystem goods and services to climate change.

Key Findings

Some of the key results from VEMAP for ecosystems in the absence of land-cover and land-use changes are as follows:

- Over the next few decades climate change is very likely to lead to increased plant productivity and increased terrestrial carbon storage for many parts of the country, especially those that get moderately warmer and wetter. Areas where soils dry out during the growing season, such as the Southeast for the climate simulated with the Canadian model, are very likely to see reduced productivity and decreases in carbon storage.
- By the end of the 21st century, many regions of the country are likely to have experienced changes in vegetation distribution. Areas in which soil moisture increases are likely to maintain or exhibit an increased woody component of vegetative cover. Areas in which soil moisture decreases are likely to lose woody vegetation. For example, in the Southeast, the climate simulated by the Canadian model causes soil drying that would lead to forest losses and savanna and grassland expansion.
- Modeling of vegetation responses to climate change is in the early stages of development. No single model simulates all of the important factors affecting vegetation responses to climate; model results must therefore be viewed with caution. The complex, non-linear nature of ecosystems almost certainly means that we will be surprised by some of the changes in ecosystem function and structure that climate changes set in motion. Keeping the magnitude of climate change as small as possible and slowing its rate are the two things we can do to minimize the negative impacts on natural ecosystems.

VEGETATION AND BIOGEOCHEMICAL SCENARIOS

INTRODUCTION

This chapter is designed to report the results of the Vegetation/Ecosystem Modeling and Analysis Project II (VEMAP II);a project that has provided data about terrestrial ecosystem responses to climate change to Assessment participants. The chapter is not meant to be a comprehensive,in-depth analysis of climate impacts on all aspects of terrestrial ecosystem structure and function. The chapter has two focus areas – biogeochemistry and plant biogeography in natural terrestrial ecosystems. While animal communities are mentioned briefly in the chapter, they were not considered in the VEMAP II analysis and so are not focused on in this chapter. These scenarios for vegetation and biogeochemical change can serve as background for analyses of changes to fauna and biological diversity by contributing broad-scale information on habitat changes.

VEMAP II is an international,collaborative effort supported by several US Global Change Research Program agencies and sponsored by the International Geosphere-Biosphere Program (IGBP) to conduct an analysis of the potential effects of climate change on ecosystem processes and vegetation distribution within the continental United States. Modeling results to date indicate that natural terrestrial ecosystems are sensitive to changes in global surface temperature,precipitation patterns,atmospheric carbon dioxide (CO_2) levels,and other climate parameters. Major ecological characteristics to be affected include the geographic distribution of dominant plant species,productivity of plants,biodiversity within natural ecosystems,and basic ecological processes and their feedbacks to the climate system.

Two types of models that have been used in VEMAP II to examine the ecological effects of climate change are biogeochemistry models and biogeography models. Biogeochemistry models project changes in basic ecosystem processes such as the cycling of carbon, nutrients,and water (ecosystem function),and biogeography models simulate shifts in the geographic distribution of major plant species and communities (ecosystem structure).

VEMAP II involves a comparison of three biogeochemistry and three biogeography models (Schimel et al.,2000;Neilson et al.,2000). The models use a common "baseline"data set and two potential climate scenarios. Common data are used to ensure that any variability in predicted responses is attributable to the different structures and formulations of individual ecological models rather than to input data.

For the National Assessment,the focus is on model outputs for two time periods:2025-2034 (near term) and 2090-2099 (long term). Outputs of the biogeochemistry models are used to consider near-term ecological impacts,while outputs of the biogeography models are used to consider longer-term impacts. This is based on the team's expert judgement that biogeochemical changes will dominate ecological responses to climate change in the next few decades,while species shifts will dominate ecological responses to climate change towards the end of the 21st century, as organisms attempt to migrate to occupy "optimal" climate space.

RESEARCH APPROACH

Biogeochemistry Models

The biogeochemistry models simulate the cycles of carbon, nutrients (e.g.,nitrogen),and water in terrestrial ecosystems which are parameterized according to life form (VEMAP Members,1995,Schimel et al., 2000). The models consider how these cycles are influenced by environmental conditions including temperature,precipitation,solar radiation,soil texture,and atmospheric CO_2 concentration. These environmental variables are inputs to general algorithms that describe plant and soil processes such as carbon capture by plants with photosynthesis, decomposition,soil nitrogen transformations mediated by microorganisms,and water flux between land and the atmosphere in the processes of evaporation and transpiration. Common outputs from biogeochemistry models are estimates of net primary productivity, net nitrogen mineralization, evapotranspiration fluxes (e.g.,PET, ET),and the storage of carbon and nitrogen in vegetation and soil. In the VEMAP II activity, three biogeochemistry models were used: BIOME-BGC (Hunt and Running,1992;Running and Hunt,1993),CENTURY (Parton et al.,1987,1988, 1993),and the Terrestrial Ecosystem Model (TEM)

(Melillo et al.,1993;McGuire et al.,1997;Tian et al., 1999). The similarities and differences among the models are summarized in Table 1. A detailed intercomparison of these biogeochemistry models has recently been published (Pan et al.,1998). The capabilities and limitations of the models are identified in this intercomparison. A comparison of model results to field data for the Mid-Atlantic region of the northeastern US is presented in Jenkins,et al.(2000).

BIOME-BGC

The BIOME-BGC (BioGeochemical Cycles) model is a multi-biome generalization of FOREST-BGC, a model originally developed to simulate a forest stand development through a life cycle (Running and Coughlan,1988;Running and Gower, 1991). The model requires daily climate data and the definition of several key climate, vegetation,and site conditions to estimate fluxes of carbon,nitrogen,and water through ecosystems (Table 4 in VEMAP Members, 1995). Allometric relationships are used to initialize plant and soil carbon (C) and nitrogen (N) pools based on the leaf pools of these elements (Vitousek et al.,1988). Components of BIOME-BGC have previously undergone testing and validation,including the carbon dynamics (McLeod and Running,1988; Korol et al.,1991;Hunt et al.,1991;Pierce,1993; Running,1994) and the hydrology (Knight et al., 1985;Nemani and Running,1989;White and Running,1995).

CENTURY

The CENTURY model is a general model of plant-soil nutrient cycling which has been used to simulate carbon and nutrient (nitrogen,phosphorus,and sulfur) dynamics for different types of ecosystems including grasslands, agricultural lands, forests,and savannas (Parton et al.,1987,1993;Metherell,1992). For VEMAP, only carbon and nitrogen dynamics are included. The model uses monthly temperature and precipitation data as well as atmospheric CO_2 and N inputs to estimate monthly stocks and fluxes of carbon and nitrogen in ecosystems. The CENTURY model also includes a water budget submodel which calculates monthly evapotranspiration,transpiration, water content of the soil layers,snow water content, and saturated flow of water between soil layers. The CENTURY model incorporates algorithms that describe the impact of fire, grazing,and storm disturbances on ecosystem processes (Ojima et al.,1990; Sanford et al.,1991;Holland et al.,1992;Metherell, 1992).

TEM

The Terrestrial Ecosystem Model (TEM version 4.1) describes carbon and nitrogen dynamics of plants and soils for non-wetland ecosystems of the globe (Tian et al.,1999). This model requires monthly climatic data along with soil and vegetation-specific parameters to estimate monthly carbon and nitrogen fluxes and pool sizes. The model includes algorithms from the water balance model of Vörösmarty et al.(1989) to calculate potential and actual evapotranspiration,soil moisture,and drainage. Estimates of net primary production and carbon storage by this version of TEM have been evaluated in previous applications of the model at both regional and global scales (Xiao et al.,1998;Tian et al.,1998,1999, 2000;Kicklighter et al.,1999;Prinn et al.,1999; Reilly et al.,1999;McGuire et al.,2000).

