Ecosystem Productivity and the Impact of Climate Change

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Introduction

Earlier analyses of the supply and demand of timber assumed the continuation of historical climate and thus, did not explicitly incorporate factors such as temperature or precipitation into the projections of timber growth. Forests are adapted to local climates and changes in these climates are likely to impact future forest growth and timber outputs. Within the strategic planning process of the Forest Service (Joyce et al. 1997), the analysis of ecosystem productivity, as influenced by climatic factors, has been identified as a critical question in order to address the challenging problems associated with climate change:

- What are the likely effects of increasing atmospheric carbon dioxide and prospective climate change on ecosystem productivity, as measured by changes in net primary productivity?

In the last RPA Assessment (USDA Forest Service 1994), the consequences of elevated carbon dioxide and climate change on net primary productivity of forests were examined using climate model scenarios and an ecological model, TEM (Joyce et al. 1995). These results were then used to examine the impact of climate change on the supply and demand for timber products on private timberlands in the United States (see fig. 1.1, Joyce and Birdsey this volume). In this analysis, most of the forest productivity changes across the United States were positive, leading to increases in the timber inventories. With this change in harvestable inventories, timber harvests across the United States shifted as demand in various regions adjusted to take advantage of lower cost raw materials. Since these last RPA analyses, new experimental data and modeling analyses enhance the picture of the potential impact of carbon dioxide and climate change on forests. In this chapter, we present the results of such research.

New experiments on the impact of carbon dioxide on vegetation and meta-analyses of the accumulated research have demonstrated the impact of carbon dioxide on plant processes. In this chapter, we compare the impact of elevated carbon dioxide on ecosystem productivity, as determined from recent experimental data, with productivity results from the last RPA and other ecological model analyses. In addition, we explore whether these potential productivity shifts are within the range of productivity shifts that timber management treatments could induce in managed forests. We compare the results of economic research analyzing the potential to increase timber growth as an incentive to store carbon with these projected changes in productivity from climate change.

In the last RPA Assessment, two of the modeling assumptions were: 1) climate and vegetation were in equilibrium, and 2) the spatial scale of the ecological model was an adequate scale for national level analyses. Recent modeling studies have examined these assumptions.

In most ecological models (even now), vegetation is represented as pristine mature vegetation, rather than the actual vegetation of many different age classes, successional stages, introduced species, and management histories. Further, for both the ecological and the economic models, a broad range of habitats and species were aggregated into ecosystems or timber management types, respectively, for modeling purposes. The vegetation aggregation schemes and the nature of the spatial extrapolation differ between the ecological and the economic models. The implications of an ecological versus a timber management classification scheme are discussed in this chapter.

Computational problems arise when integrating or linking models that operate at different temporal and spatial scales. Computational limitations force a tradeoff between the spatial extent of the analysis (often dictated by policy considerations) and the grain of the analysis. Climate models, in order to compute global dynamics, operate at large spatial scales; grid cells range from 4 degrees to 10 degrees, resulting in coarse resolution of mountainous regions and small scale climate features. Meso-scale climate modeling now offers a finer depiction of climate features and the possibility to incorporate the effects of vegetation and land use feedbacks onto the atmospheric processes, but at large computational cost. Given this opportunity, it is important to understand the utility of going to a finer scale in the ecological analyses because the computational intensity increases by an order of magnitude when a 10 km scale is used instead of the traditional 0.5 degree scale. In this chapter, we report research results quantifying the climate change responses in ecosystem productivity at finer versus coarser spatial scales.

Plant and Ecosystem Productivity

Impact of Elevated Carbon Dioxide on Productivity

Net primary production (NPP) is the process by which the vegetation in an ecosystem captures carbon from the atmosphere. The changes in ecosystem productivity projected from ecological models reflect climate changes as well as the potential influence of carbon dioxide fertilization on net primary production. In the last RPA analysis (Joyce 1995), NPP of temperate forests in the U.S. increased from 8 percent to 27.2 percent, depending upon the climate scenario used (table 3.1). More recent analyses using a revised version of the Terrestrial Ecosystem Model (TEM) corroborate these earlier results, with some exceptions. A large modeling study compared the responses of several biogeochemistry models for all ecosystems within the conterminous United States to altered climate and elevated carbon dioxide (VEMAP members 1995). Averaged across all ecosystems, NPP responses increased from 1.7 to 34.6 percent (table 3.1). The NPP responses from TEM were higher than the responses for the Century Model (Parton et al. 1987, 1993) and the Biome-BGC model (Running 1994; Running and Coughlan 1988) (table 3.1). The largest NPP response for both TEM and Century (34.6 and 23.6 percent respectively) was for the UKMO scenario, in contrast to the response of Biome-BGC (1.7 percent increase). The lowest NPP increase for both TEM and Century was reported for the OSU scenario, again in contrast to the response of Biome-BGC. At the global scale, the NPP responses to climate change and elevated carbon dioxide for a revised version of TEM (Xiao et al. 1997) are lower than the NPP responses reported for the last RPA analysis. However, this result reflects the global extent of these measures.

These projected responses to altered climate and elevated atmospheric carbon dioxide incorporate the variation of climate and ecosystems across the United States or the globe. In contrast, experimental studies explore the underlying mechanisms for a plant's response to a change in atmospheric carbon dioxide in a controlled environment. Elevated atmospheric carbon dioxide has been shown to increase photosynthesis, enhance rates of carbon assimilation, increase stem and root biomass, and interact with other plant nutrients (Ceulemans and Mousseau 1994; Curtis and Wang 1998; McGuire et al. 1995b; Saxe et al. 1998). In a review of woody plants, Ceulemans and Mousseau (1994) reported the mean biomass increment from elevated CO_2 was +38 percent for coniferous trees and +63 percent for deciduous trees. For coniferous trees, the range of responses was from +0 percent to +95 percent. For deciduous trees, the range was from –47 to +290 percent. Summarizing studies not involving stress components, Saxe et al. (1998) reported larger average long-term biomass increment differences under elevated CO_2 for conifers of +130 percent and smaller averages for deciduous trees, +49 percent.

Table 3.1—Net primary production response (%) to climate change and elevated carbon dioxide for different biogeochemical models (TEM: Terrestrial Ecosystem Model; Cen: Century Model; BBGC: Biome-BGC) and at different spatial extents.