BIOGEOGRAPHY MODELS

The models used to estimate biogeographic responses to climate change in VEMAP II include LPJ, MAPSS (Mapped Atmosphere-Plant-Soil System) and MC1. These three models project the local dominance of various terrestrial vegetation forms based on (1) ecophysiological constraints,which determine the broad distribution of major categories of woody plants,and (2) response limitations,which determine specific aspects of community composition, such as the competitive balance of trees and grasses. Though similar in some respects,these models simulate potential evapotranspiration and direct CO_2 effects differently, and as a result they show varying sensitivities to temperature,CO_2 levels,and other factors. Two of the models,LPJ and MC1 have biogeochemistry modules while the third,MAPSS,does not. Both LPJ and MC1 are dynamic vegetation models,while MAPSS is an equilibrium model.

LPJ

The LPJ-Model was constructed in a modular framework. Individual modules describe key ecosystem processes,including vegetation establishment, resource competition, growth,and mortality (Sitch, 2000). Vegetation structure and composition is described by nine plant functional types (PFTs) which are distinguished according to their plant physiological (C_3, C_4 photosynthesis),phenological (deciduous, evergreen) and physiognomic (tree, grass) attributes. The model is run on a grid cell basis with input of soil texture,monthly fields of temperature,precipitation,and percentage sunshine hours. Each grid cell is divided into fractions covered by the PFTs and bare ground. The presence and fractional coverage of an individual PFT depends on its specific environmental limits,and on the outcome of resource competition with the other PFTs.

Table 1. Key Characteristics of the Three Biogeochemical Models used in VEMAP II.

References	Biome-BGC Running and Hunt (1993)	Century Parton et al.(1994)	TEM Tian et al.(1999)
Responses of Plant Physiology			
CO_2	Reduction in canopy conductance and leaf N concentration;and increases in intercellular CO_2 concentration,production and water-use efficiency	Reductions in transpiration and leaf N concentration;and prescribed increases in potential production	Increases in intercellular CO_2 concentration and production
Temperature	Optimum temperature for photosynthesis;maintenance respiration increases with temperature; growth respiration increases with photosynthesis	Optimum temperature of production	Optimum temperature of gross primary production (GPP);maintenance respiration increases with temperature; growth respiration increases with GPP
Moisture regime	Canopy conductance increases with enhanced soil moisture and reduced vapor pressure deficit	Potential production increases with enhanced soil moisture	GPP increases with enhanced evapotranspiration;phenology modified with enhanced evapotranspiration
Solar radiation	Photosynthesis increases with enhanced photosynthetically active radiation (PAR)	None	GPP increases with enhanced PAR
Responses of Soil Processes			
CO_2	Soil moisture increases with reduced canopy conductance;decomposition decreases with lower N concentration in litterfall	Soil moisture increases with reduced transpiration;decomposition decreases with lower N concentration in litterfall	Decomposition decreases with lower N concentration in litterfall
Temperature	with increases in temperature:1) decomposition increases;2) soil moisture decreases:and 3) net N mineralization increases	with increases in temperature:1) decomposition increases;2) soil moisture decreases:and 3) net N mineralization increases	with increases in temperature:1) decomposition increases;2) soil moisture decreases:and 3) net N mineralization increases
Precipitation	Soil moisture increase with enhanced precipitation;optimum soil moisture for decomposition	Soil moisture increase with enhanced precipitation;optimum soil moisture for decomposition	Soil moisture increase with enhanced precipitation;optimum soil moisture for decomposition
Solar radiation	Soil moisture decreases with enhanced solar radiation	None	Soil moisture decreases with enhanced solar radiation
Disturbance Regimes	Prescribed mortality	Scheduled fire regimes	Implicitly implemented through litterfall fluxes

The two-layer soil water balance model is based on Haxeltine and Prentice (1996). Moisture in each layer, expressed as a fraction of water holding capacity, is updated daily. Percolation from the upper to the lower layer, and absolute water holding capacity are soil texture dependent.

Establishment and mortality are modeled on an annual basis. Plant establishment,in terms of additional PFT individuals,depends on the fraction of bare ground available for seedlings to successfully establish. Natural mortality is taken as a function of PFT vigor, and corresponds to an annual reduction in the number of PFT individuals. Dead biomass enters the litter pool,and the soil pools. Mortality also occurs due to disturbance (Thonicke et al.,2000).

MAPSS

The MAPSS (Mapped Atmosphere-Plant-Soil System) model begins with the application of ecophysiological constraints to determine which plant types can potentially occur at a given location. A two-layer hydrology module (including gravitational drainage) with a monthly time step then allows simulation of leaf phenology, leaf area index (LAI) and the competitive balance between grass and woody vegetation. A productivity index is derived based on leaf area duration and evapotranspiration. This index is used to assist in the determination of leaf form,phenology, and vegetation type,on the principle that any successful plant strategy must be able to achieve a positive Net Primary Production (NPP) during its growing season.

The LAI of the woody layer provides a light-limitation to grass LAI. Stomatal conductance is explicitly included in the water balance calculation,and water competition occurs between the woody and grass life forms through different canopy conductance characteristics as well as rooting depths. The direct effect of CO_2 on the water balance is simulated by reducing maximum stomatal conductance. The MAPSS model is calibrated against observed monthly runoff, and has been validated against global runoff (Neilson and Marks,1995). A simple fire model is incorporated to limit shrubs in areas such as the Great Plains (Neilson,1995).

The forest-grassland ecotone is reproduced by assuming that closed forest depends on a predictable supply of winter precipitation for deep soil recharge (Neilson et al.,1992). An index is used that decrements the woody LAI as the summer dependency increases.

MC1

MC1 consists of three linked modules simulating biogeography, biogeochemistry, and fire disturbance (Lenihan et al.,1998;Daly et al.,2000). The main functions of the biogeography module are:(1) to simulate the composition of deciduous/evergreen, needleleaf/broadleaf tree and C_3/C_4 grass life-form mixtures from climatic thresholds;and (2) to classify those woody and herbaceous life forms into different vegetation classes based on their biomass (or leaf area index) simulated by the biogeochemistry module.

The biogeochemistry module,which is based on the CENTURY model (Parton et al.,1987),simulates monthly carbon and nutrient dynamics for a given life-form mixture. It was configured to always allow tree-grass competition. Above- and below-ground processes are modeled in detail,and include plant production,soil organic matter decomposition,and water and nutrient cycling. Nitrogen (N) demand is always assumed to be met in this study and never limited by local conditions since there were no soil N data available to initialize and calibrate the model.

Parameterization of this module is based on the life form composition of the ecosystems,which is updated annually by the biogeography module. The fire module simulates the occurrence,behavior and effects of severe fire. Allometric equations, keyed to the life-form composition supplied by the biogeography module,are used to convert above-ground biomass to fuel classes. Fire effects (i.e.,plant mortality and live and dead biomass consumption) are estimated as a function of simulated fire behavior (i.e., fire spread and fire line intensity) and vegetation structure. Fire effects feed back to the biogeochemistry module to adjust the levels of the carbon and nutrient pools. A detailed description of the model can be found in Daly et al.(2000).

Simulated grazing is species-independent and only occurs in the model between April and September. Only grasses are consumed and there is no tree death assumed due to either consumption or trampling by herbivores. A fraction of the material consumed by the grazers (C and N) is returned to the site.

DATABASES

To meet the various input requirements of the biogeochemistry and biogeography models and ensure a common starting point for the VEMAP II simulations,the “baseline”database was created to incorporate "current" climate parameters (including atmospheric CO_2 of 354 ppmv in 1990), existing soil properties, a uniform vegetation classification, and two climate-change scenarios. Key database design criteria include temporal consistency, with daily and monthly climate sets having the same monthly average. The database is also spatially consistent with, for example, climate and vegetation reflecting topographic effects. And finally, the database is physically consistent, with relations maintained among climate variables and among soil properties in soil profiles.