	Conterminous United States					Globe
	All forests		All ecosystems			Ecosystems
Climate scenario	TEM[1]	TEM[2]	TEM[3]	Cen[3]	BBGC[3]	TEM[4]
GISS[5]	27.2					20.6
GFDL-1	8.0					
GFDL-Q	12.1	13.1				18.5
OSU	17.4	29.6	26.5	14.6.	9.4	
GFDL-R30			30.5	22.1	20.2	
UKMO			34.6	23.6	1.7	
MIT L-O						17.8

[1] Joyce (1995)

[2] Nungesser et al. (1999)

[3] VEMAP members (1995)

[4] Xiao et al. (1997)

[5] GISS refers to the scenario from the Goddard Institute for Space Science model, GFDL-1 and GFDL-Q refer to results from the Geophysical Dynamics Lab model, OSU refers to a climate model developed by Schlesinger and others at Oregon State University, UKMO refers to the United Kingdom Meteorology Office model, and MIT refers to the Massachusetts Institute of Technology model

These responses from experimental studies are not without controversy. Of particular concern is whether the response is sustained over the life span of the tree. Most of these studies are done with seedlings or juvenile trees. Norby et al. (1992) concluded that a response in productivity was the result of an early stimulus and that no further sustained response was observed. Gorissen et al. (1995) suggest that an initial growth stimulation may be canceled by later physiological or morphological adaptations. For Yellow-popular (*Liriodendron tulipifera L.*), whole-plant carbon storage did not increase even though leaf-level photosynthesis and lower rates of foliar respiration in CO_2 enriched trees was observed (Norby et al. 1992). A number of studies have suggested that there may be a response specificity among tree genera (Ceulemans and Mousseau 1994) to an increase in atmospheric CO_2 as well as within genera (Ceulemans et al. 1996). DeLucia et al. (1994) suggested that allocation patterns in ponderosa pines may offset any increases in photosynthesis, resulting in potential declines in productivity under altered climate and elevated atmospheric carbon dioxide. Responses in natural stands are uncertain.

Curtis and Wang (1998) conducted a meta-analysis of over 500 reports on experiments on the effect of elevated carbon dioxide on woody plant mass, form, and physiology. These studies showed substantial variation in plant response to elevated CO_2, ranging from inhibition of growth to over 500 percent enhancement relative to plants grown in ambient conditions. Irrespective of the growing conditions, they found that total biomass increased significantly at about twice ambient atmospheric carbon dioxide concentrations, averaging a 31 percent increase. Stress altered the responses. Low nutrient availability reduced the CO_2 response to a 16 percent increase. Low light increased the response to 52 percent. They found no shifts in biomass allocation under elevated CO_2. Belowground responses were sensitive to length of the study and the stresses induced.

Pan et al. (1998) examined the modeled responses of terrestrial ecosystems to elevated atmospheric carbon dioxide. The forested ecosystem NPP response ranged from +3 to +23 percent increases (table 3.2). While these biogeochemistry models assume optimal responses similar to those observed experimentally (e.g., 25–50 percent), these spatially extrapolated responses to elevated carbon dioxide by ecosystem are substantially lower. When examined for underlying differences, Pan et al. (1998) noted that the three models tend to agree in their projected estimates of NPP response to doubled carbon dioxide along precipitation gradients, but differ along temperature gradients. Although the experimental literature is expanding with CO_2- impact studies, there is little information on the relative ecosystem-level response of NPP to elevated CO_2 along climatic gradients (Pan et al. 1998). These biogeochemistry models serve as different hypotheses on how ecosystem processes control the NPP response to elevated CO_2.

Table 3.2—Net primary production (NPP) response (%) to doubled atmospheric CO_2 (710 versus 355 ppmv) simulated by the VEMAP biogeochemistry models (Pan et al. 1998).

Forest type	BIOME-BGC	Century	TEM
Boreal conifer	6.05	3.37	3.50
Maritime conifer	10.09	4.10	7.59
Continental conifer	15.97	4.51	4.12
Cool temperate mixed	12.74	1.88	3.08
Warm temperate/subtropic mixed	6.69	2.25	11.82
Temperate deciduous	15.50	4.16	8.19
Temperate mixed xeromophic	10.94	10.00	21.22
Temperate conifer xeromophic	22.59	4.95	23.31

When experimental studies (since 1993) reporting changes in biomass are grouped by forest type, the species response is variable (table 3.3). This variability is explained, in some cases, by the different treatments. Optimal conditions, such as high N, tend to improve the biomass response to elevated carbon dioxide.

Within forest types, NPP responses (table 3.4) from the last RPA analysis ranged from a 0.9 percent decline for temperate deciduous forest productivity to an increase of 38.6 percent for boreal forest productivity. The experimental studies on woody species associated with boreal forest types showed responses to elevated carbon dioxide of 13 to 50 percent increases (table 3.3). Results from the modeling studies, which include potential changes in climate as well as carbon dioxide, ranged from increases of 23.8 to 38.6 percent (table 3.4). For the temperate deciduous species, the experimental results included a decline of 16 percent to an increase of 224 percent. Results in the modeled studies for temperate deciduous forests ranged from a decline of 0.9 percent to an increase of 36.6 percent. For conifer species, the experimental results ranged from no significant increases to an increase of 225 percent. Responses from the modeled studies for temperate coniferous forests ranged from a 15.7 percent increase to a 48.3 percent increase in NPP. These projected responses to elevated CO_2 and climate in the last RPA analyses are lower than the potential responses in the experimental studies (table 3.3 versus table 3.4).

Pan et al. (1998) detected the different ecosystem-level hypotheses that these biogeochemistry models reflect. These areas of uncertainty, if examined, identify opportunities to refine our ability to assess the impact of climate change on ecosystems:

- What role does the hydrological cycle play in controlling the CO_2 responses of leaf area and soil moisture along temperature and moisture gradients?

Table 3.3—Biomass response (percent) by woody species under elevated carbon dioxide in experimental studies.