The database covers the coterminous United States with a spatial resolution of 0.5°. The coterminous United States is made of about 3100 of the 0.5° x 0.5° grid cells. The baseline vegetation is assumed to be in equilibrium under current climate. The current vegetation distribution is determined by first defining a "potential" vegetation distribution based on ecophysiological and resource constraints.

VEGETATION IN THE FUTURE

Current cropland and urban areas are defined and a cropland and urban "mask" is applied to the potential vegetation distribution to define the extent of current natural vegetation. This same unchanged cropland and urban mask is used in throughout the 21st century in VEMAP II and so shifts in cropland areas and expansion of urban areas is not included.

Climate change scenarios are based on two atmospheric general circulation model (GCM) experiments – one conducted at the Hadley Centre for Climate Prediction and Research of the Meteorological Office of the United Kingdom (HadCM2 version) (henceforth, Hadley) and the other at the Canadian Centre for Climate Modelling and Analysis (henceforth, Canadian). These scenarios were selected because they are representative of the higher and lower halves of the range of temperature sensitivity among the "transient" GCMs available at the beginning of VEMAP II.

Because elevated CO_2 may directly affect plants independently of whether it causes any change in climate, VEMAP II included a partial factorial experimental design in which simulations were run with both climate and CO_2 changing through time and then only climate changing through time. Both the biogeochemistry and biogeography models were run with both transient climate and CO_2 and with transient climate alone.

For the biogeochemistry models, several aspects of carbon cycle changes were analyzed including changes in annual net primary production, and in annual net carbon storage. For the biogeography models, the focus was on changes in the area of major vegetation assemblages.

Table 2. Simulated Changes in Annual Net Primary Production due to Changes in Climate plus CO_2 and Climate only in the Conterminous United States.

Models	Modeled Current NPP	Factors affecting NPP	Changes Hadley Climate Simulation	 Canadian Climate Simulation
Biome-BGC	2800	Climate + CO_2	+439 (15.7%)	+222 (7.9%)
		Climate	+98 (3.6%)	-274 (-10.0%)
CENTURY	3300	Climate + CO_2	+177 (7.1%)	+72 (2.9%)
		Climate	+109 (4.4%)	+3 (0.1%)
TEM	3500	Climate + CO_2	+539 (15.4%)	+397 (11.3%)
		Climate	+221 (6.6%)	-102 (-3.1%)

Changes are given as deviations from "current" NPP as both absolute (Tg C/yr) and relative (%) values. Simulations are for the period 2025-2034.

BIOGEOCHEMICAL SIMULATION RESULTS

The three biogeochemistry models estimate continental scale Net Primary Production (NPP) in natural ecosystems for contemporary climate and CO_2. For NPP, estimates range from 2.8 Pg C/yr to 3.5 Pg C/yr. In the near term (2025-2034),all three models project small increases in continental NPP for both climate simulations when climate and CO_2 effects are considered (Table 2). For the scenario used,the CO_2 concentration in 2025-2034 averaged about 425 ppmv. The magnitude of the CO_2 fertilization effect in the decade 2025-2034 ranges from a low of about 3% in CENTURY to a high of 18% in Biome-BGC. These sensitivities to CO_2 differ from experimental results,in part,because most field experiments are done at doubled pre-industrial CO_2 (about 300 ppmv CO_2),higher than the projected levels in 2025-2034 in the mid-range IPCC emissions scenario used in this assessment. For the near-term climate simulated by the Canadian model,both Biome-BGC and TEM suggest that without a CO_2 fertilization effect, average annual NPP for the period 2025-2034 would decline relative to current average annual NPP. This is an important point since the exact magnitude of the CO_2 fertilization effect on NPP is uncertain for many natural ecosystems,especially forests.

Annual net carbon storage at the continental level is projected by all three biogeochemistry models to increase in the near term for both climate simulations,when climate and CO_2 effects are considered (Table 3). The biogeochemistry models estimate

Changes in Vegetation Carbon

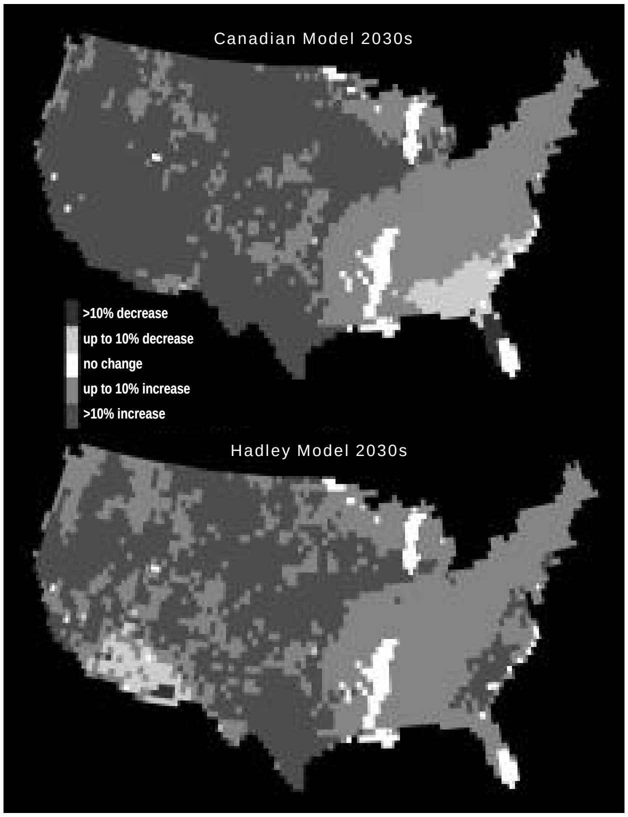


Figure 1. The maps above show projections of relative changes in vegetation carbon between 1990 and the 2030s for two climate scenarios. Under the Canadian model scenario, vegetation carbon losses of up to 20% are projected in some forested areas of the Southeast in response to warming and drying of the region by the 2030s. A carbon loss by forests is treated as an indication that they are in decline. Under the same scenario, vegetation carbon increases of up to 20% are projected in the forested areas in the West that receive substantial increases in precipitation. Output from TEM (Terrestrial Ecosystem Model) as part of the VEMAP II (Vegetation Ecosystem Modeling and Analysis Project) study.
See Color Plate Appendix

Table 3. Simulated Annual Net Carbon Storage due to Changes in Climate and CO_2 in the Major Regions of the Conterminous United States for "Today" and the Period 2025-2034 in Tg C/yr.

Region	Current	Future (2025-2034)	
		Canadian	Hadley
Northeast	3	9	13
Southeast	14	-4	34
Midwest	6	17	27
Great Plain	14	16	16
West	22	41	16
Northwest	7	17	11
Conterminous US Total	66	96	117

Results are the mean of three biogeochemistry models.

that today, the average carbon storage rate of 66 Tg/yr. For the climate simulated with the Hadley model over the period 2025-2034,the biogeochemistry models estimate an average carbon storage rate of 117 Tg/yr, almost a 100% increase relative to present. For the climate simulated with the Canadian model for the same period,the biogeochemistry models estimate an average carbon storage rate of 96 Tg/yr. One particularly interesting result becomes apparent when the annual carbon storage data are analyzed by regions (Table 3). For the climate simulated with the Canadian model,the mean projection of the biogeochemistry models is that the southeastern ecosystems will loose carbon in the near term (Figure 1). This ecological response is consistent with the hot,dry climate conditions the model projects for this region during the period of 2025-2034.

BIOGEOGRAPHY SIMULATION RESULTS

For both the Hadley and Canadian climate scenarios,the biogeography models project shifts in the distribution of major vegetation types as plant species move in response to climate change (Figure 2). An implicit assumption in the biogeography models is that vegetation will be able to move freely from location to location;an assumption that may be at least in part unwarranted because of the barriers to plant migration that have been put in place on landscapes through agricultural expansion and urbanization.