Species	Significant	Non-significant	Percent Response	Source
Boreal				
Picea abies	Above-ground biomass (fresh wt)		16	Polle et al. (1993)
Picea glauca	Total biomass		44	Yakimchuk and Hoddinott (1994)
Picea mariana	Total biomass		13	Lord et al. (1993)
Picea mariana	Total biomass		50	Yakimchuk and Hoddinott (1994)
Picea sitchensis	Total biomass-irrigation/fertilization		52	Townend (1995)
Picea sitchensis		Total biomass-irrigation	19	Townend (1995)
Picea sitchensis	Total biomass-fertilization		44	Townend (1995)
Picea sitchensis	Total biomass-no irrigation or fertilization		49	Townend (1995)
Temperate coniferous				
Pinus banksiana		Total biomass	82	Yakimchuk and Hoddinott (1994)
Pinus silvestris		Shoot biomass	NS	Ineichen et al. (1995)
Pinus silvestris	Root biomass		57	Ineichen et al. (1995)
Pinus taeda		Total biomass-low N	37	Griffin et al. (1995)
Pinus taeda	Total biomass-high N		82	Griffin et al. (1995)
Pinus taeda	Total root biomass		124	King et al. (1996)
Pinus taeda	Total root biomass		225	King et al. (1996)
Pinus taeda	Total root biomass		64	King et al. (1996)
Pinus taeda	Total root biomass		102	King et al. (1996)
Pinus taeda	Total biomass		111	Tissue et al. (1996)
Pinus ponderosa		Total biomass-low temp	6	Delucia et al. (1994)
Pinus ponderosa	Total biomass-high temp		30	Delucia et al. (1994)
Pinus ponderosa		Total biomass-low N	48	Griffin et al. (1995)
Pinus ponderosa	Total biomass-high N		82	Griffin et al. (1995)
Pinus ponderosa	Total root biomass		97	King et al. (1996)
Pinus ponderosa	Total root biomass		86	King et al. (1996)
Pinus ponderosa	Total root biomass		153	King et al. (1996)
Pseudotsuga menziesii		Total biomass-age 3	37	Gorissen et al. (1995)
Pseudotsuga menziesii		Total biomass-age 4	3	Gorissen et al. (1995)
Temperate deciduous				
Prunus avium	Total biomass-low N		12	Wilkins et al. (1994)
Prunus avium	Total biomass-decline		-13	Wilkins et al. (1994)
Prunus avium	Total biomass-high N		81	Wilkins et al. (1994)
Prunus avium	Total biomass-high N		57	Wilkins et al. (1994)
Prunus avium X pseudocerasus	Leaf, shoot-2 month	Leaf, shoot, root-10 month	51	Atkinson et al. (1997)
Quercus robur	Leaf, shoot-10 month		224	Atkinson et al. (1997)
Quercus rubra	Total biomass, leaf mass		121	Lindroth et al. (1993)
Quercus rubra	Total biomass		47	Miao (1995)
Alnus rubra	Total biomass		72	Hibbs et al. (1995)
Alnus rubra	Total biomass		59	Hibbs et al. (1995)
Populus deltoides x nigra	Stem volume		58	Ceulemans et al. (1996)
Populus deltoides x nigra	Total branch biomass		108	Ceulemans et al. (1996)
Populus deltoides x nigra	Total biomass of leaves		49	Ceulemans et al. (1996)

continued

Table 3.3 (continued).

Species	Significant	Non-significant	Percent Response	Source
Populus deltoides x nigra	Total biomass		49	Curtis et al. (1995)
Populus deltoides x nigra	Total biomass		25	Curtis et al. (1995)
Populus tremuloides	Total biomass, leaf mass		48	Lindroth et al. (1993)
Populus trichocarpa x deltoides	Stem volume		43	Ceulemans et al. (1996)
Populus trichocarpa x deltoides	Total branch biomass		81	Ceulemans et al. (1996)
Populus trichocarpa x deltoides	Total biomass of leaves		36	Ceulemans et al. (1996)
Acer rubrum		Total, fine/coarse root mass	6	Berntson and Bazzaz (1996)
Acer saccharum		Total biomass	44	Lindroth et al. (1993)
Acer saccharum		Total biomass	7	Noble et al. (1992)
Acer saccharum		Total biomass	103	Noble et al. (1992)
Betula alleghaniensis	Stem mass, root mass, leaf mass		94	Rochefort and Bazzaz (1992)
Betula alleghaniensis family *G*	Total biomass		51	Wayne and Bazzaz (1997)
Betula alleghaniensis family *W*	Total biomass		30	Wayne and Bazzaz (1997)
Betula alleghaniensis family *Y*		Total biomass	–16	Wayne and Bazzaz (1997)
Betula lenta	Stem mass, root mass, leaf mass		119	Rochefort and Bazzaz (1992)
Betula papyrifera	Total biomass, fine/coarse root mass		43	Berntson and Bazzaz (1996)
Betula papyrifera	Stem mass, root mass, leaf mass		52	Rochefort and Bazzaz (1992)
Betula populifolia	Stem mass, root mass, leaf mass		144	Rochefort and Bazzaz (1992)
Liriodendron tulipifera	Tap root		12	Norby et al. (1992)
Liriodendron tulipifera		Branches, leaves, bole	37	Norby et al. (1992)

Table 3.4—Comparison of projected changes in forest productivity under climate change and elevated carbon dioxide.

	TEM[1]				TEM[2]	
Forest type	GFDL-1	GFDL-Q	GISS	OSU	OSU	GFDL-Q
Boreal	38.6	34.6	35.9	24.5	23.8	30.9
Boreal forest wetland	39.0	26.1	29.6	25.8	19.3	23.5
Temperate conifer	24.1	21.1	26.5	15.7	35.3	48.3
Temperate deciduous	–0.9	4.2	36.6	18.8	29.9	7.5
Temperate mixed	7.9	14.4	21.8	14.5	27.4	9.3
Temperate broad-leaved evergreen	23.0	20.7	24.8	17.2		
Temperate forest wetland	–0.1	3.6	25.4	34.8	42.2	2.3
All forests	8.1	12.2	27.2	17.4	29.6	13.1

[1] Joyce (1995)

[2] Nungesser et al. (1999)

- What role does the nitrogen cycle play in the CO_2 responses of leaf area and leaf nitrogen content along temperature and moisture gradients?
- What is the relative role of changes in nitrogen requirements, allocation, tissue C to N ratios, and rates of decomposition in determining CO_2 responses along temperature and moisture gradients?
- What are the relative contributions and importance of interactions between the hydrological and nutrient cycles in controlling NPP responses to elevated CO_2?

Importantly, Pan et al. (1998) conclude that future studies should measure the fluxes and the pools of carbon, nitrogen, and water. A clear picture of both fluxes and pools is important in improving our understanding of the interactions among processes that control CO_2 responses of ecosystems. Our understanding of these processes is the basis for the development of policies on carbon sequestration options in forests.

Climate Versus Management Influences in Timber Productivity

The productivity shifts in the last RPA climate change analysis were a response to increased atmospheric carbon dioxide and changes in temperature and precipitation. The time period was 50 years. Are those productivity shifts similar to the biological potential of current U.S. forests? Or are those productivity shifts similar to increases seen under economic opportunities fostered by timber management over a similar time frame? Vasievich and Alig (1996) used forest inventory data to assess the potential to increase timber growth for carbon storage. Biological opportunities were defined as the potential net annual growth of the most productive plots (top 20% of measured plots) for each site class, forest management type, and treatment opportunity on timberland suitable for treatment. This estimate represents actual management being applied to current stands, and was thus deemed achievable. Economic opportunities were defined as increases in growth on timberland that could be treated and yield 4% or more on the direct costs of treatment.

Based on Vasievich and Alig's (1996) analysis, biological opportunities exist to increase timber growth by about 8.6 billion cubic feet over 202 million acres, an increase of 39 percent over the current net annual growth of 22 billion cubic feet. Several decades would be required to implement the treatments to attain these increases. For economic opportunities, Vasievich and Alig (1996) estimated that net annual growth could be increased by 5.8 billion cubic feet, approximately 25 percent of the current net annual growth. Capital investment costs would be $10.9 billion. These biological and economic opportunities would take decades to implement, with the full effect not being seen until near the end of the 21st century. Thus, timber management could potentially enhance forest productivity to a larger degree (25 to 39 percent) than is currently projected for the productivity responses to changes in carbon dioxide or climate (8 to 29 percent, table 3.4).

Potential Vegetation and Current Vegetation Descriptions

In the last Forest Service climate change assessment, NPP response from the ecological model (TEM) was used to adjust growth in the forest sector model (TAMM-ATLAS-NAPAP) (fig. 1.1, Joyce and Birdsey this volume). The vegetation classification systems of these two models differed. Classification systems within the forestry sector have focused on commercial timber, while classification systems within botany and ecology have focused on the dynamics of pristine plant communities. Imbedded in the last RPA climate change assessment is the conversion of NPP responses from the ecosystem classification used in TEM into the forest management types used in the TAMM-ATLAS-NAPAP model.

Within the forest sector model, yield tables to project timber growth are derived from inventory plot data collected over a period of several years within each of the six forest inventory regions in the United States. One of the stratifications for these yield tables is timber types (table 3.5). The Forest Service inventory classifies forest land by forest types in which the named species, either singly or in combination, comprise a plurality of live tree stocking. The inventory types are based on a standard set of local forest types in the Forest Service Handbook, organized into broader forest type groups to facilitate reporting. There is some aggregation of the inventory forest types into the forest management types used in the TAMM-ATLAS-NAPAP model. The named species typically refers to a commercial tree species, for example Douglas fir, or to a class of fiber, such as softwood mix. The TAMM-ATLAS-NAPAP model was not developed to model geographically resolved data, hence the yield tables represented larger geographic regions, typically a multi-state grouping of ownership-forest type-age classes.

For the TEM model, similar to other biogeochemistry models, data from intensively studied ecosystems, representative of particular vegetation types, are used for calibration of model behavior. These models are spatially extrapolated by using vegetation maps. For the TEM model, the United States has been gridded into 0.5 degree by 0.5 degree grid cells. The Küchler classification system (Küchler 1964, 1978) has been used to assign the dominant potential natural vegetation (PNV) type to each

Table 3.5—Timber types used in the TAMM-Atlas forest sector model.

	Pacific Northwest			Rocky Mountain				
	West	East	Pacific Southwest	North	South	Northcentral	North	South
Douglas fir	X		X	X	X			
Douglas fir-mixed	X							
Douglas fir-larch		X						
Pure hemlock	X							
Fir-spruce	X	X		X	X			
True fir		X	X					
Pines	X							
Lodgepole pine		X			X			
Ponderosa pine		X	X	X	X			
Softwood mix	X							
Jack pine						X		
Red pine						X		
White pine						X		
White-red-jack pine							X	
Spruce-fir						X	X	
Red alder	X							
Redwood			X					
Hardwood mix	X							
Hardwood			X		X			
Mixed conifer			X					
Swamp conifer						X		
Oak-hickory						X	X	
Lowland hardwoods						X		
Maple-beech						X		
Loblolly-SRT-oak-gum							X	
Oak-pine							X	X
Elm-ash-red maple							X	
Maple-beech-birch							X	
Aspen-birch							X	
Planted pine								X
Natural pine								X
Upland hardwood								X
Lowland hardwood								X

grid cell (McGuire et al. 1992), and these types were then aggregated into a smaller set of ecosystem types, including 7 forest types: boreal forest, boreal forest wetland, temperate coniferous forest, temperate deciduous forest, temperate mixed forest, temperate broadleaf evergreen forest, and temperate forest wetland. This spatially explicit vegetation information is then used to extrapolate the ecological model to the larger spatial scale of the United States. In the last RPA analysis (Joyce 1995), NPP responses to climate change were computed for each 0.5 degree grid cell in the United States. Thus, NPP response data in TEM was resolved at a finer geographic scale than regional volume changes in the TAMM-ATLAS-NAPAP model.

A method was necessary to reclassify information from TEM so that this information could be used at the scale of the forest policy model. As the ecological and the timber classification systems had both been related to the PNV classification (McGuire et al. 1992, Garrison et al. 1977, Eyre 1980), this classification was used to link TEM ecosystem types with timber management types (table 3.6). The conversion process involved associating the TEM ecosystem type and the PNV type within each 0.5 grid cell (McGuire et al. 1992) to the forest type corresponding to that PNV type as defined by Garrison et al. (1977).

Several assumptions were made if no grid cell within a region was dominated by the PNV type associated with the forest management type. This situation might arise

Table 3.6—Translation of the Forest Classification used in the Forest Service FIA inventory using Potential Vegetation of Küchler (1964) to the VEMAP classification.