The projected changes in vegetation distribution with climate change vary from region to region (Figure 3a-f; Tables 4-9). Some of the major changes as simulated by the biogeography models for the six National Assessment regions of the coterminous US can be summarized as follows:

Northeast

- Under both simulated climates, forests remain the dominant natural vegetation,but the mix of forest types changes. For example,winter-deciduous forests expand at the expense of mixed conifer-broadleaf forests.
- Under the climate simulated by the Canadian model,there is a modest increase in savannas and woodlands.

Southeast

- Under the climate simulated by the Hadley model, forest remains the dominant natural vegetation,but once again the mix of forest types changes.
- Under the climate simulated by the Canadian model,all three biogeography models show an expansion of savannas and grasslands at the expense of forests. For two of biogeography models,LPJ and MAPSS,the expansion of these non-forest ecosystems is dramatic by the end of the 21st century. Both drought and fire play an important role in the forest breakup.

Midwest

- Under both simulated climates, forests remain the dominant natural vegetation,but the mix of forest types changes.
- One biogeography model,LBJ, simulates a modest expansion of savannas and grasslands.

Great Plains

- Under the climate simulated by the Hadley model,two biogeography models project an increase in woodiness in this region,while the third projects no change in woodiness.
- Under the climate simulated by the Canadian model,the biogeography models project either no change in woodiness or a slight decrease.

West

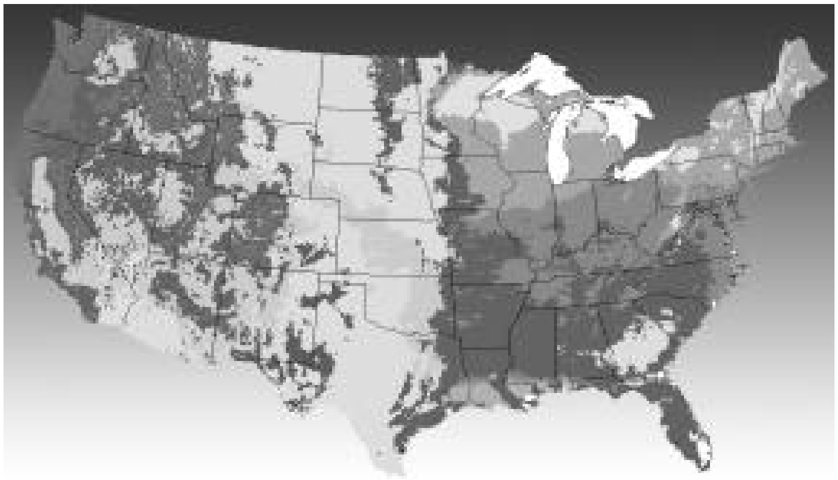
- Under the climate simulated by both the Hadley and Canadian models,the area of desert ecosystems shrinks and the area of forest ecosystems grows.

Northwest

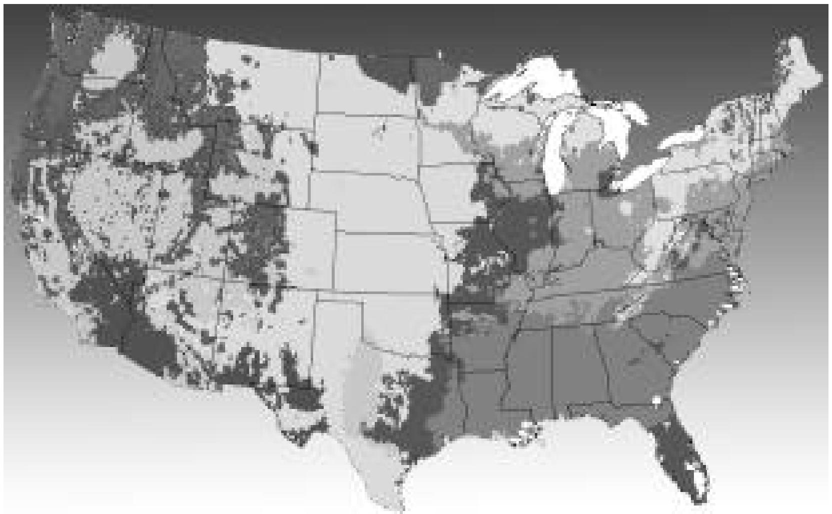
- Under both simulated climates,the forest area grows slightly.

Ecosystem Models

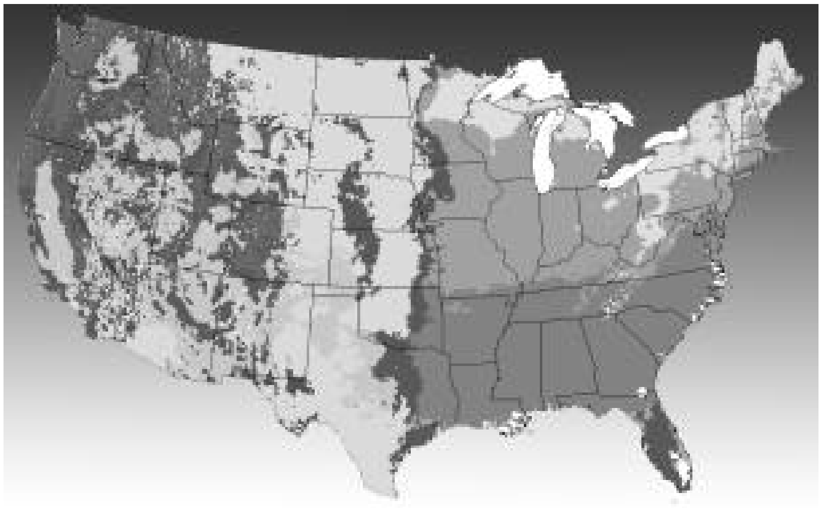
Current Ecosystems



Canadian Model



Hadley Model



- ▨ **Tundra**
- ▨ **Taiga / Tundra**
- ▨ **Conifer Forest**
- ▨ **Northeast Mixed Forest**
- ▨ **Temperate Deciduous Forest**
- ▨ **Southeast Mixed Forest**
- ▨ **Tropical Broadleaf Forest**
- ▨ **Savanna / Woodland**
- ▨ **Shrub / Woodland**
- ▨ **Grassland**
- ▨ **Arid Lands**

Figure 2. The models used to estimate biogeographic responses to climate change in VEMAP II include LPJ, MAPSS, and MC1. These three models predict the local dominance of various terrestrial vegetation forms based on: (1) ecophysiological constraints, which determine the broad distribution of major categories of woody plants; and (2) response limitations, which determine specific aspects of community composition, such as the competitive balance of trees and grasses. Though similar in some respects, these models simulate potential evapotranspiration and direct CO_2 effects differently, and as a result they show varying sensitivities to temperature, CO_2 levels, and other factors. Two of the model models, LPJ and MC1 have biogeochemistry modules, while the third, MAPPS, does not. For both the Hadley and Canadian climate scenarios, the biogeography models project shifts in the distribution of major vegetation types as plant species move in response to climate change. The projected changes in vegetation distribution with climate change vary from region to region. (Source: VEMAP, 1998).