VEMAP vegetation	Kuchler[1]	FIA	TEM
Boreal coniferous (2)	15 Western spruce-fir (14)	Fir-spruce (17)	Boreal coniferous forest
	21 Southwestern spruce-fir (20)	Fir spruce (17)	
	93 Great Lakes spruce-fir (84)	Spruce-fir (2)	
	96 Northeastern spruce-fir (87)	Spruce-fir (2)	
	*97 Southeastern spruce-fir (88)	Spruce-fir (2)	
Temperate maritime coniferous forest (3)	1 Spruce-cedar-hemlock (1)	Hemlock-Sitka spruce (12)	Maritime temperate coniferous forest
	2 Cedar-hemlock-Douglas fir (2)	Douglas-fir (11)	
	3 Silver fir-Douglas fir (3)	Fir-spruce (17)	
	4 Fir-hemlock (4)	Fir spruce (17)	
	5 Mixed conifer (5)	Ponderosa pine (13)	
	6 Redwood (6)	Redwood (18)	
Temperate continental coniferous forest (4)	*7 Red fir (7)	Fir-spruce (17)	Continental temperate coniferous forest
	*9 Pine-cypress (9)	Ponderosa pine (13)	
	8 Lodgepole pine-subalpine (8)	Lodgepole pine (15)	
	10 Ponderosa shrub (none)	Ponderosa pine (13)	
	11 Western ponderosa (10)	Ponderosa pine (13)	
	12 Douglas fir (11)	Douglas fir (11)	
	13 Cedar hemlock pine (12)	Western white pine (14)	
	14 Grand fir Douglas fir (13)	Larch (16)	
	16 Eastern ponderosa pine (15)	Ponderosa pine (13)	
	17 Black Hills pine (16)	Ponderosa pine (13)	
	18 Pine Douglas fir (17)	Ponderosa pine (13)	
	19 Arizona pine (18)	Fir-spruce (17)	
	20 Spruce fir - Douglas fir (19)	Fir-spruce (17)	
	95 Great Lakes pine (86)	White-red-jack pine (1)	
Cool temperate mixed forest (5)	28 Mosaic of cedar hemlock-Douglas fir forest and Oregon oakwoods (24)	Douglas fir (11)	50% continental temperate coniferous forest, 50% temperate deciduous forest
	106 Northern hardwoods (97)	Maple-beech birch (9)	
	107 Northern hardwoods fir (98)	Maple-beech-birch (9)	
	108 Northern hardwoods spruce (99)	Maple-beech-birch (9)	
	109 Mosaic of Appalachian oak and Northern hardwoods		
	110 Northeastern oak-pine (100)	Loblolly-shortleaf (4)	
	106 Seral northern hardwoods (97)	Aspen-birch EAST	
	107 Seral northern hardwoods fir (98)	Aspen-birch EAST	
	108 Northern hardwoods spruce (99)	Aspen-birch EAST	

continued

Table 3.6 (continued).

VEMAP vegetation	Kuchler[1]	FIA	TEM
Warm temperate/subtropical mixed forest (6)	29 California mixed evergreen (25)	Douglas fir (11)	33% continental temperate coniferous forest, 33% temperate deciduous forest, 34% temperate broadleaved evergreen forest
	89 Blackbelt (80)	Oak-hickory (6)	
	90 Live oak sea oats (81)	Oak-gum-cypress (7)	
	*91 Cypress savanna (82)	Oak-gum-cypress (7)	
	*105 Mangrove (96)	Oak-gum-cypress (7)	
	111 Oak-hickory-pine (101)	Loblolly shortleaf pine (4) and oak-pine (5)	
	112 Southern mixed (102)	Longleaf-slash pine (3) and oak-pine (5)	
	*115 Sand pine scrub (105)	Loblolly-shortleaf (4)	
	*116 Subtropical pine forest (106)	Longleaf-slash (3)	
Temperate deciduous forest (7)	26 Oregon oakwoods (22)	Western hardwoods (21)	Temperate deciduous forest
	98 Northern floodplain (89)	Elm-ash-cottonwood (8)	
	99 Maple-basswood (90)	Maple-beech-birch (9)	
	100 Oak-hickory (91)	Oak-hickory (6)	
	101 Elm-ash (92)	Elm-ash-cottonwood (8)	
	102 Beech maple (93)	Maple-beech-birch (9)	
	103 Mixed mesophytic (94)	Maple-beech-birch (9)	
	104 Appalachian oak (95)	Oak-hickory (6)	

[1] Küchler numbering scheme. The first number in each box is the number reported in the 1964 Küchler publication. The number in () after the type name is the number reported on the 1978 map, which was also the number used in the 1997 Forest Service publication mapping FRES Ecosystems and the Küchler System.

In VEMAP, vegetation types represented by map symbols 7, 9, 22, 25, 27, 72, 73, 91, 97, 105, 116, 117 never dominated at the 0.5 longitude × 0.5 latitude grid cell representation. Types 27 Mesquite bosques, 72 Sea oats prairie, and 73 Northern cordgrass prairie are non-forest types. For these types, I used a table provided by Dave Kicklighter that had identified the TEM/VEMAP type associated with these Küchler types.

FIA types of Aspen-birch 10 and 22 are east and west expressions of the Aspen-birch type. In the East, this type was indexed to the seral stages of Northern hardwoods, Northern hardwoods-fir forests, and Northern hardwoods-spruce forest and identified as temperate deciduous VEMAP type. In the West, this type was also coded as temperate deciduous VEMAP type. All FIA western hardwoods type were identified as temperate deciduous VEMAP type.

if silvicultural management favored a seral species, or if climax vegetation were not dominant within parts of the region, or if the commercial species happened not to be the tree species named in the climax type. For example, softwood mix, a forest management type used in the Pacific Northwest-west timber supply region, was a mix of two forest types: redwood and larch. No PNV type was representative of redwood within the Pacific Northwest-west region (west side of Oregon and Washington). The nearest PNV type was the redwood type in the Pacific Southwest region. Here, the assumption was made that the response to climate change would be more appropriately described by using a similar ecosystem type, but outside of the region rather than a different vegetation but inside the region. In another example in the Pacific Northwest-west region, red alder was a forest management type that did not have a corresponding PNV type. According to Eyre (1980), red alder is a successional type replaced by the Pacific Douglas fir and western hemlock-sitka spruce types. Eyre (1980) did assign red alder to the inventory type of western hardwoods, and Garrison et al. (1977) assigned the PNV type Oregon oakwood with the inventory type of western hardwoods. However, this PNV type occurs solely along the Oregon-California border in the Pacific Northwest-west region, and red alder is common on bottom lands, sheltered coves, and on moist slopes of the Coast and Cascade ranges (Eyre 1980). Thus, the PNV type associated with the climax vegetation that typically replaces red alder, the cedar hemlock-Douglas fir type, was used to modify the yield table for red alder.

In the Pacific Northwest-east region, lodgepole pine was a forest management type used in the forest sector model. However the PNV type, lodgepole pine, did not dominate any of the grid cells within this region. According to Eyre (1980), lodgepole pine within this region was associated with subalpine fir, Engelmann spruce, white spruce, and Rocky Mountain Douglas fir. The PNV types with these associates (fir-hemlock, Douglas fir, western spruce-fir) were used to define the response of lodgepole pine within this region.

The aspen-birch type used as a forest management type in the Northeast region is considered by Küchler to be a seral vegetation, replaced by Northeastern spruce-fir. Eyre (1980) considered aspen-birch to be a boreal hardwood. Aspen will be replaced by the PNV types of northern hardwoods or spruce-fir types, and succession to these types is more rapid than to pine (Eyre 1980). The volume of aspen-birch was modified by the TEM NPP response from an aggregation of Northeastern spruce fir, northern hardwoods, and northern hardwoods-spruce PNV types.

In the Southern region, planted pine and natural pine were two forest management types (table 3.5). There were no corresponding PNV types for these forest types. For the last RPA analysis, the oak-hickory pine and the southern mixed forest PNV types were used to assess the impact of climate change on timber volume of the two forest management types.

Clearly there are limitations with assigning forest management types to potential natural vegetation types. Ecological models represent the most current understanding of how ecological processes operate at the ecosystem scale. The potential distribution of these ecosystems implies a similarity of ecosystem function within the range of each ecosystem type as well as a geographic presence unaltered by land use. Forest management models have focused on the yield of wood from forestland. The aggregation of inventory plots into a forest management type implies a similarity in timber production with the geographic range of that forest management type. For both of these classification systems, the ecosystem dynamics or timber production within a type may be quite variable. Current land uses have altered potential distributions. Inventory data is more likely to represent the current distribution of forests.

Use of vegetation types presents problems by potentially ignoring differences between species and new associations and how both may affect ecosystems under climate change. The assumption that species associations will remain constant is a consequence of lumping species-specific information into a "type" (Kirschbaum and Fischlin 1996). Species associations have been very different in the past under different climates. Davis (1989) reports paleoecological evidence of community types no longer present, such as the spruce-oak woodland association. The approach of using functional types (Henderson-Sellers and McGuffie 1995; Woodward et al. 1995) in lieu of species in climate change modeling is attractive because this approach reduces the computational complexity associated with projecting each plant species. However, the use of functional types often assumes that these groupings of species will remain together and respond to climate change as a unit. The use of functional types raises the issue of whether "functional types" preserve species differences (Solbrig 1994). The value of these functional types is that they group similar physiological and ecological roles (Solbrig 1994; Vinton and Burke 1995), but species behavioral differences may be overlooked. For example, is the rate of reaching equilibrium with climate the same for all species within a functional group?

Similarly, the aggregation of diverse tree species into forest management types presents problems by ignoring potential differences between commercial timber species, and how climate change might alter wood fiber production; for example, how volumes might shift, when wood develops, and the quality of wood under altered climate. Experimental results suggest that the responses to climate change might be genera, if not species, specific (see earlier discussion).

Within the last RPA analysis, the impact of climate change on NPP was assessed using the historical range of temperate forests (fig. 3.1), not the current distribution as affected by land use. Thus, the ecological variability analyzed under climate change represented a greater ecological amplitude than forests currently represent. The spatial distribution of existing forests using the forest management type classification has been recently mapped. We used this spatial distribution to develop a map of vegetation classified by the same system used by the VEMAP members. The forest management type information was available at the 1 km scale. We identified a Küchler PNV type for each grid cell on the forest management map, based on Garrison et al. (1977) (table 3.6). Once the Küchler type was associated with each grid cell, we then used the classification given in VEMAP members (1995) to link the cell to a VVEG type (table 3.6). The map was then resampled to the 10 km scale (fig. 3.2). The finer scale of this map allows smaller isolated patches of forest to remain on the map, particularly in the Southwest and in the Great Plains. However, this distribution contrasts with the distribution used in the last RPA analysis (fig. 3.1) in the drastically reduced area of forests in the eastern part of the United States, and in the patchiness of the forests across the United States. The area of forests in the Midwest region and the Mississippi River valley declines when the land use in agriculture is removed. The homogeneity of vegetation types is lessened in figure 3.2, particularly for the New England states, where boreal, temperate coniferous, and cool temperate mixed forest types intermingle in contrast to the uniformity in figure 3.1. This re-examination of forest types (fig. 3.2) could be used as the basis for an analysis of the impact of climate change on forest productivity. It would likely reflect the potential shifts in forest productivity more closely because climate shifts in regions of existing forests would be used as climate input to a model such as TEM.

Projecting Ecosystem Productivity at Different Spatial Scales

Climate, topography, vegetation, and soils input data for ecological models used in large-scale integrated assessments are typically gridded at the 0.5 degree longitude by 0.5 degree latitude scale (Cramer et al. 1999; Heimann et al. 1998; Kicklighter et al. 1999; Melillo et al. 1993; VEMAP members 1995). Use of gridded input data implicitly assumes that the mean or dominant surface features represent the entire grid cell. Inherent in this assumption is the uncertainty with which this gridded value represents the heterogeneity of the actual coarse grid cell features and the representativeness of this gridded value when used in the ecological models to describe the biological processes operating within the grid cell. While opportunities exist to move the analysis of the impact of climate change on forests to a finer grid scale, this reduction in grid size would increase the processing time by an order of magnitude. Hence it is important to assess the uncertainty that aggregation of climate data contributes to the estimation of forest productivity under climate change. Nungesser et al. (1999) used the Terrestrial Ecosystem Model (TEM version 4.0; McGuire et al. 1995a) to evaluate the utility of moving the climate change impact analysis from the 0.5 degree scale used in the last RPA analysis to the 10 km scale.

The effect of aggregation on the estimation of productivity has been studied. Net primary production (NPP) estimates differed by 20 percent when coarse grain versus fine grain soils data were used as input data for the PnEt model (Lathrop et al. 1995). Pierce and Running (1995) obtained overestimates of up to 30 percent in NPP from the FOREST-BGC model when sub-grid variations in climate, topography, soils, and vegetation were averaged across a series of grain sizes from 1 km to 1 degree. Most of this error was produced by average temperature, while average topography, soils, and vegetation types also contributed.