See Color Plate Appendix

LPJ, MC1 and MAPSS Estimates

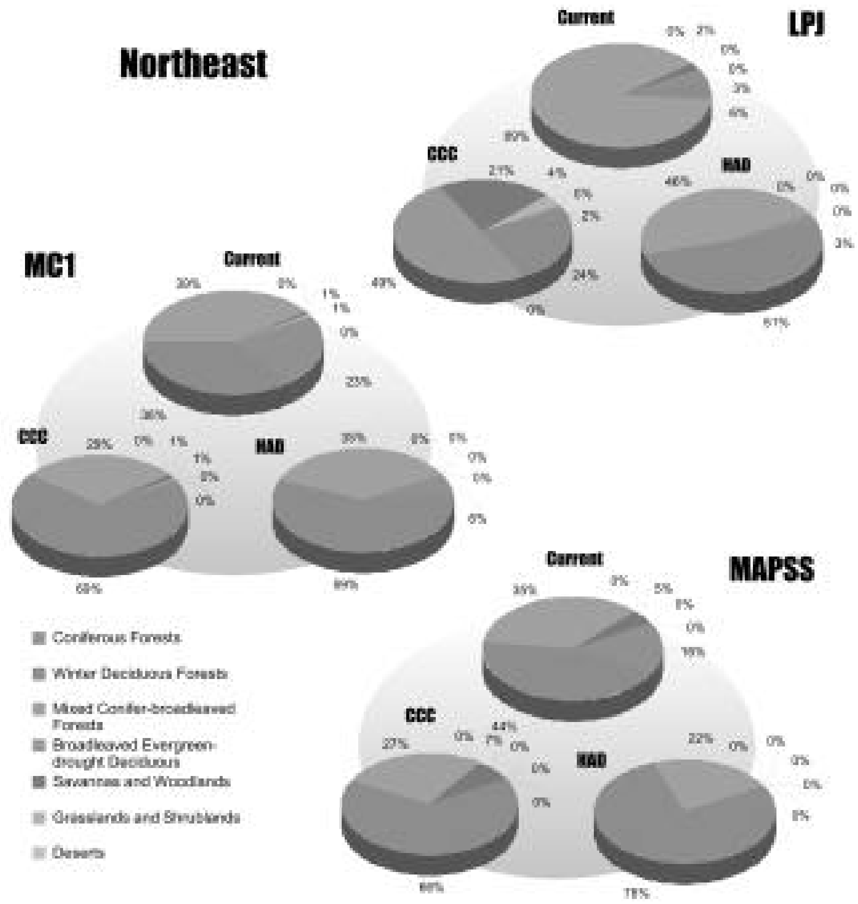


Figure 3(a) Under both simulated climates, forests remain the dominant natural vegetation, but the mix of forest types changes. For example, winter-deciduous forests expand at the expense of mixed conifer-broad-leaved forests. Under the climate simulated by the Canadian model, there is a modest increase in savannas and woodlands. **See Color Plate Appendix.**

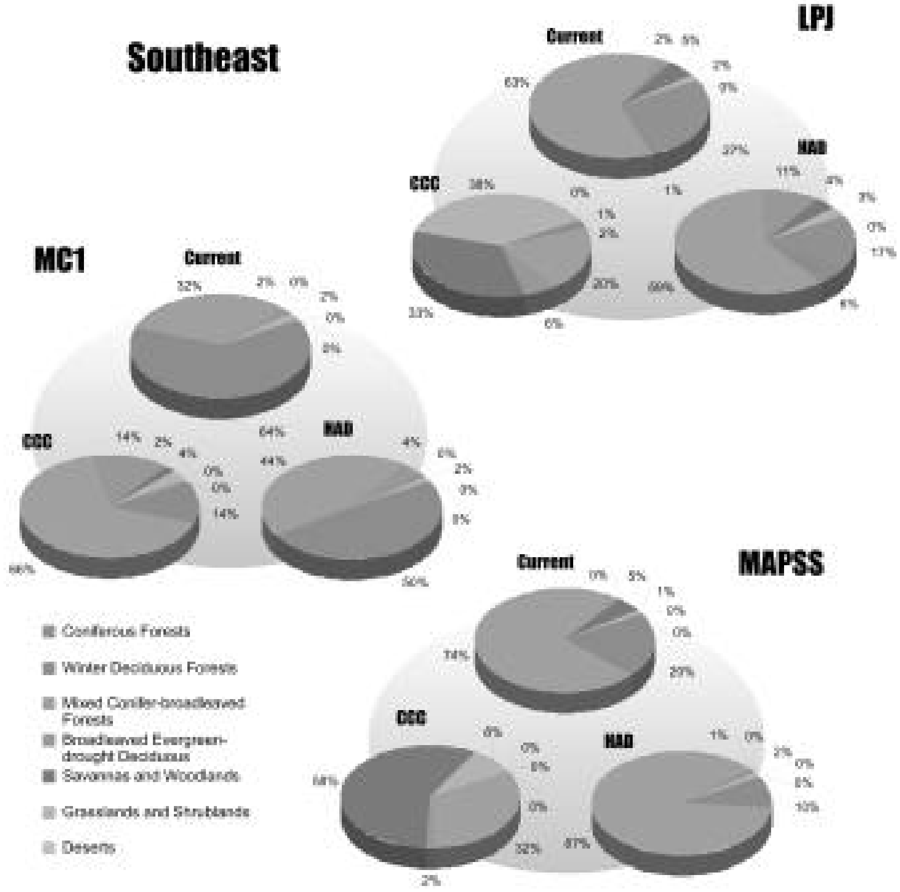


Figure 3(b) Under the climate simulated by the Hadley model, forest remains the dominant natural vegetation, but once again the mix of forest types changes. Under the climate simulated by the Canadian model, all three biogeography models show an expansion of savannas and grasslands at the expense of forests. For two of biogeography models, LPJ and MAPSS, the expansion of these non-forest ecosystems is dramatic by the end of the 21st century. Both drought and fire play an important role in the forest breakup. **See Color Plate Appendix.**

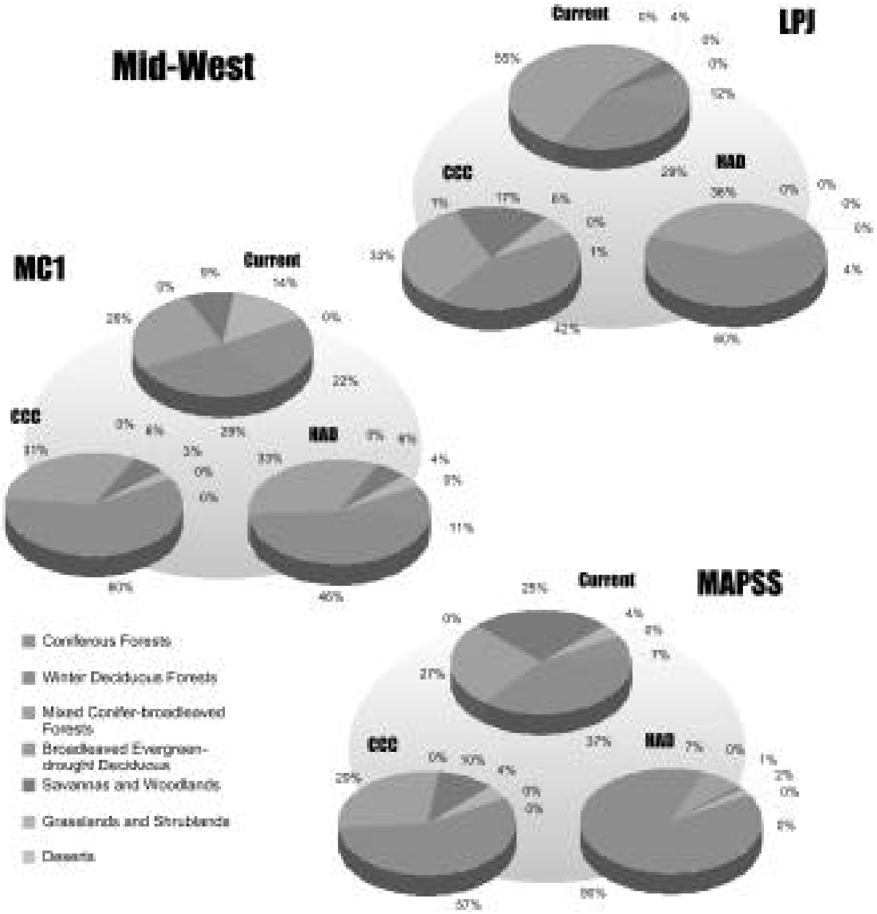


Figure 3(c) Under both simulated climates, forests remain the dominant natural vegetation, but the mix of forest types changes. One biogeography model, LBJ, simulates a modest expansion of savannas and grasslands. See Color Plate Appendix.

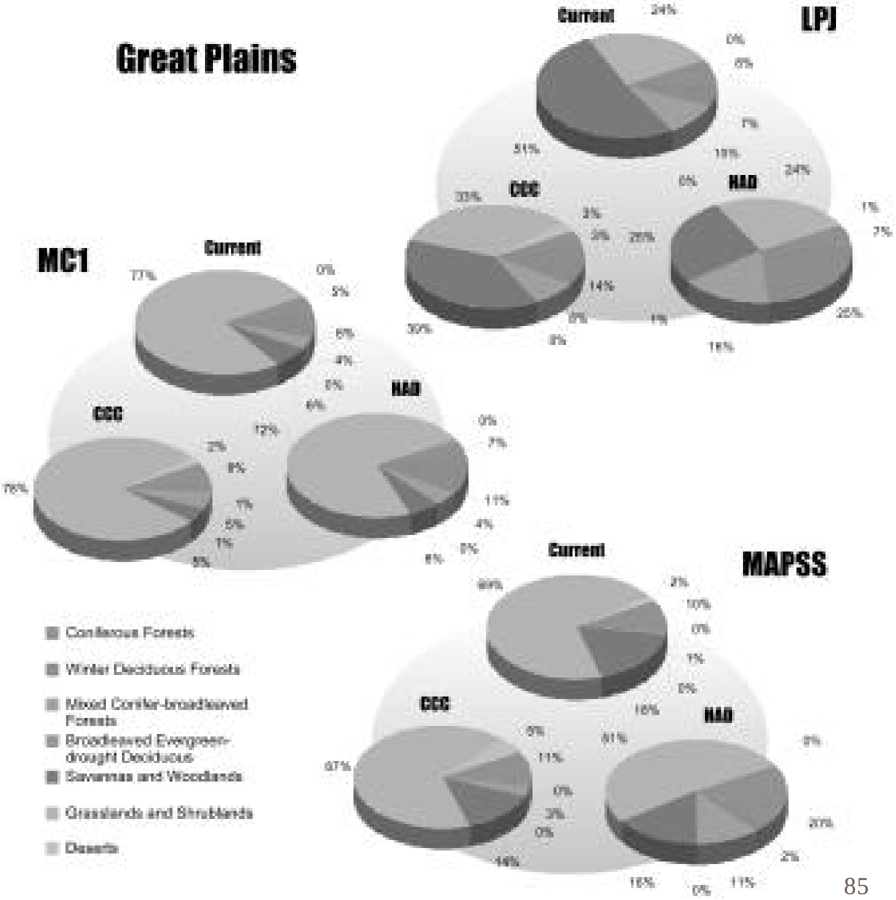


Figure 3(d) Under the climate simulated by the Hadley model, two biogeography models project an increase in woodiness in this region, while the third projects no change in woodiness. Under the climate simulated by the Canadian Model, the biogeography models project either no change in woodiness or a slight decrease. See Color Plate Appendix.

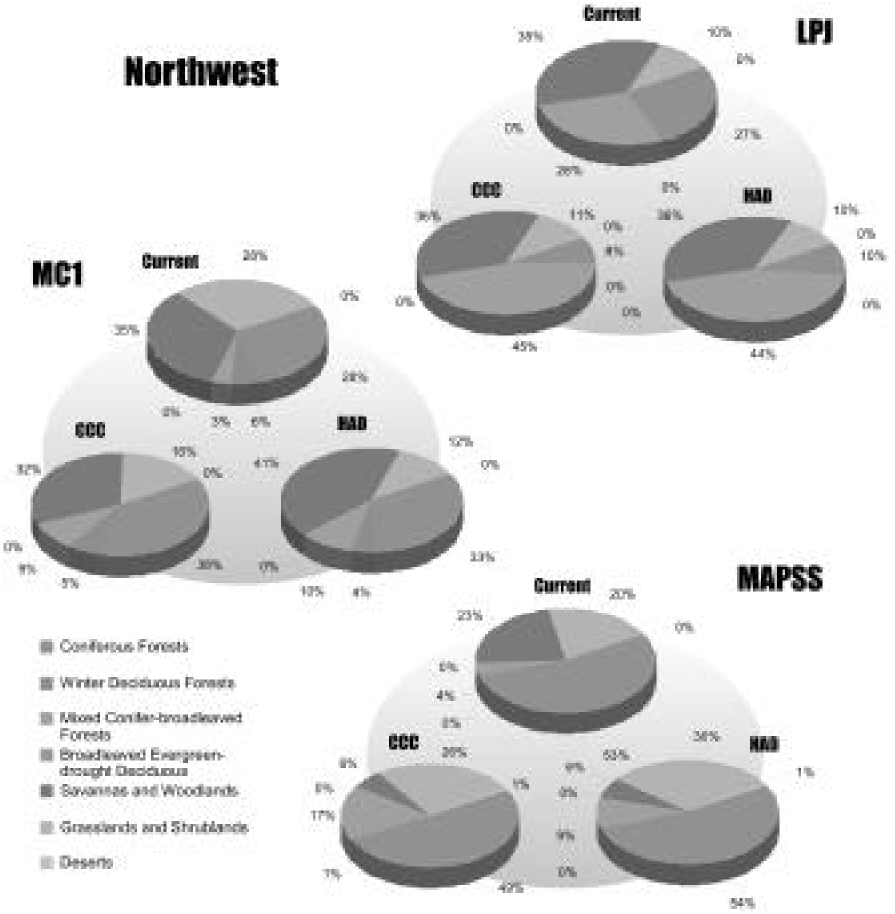


Figure 3(e): Under both simulated climates, the forest area grows slightly. See Color Plate Appendix.

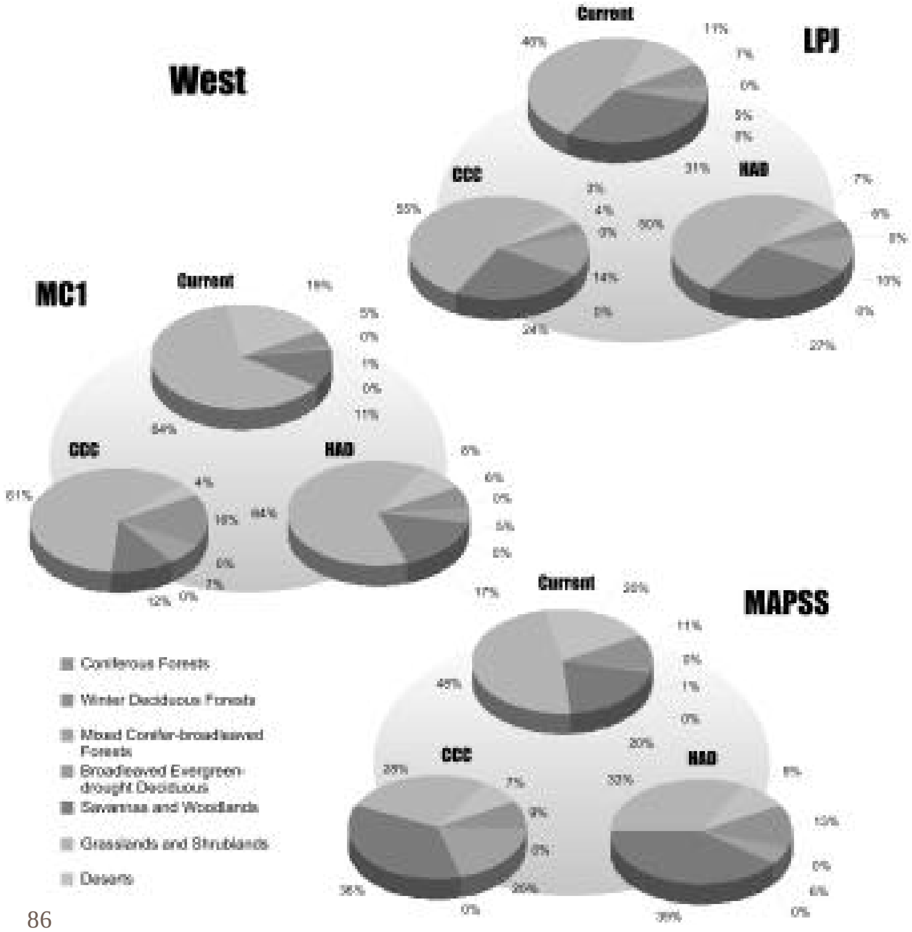


Figure 3(f). Under the climate simulated by both the Hadley and Canadian models, the area of desert ecosystems shrinks and the area of forest ecosystems grows. See Color Plate Appendix.