Nungesser et al. (1999) examined the impact of two different spatial resolutions on the simulated forest ecosystem responses for a baseline climate and two climate change scenarios. The TEM model uses spatially resolved information on climate (monthly precipitation, monthly mean air temperature, and cloudiness), soil texture (percent sand, silt, and clay), vegetation type, and elevation. The fine resolution grid cells were 100 km^2 in size, and 25 of these cells were nested within a coarse resolution grid cell of approximately a half degree in size (2500 km^2). The 10 km × 10 km raster data for climate (monthly precipitation, monthly mean air temperature) were obtained from Neilson (personal communication) as described in Daly et al. (1994), Marks (1990), and Neilson (1995). For the 50 km × 50 km input data, the fine scale input data sets for continuous variables were averaged to the 50 km × 50 km resolution. Averaging to the 50-km scale results in the smoothing out of precipitation and temperature values along the gradients of change and the loss of finer detail in some areas (fig. 3.3 and 3.4). Areas of fine scale patchiness of precipitation in the western mountains and the southern coastal plains are smoothed out at the 50-km grid scale (fig. 3.3). Annual average temperature values are influenced in areas where there is substantial temperature variability such as around the mountainous areas in the West (fig. 3.4)

The historical range of temperate forests was the spatial extent of the Nungesser study. Küchler vegetation

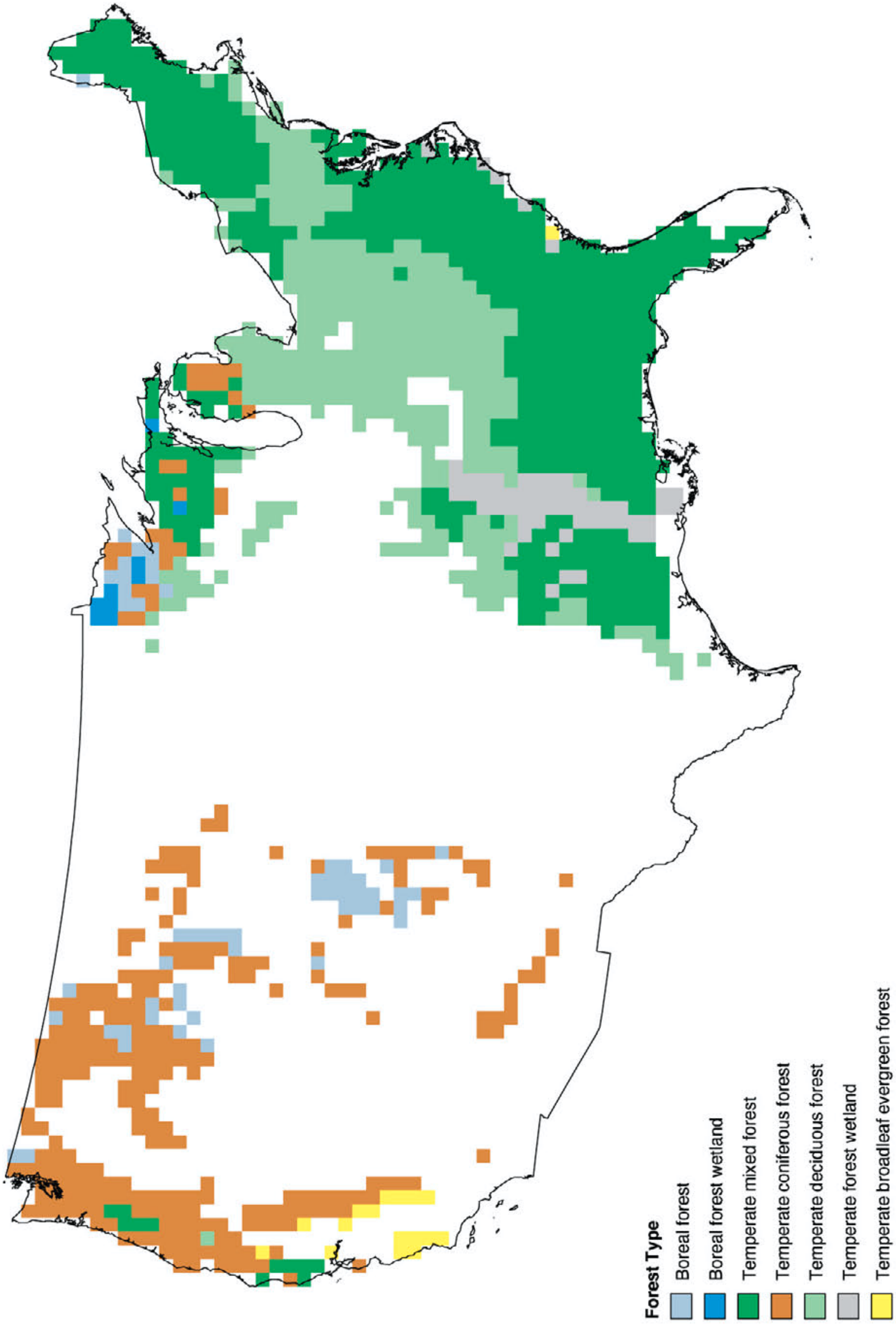


Figure 3.1—Forest type distribution used in the last RPA analysis (Joyce et al. 1995).