Table 4. Vegetation redistribution associated with climate change as estimated by LPJ using Hadley Climate. Current and future (2090-2099) distributions are presented as percentages of the total non-agricultural area in the region. (Neilson et al., 2000; EOS Webster, 2000)

Vegetation Type	Northeast		Southeast		Mid-west		Great Plains		Northwest		West	
	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future
Coniferous Forests	3.3	2.9	26.8	16.5	11.9	4.2	7.6	6.6	26.7	10.2	6.9	5.5
Winter Deciduous Forests	6.1	51.3	0.5	6.4	29.0	60.0	7.1	25.2	0.0	0.0	0.0	0.1
Mixed Conifer-broadleaved Forests	88.3	45.8	63.4	59.5	54.9	35.8	10.4	15.8	27.8	44.3	5.3	10.2
Broadleaved Evergreen-drought Deciduous	0. 0	0.0	2.0	10.6	0.0	0.0	0.0	0.7	0.0	0.0	0.0	0.0
Savannas and Woodlands	2.3	0.0	5.3	4.0	4.3	0.0	51.3	26.7	35.1	35.7	30.5	27.2
Grasslands and Shrublands	0.0	0.0	2.0	3.0	0.0	0.0	23.7	24.0	10.5	9.9	45.9	50.0
Deserts	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.9	0.0	0.0	11.3	7.0
Total	100	100	100	100	100	100	100	100	100	100	100	100

Table 5. Vegetation redistribution associated with climate change as estimated by LPJ using Canadian Climate. Current and future (2090-2099) distributions are presented as percentages of the total non-agricultural area in the region. (Neilson et al., 2000; Neilson and Drapek, 1998)

Vegetation Type	Northeast		Southeast		Mid-west		Great Plains		Northwest		West	
	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future
Coniferous Forests	3.3	1.9	26.8	1.1	11.9	0.5	7.6	3.4	26.7	8.3	6.9	5.6
Winter Deciduous Forests	6.1	23.9	0.5	1.6	29.0	42.9	7.1	13.7	0.0	0.0	0.0	0.0
Mixed Conifer-broadleaved Forests	88.3	0.0	63.4	20.2	54.9	32.5	10.4	8.4	27.8	45.3	5.3	13.7
Broadleaved Evergreen-drought Deciduous	0.0	49.6	2.0	6.3	0.0	1.1	0.0	0.0	0.0	0.0	0.0	0.0
Savannas and Woodlands	2.3	20.8	5.3	33.2	4.3	17.0	51.3	38.0	35.1	35.3	30.5	24.1
Grasslands and Shrublands	0.0	3.9	2.0	37.5	0.0	6.0	23.7	33.4	10.5	10.5	45.9	55.3
Deserts	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.1	0.0	0.0	11.3	3.2
Total	100	100	100	100	100	100	100	100	100	100	100	100

Table 6. Vegetation redistribution associated with climate change as estimated by MC1 using Hadley Climate. Current and future (2090-2099) distributions are presented as percentages of the total non-agricultural area in the region. (Neilson et al., 2000; Bachelet, et al., 2000)

Vegetation Type	Northeast		Southeast		Mid-west		Great Plains		Northwest		West	
	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future
Coniferous Forests	22.8	6.1	0.0	0.0	22.2	10.8	5.3	6.5	28.1	32.8	5.0	6.4
Winter Deciduous Forests	35.9	58.5	63.9	49.4	28.3	46.7	7.8	10.8	6.4	4.2	0.0	0.2
Mixed Conifer-broadleaved Forests	39.5	35.3	31.7	44.1	26.2	32.7	3.8	4.3	3.3	9.5	1.4	4.7
Broadleaved Evergreen-drought Deciduous	0.0	0.0	2.3	4.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Savannas and Woodlands	0.7	0.0	0.0	0.4	8.9	5.9	6.3	6.0	33.9	41.8	11.6	17.1
Grasslands and Shrublands	1.1	0.0	2.1	1.7	14.4	3.9	76.8	72.3	28.3	11.6	63.7	63.4
Deserts	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	19.7	8.3
Total	100	100	100	100	100	100	100	100	100	100	100	100

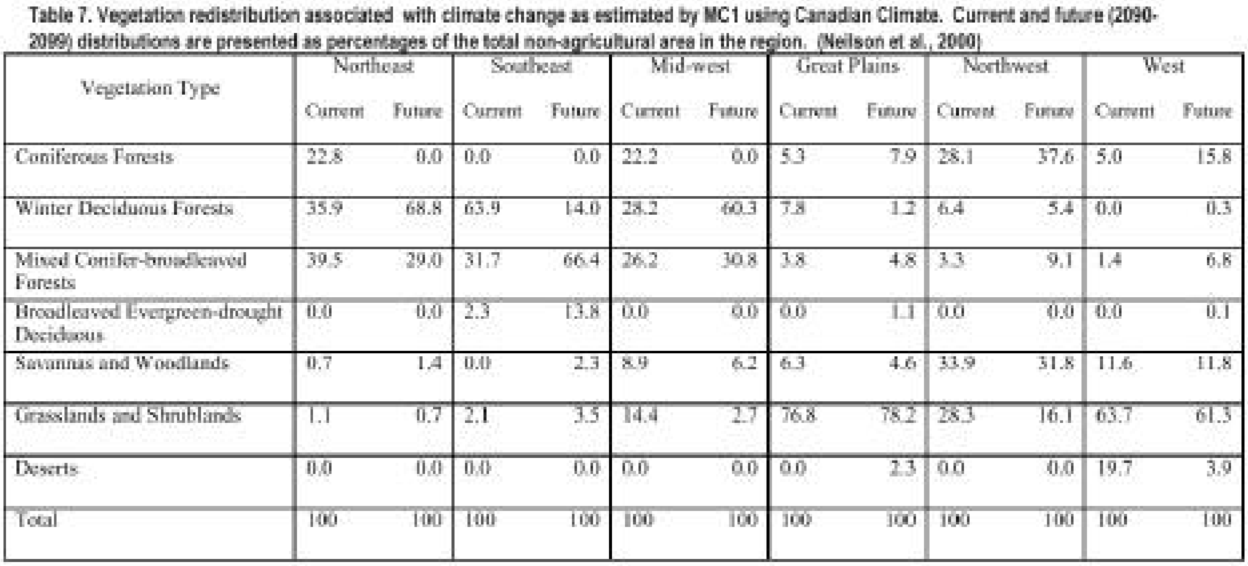


Table 7. Vegetation redistribution associated with climate change as estimated by MC1 using Canadian Climate. Current and future (2090-2099) distributions are presented as percentages of the total non-agricultural area in the region. (Neilson et al., 2000)

Vegetation Type	Northeast		Southeast		Mid-west		Great Plains		Northwest		West	
	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future
Coniferous Forests	22.8	0.0	0.0	0.0	22.2	0.0	5.3	7.9	28.1	37.6	5.0	15.8
Winter Deciduous Forests	35.9	68.8	63.9	14.0	28.2	60.3	7.8	1.2	6.4	5.4	0.0	0.3
Mixed Conifer-broadleaved Forests	39.5	29.0	31.7	66.4	26.2	30.8	3.8	4.8	3.3	9.1	1.4	6.8
Broadleaved Evergreen-drought Deciduous	0.0	0.0	2.3	13.8	0.0	0.0	0.0	1.1	0.0	0.0	0.0	0.1
Savannas and Woodlands	0.7	1.4	0.0	2.3	8.9	6.2	6.3	4.6	33.9	31.8	11.6	11.8
Grasslands and Shrublands	1.1	0.7	2.1	3.5	14.4	2.7	76.8	78.2	28.3	16.1	63.7	61.3
Deserts	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.3	0.0	0.0	19.7	3.9
Total	100	100	100	100	100	100	100	100	100	100	100	100

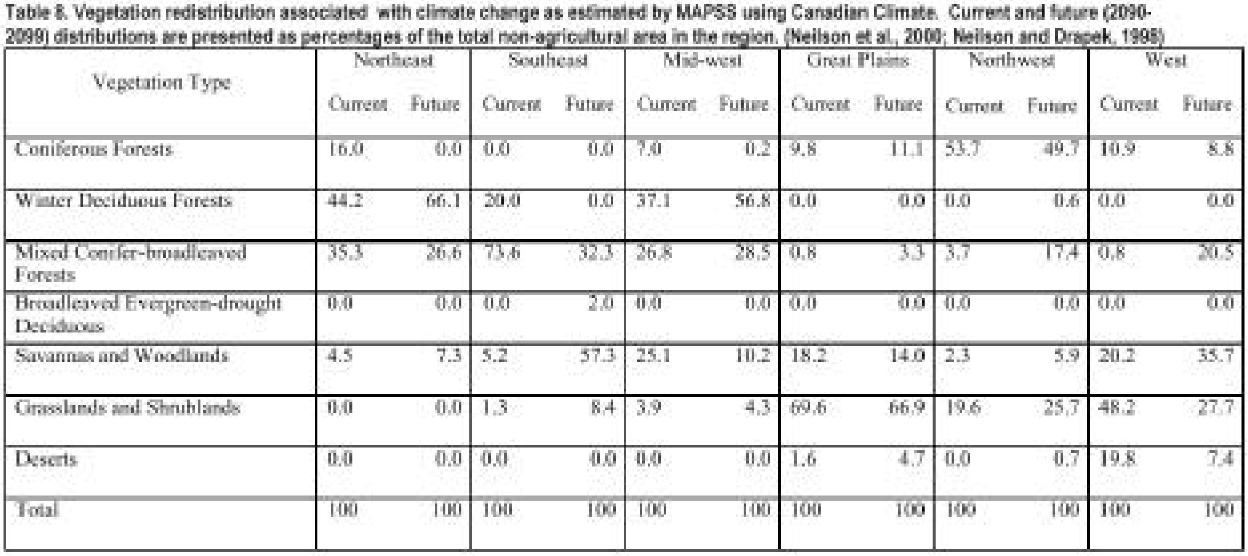


Table 8. Vegetation redistribution associated with climate change as estimated by MAPSS using Canadian Climate. Current and future (2090-2099) distributions are presented as percentages of the total non-agricultural area in the region. (Neilson et al., 2000; Neilson and Drapek, 1998)

Vegetation Type	Northeast		Southeast		Mid-west		Great Plains		Northwest		West	
	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future
Coniferous Forests	16.0	0.0	0.0	0.0	7.0	0.2	9.8	11.1	53.7	49.7	10.9	8.8
Winter Deciduous Forests	44.2	66.1	20.0	0.0	37.1	56.8	0.0	0.0	0.0	0.6	0.0	0.0
Mixed Conifer-broadleaved Forests	35.3	26.6	73.6	32.3	26.8	28.5	0.8	3.3	3.7	17.4	0.8	20.5
Broadleaved Evergreen-drought Deciduous	0.0	0.0	0.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Savannas and Woodlands	4.5	7.3	5.2	57.3	25.1	10.2	18.2	14.0	2.3	5.9	20.2	35.7
Grasslands and Shrublands	0.0	0.0	1.3	8.4	3.9	4.3	69.6	66.9	19.6	25.7	48.2	27.7
Deserts	0.0	0.0	0.0	0.0	0.0	0.0	1.6	4.7	0.0	0.7	19.8	7.4
Total	100	100	100	100	100	100	100	100	100	100	100	100

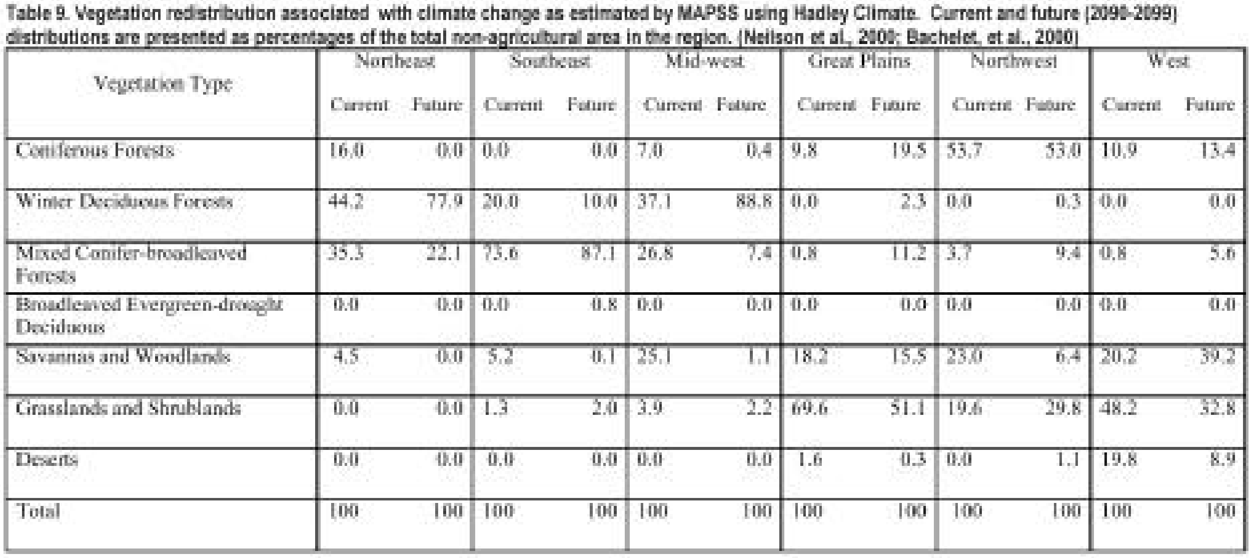


Table 9. Vegetation redistribution associated with climate change as estimated by MAPSS using Hadley Climate. Current and future (2090-2099) distributions are presented as percentages of the total non-agricultural area in the region. (Neilson et al., 2000; Bachelet, et al., 2000)

Vegetation Type	Northeast		Southeast		Mid-west		Great Plains		Northwest		West	
	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future
Coniferous Forests	16.0	0.0	0.0	0.0	7.0	0.4	9.8	19.5	53.7	53.0	10.9	13.4
Winter Deciduous Forests	44.2	77.9	20.0	10.0	37.1	88.8	0.0	2.3	0.0	0.3	0.0	0.0
Mixed Conifer-broadleaved Forests	35.3	22.1	73.6	87.1	26.8	7.4	0.8	11.2	3.7	9.4	0.8	5.6
Broadleaved Evergreen-drought Deciduous	0.0	0.0	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Savannas and Woodlands	4.5	0.0	5.2	0.1	25.1	1.1	18.2	15.5	23.0	6.4	20.2	39.2
Grasslands and Shrublands	0.0	0.0	1.3	2.0	3.9	2.2	69.6	51.1	19.6	29.8	48.2	32.8
Deserts	0.0	0.0	0.0	0.0	0.0	0.0	1.6	0.3	0.0	1.1	19.8	8.9
Total	100	100	100	100	100	100	100	100	100	100	100	100

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