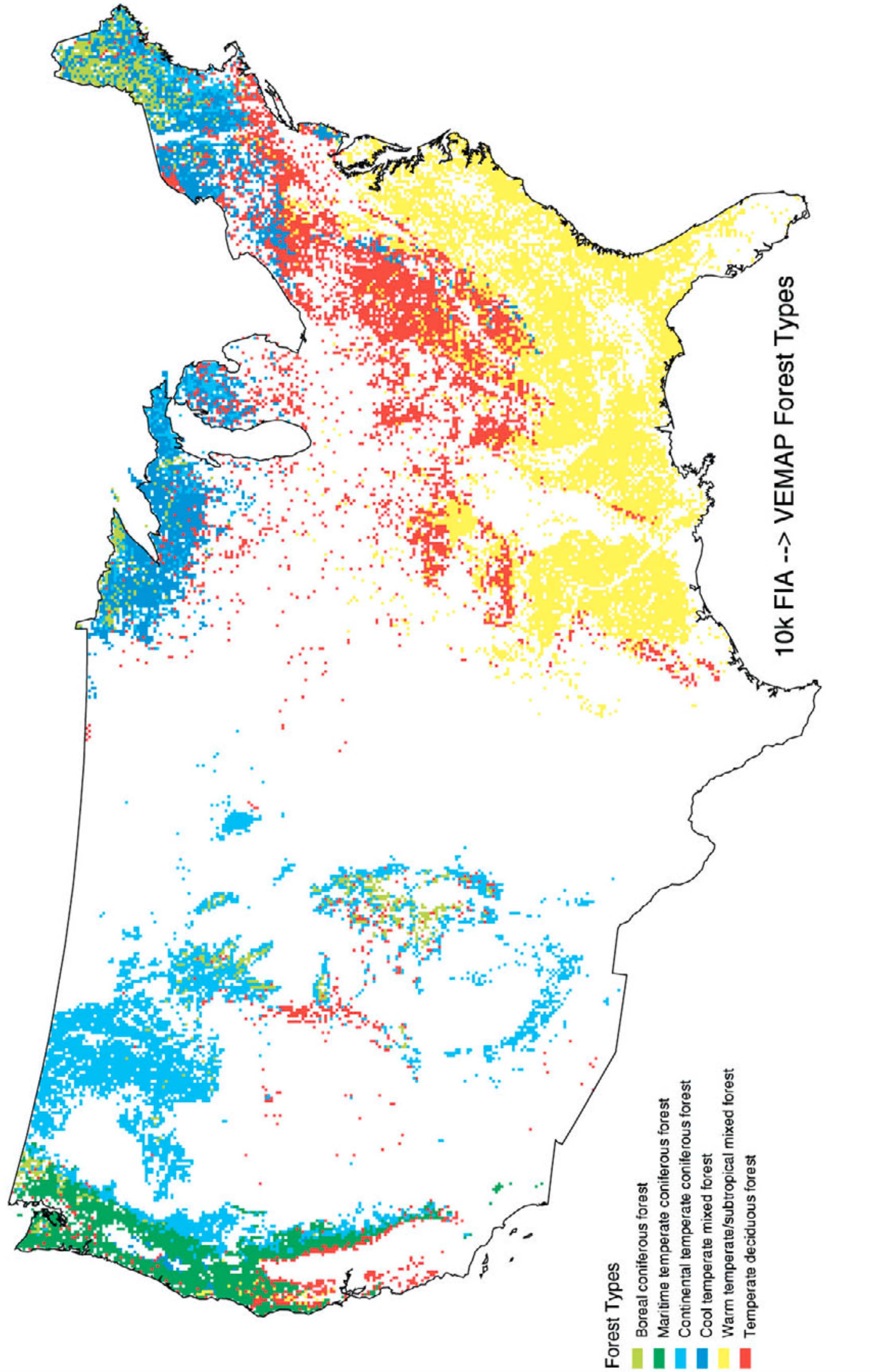
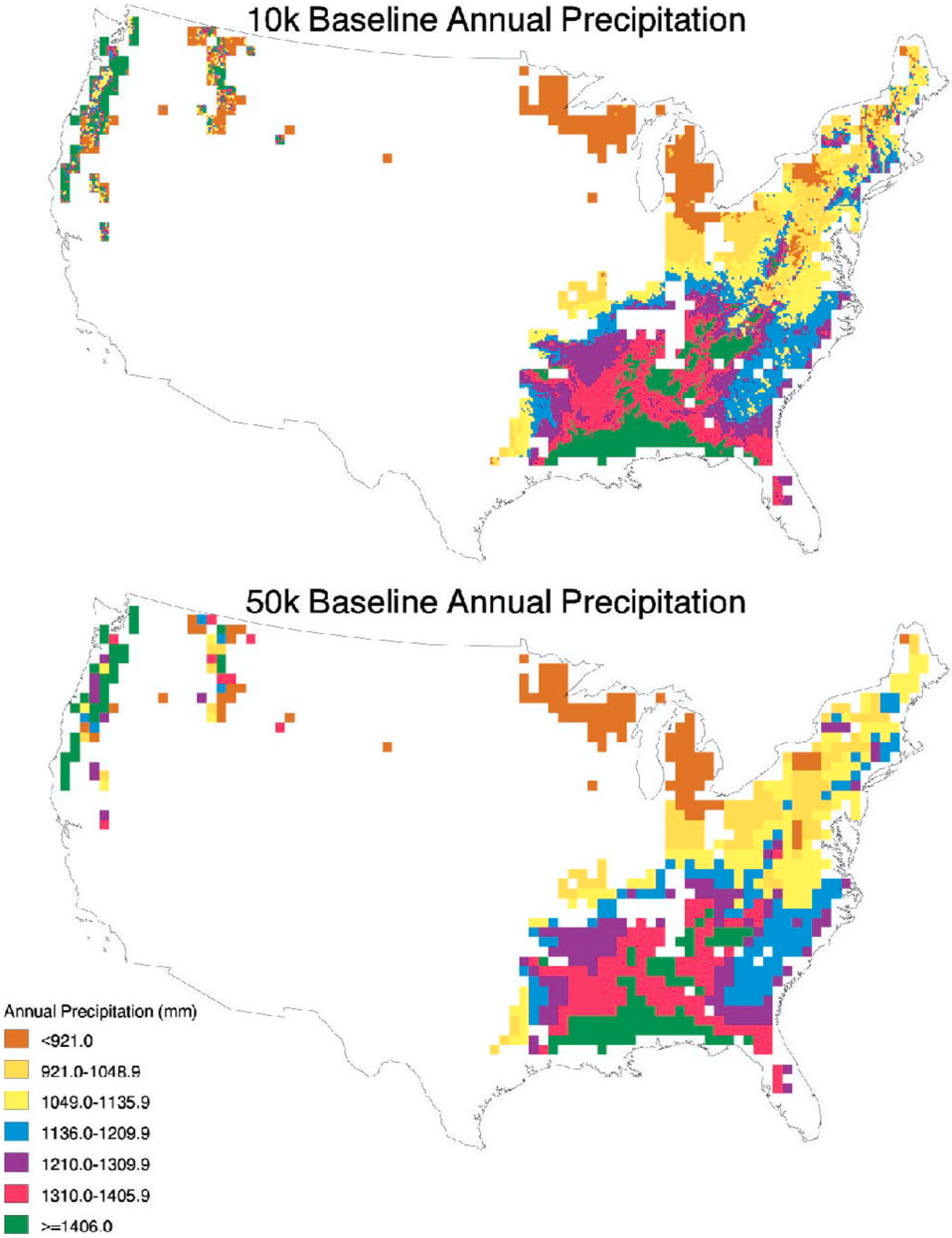


Figure 3.2—VEMAP vegetation classification associated with the current distribution of forests based on USDA Forest Service inventory plots.



10k Baseline Annual Precipitation

50k Baseline Annual Precipitation

Figure 3.3—Baseline annual precipitation at 50 km scale and 10 km scales.

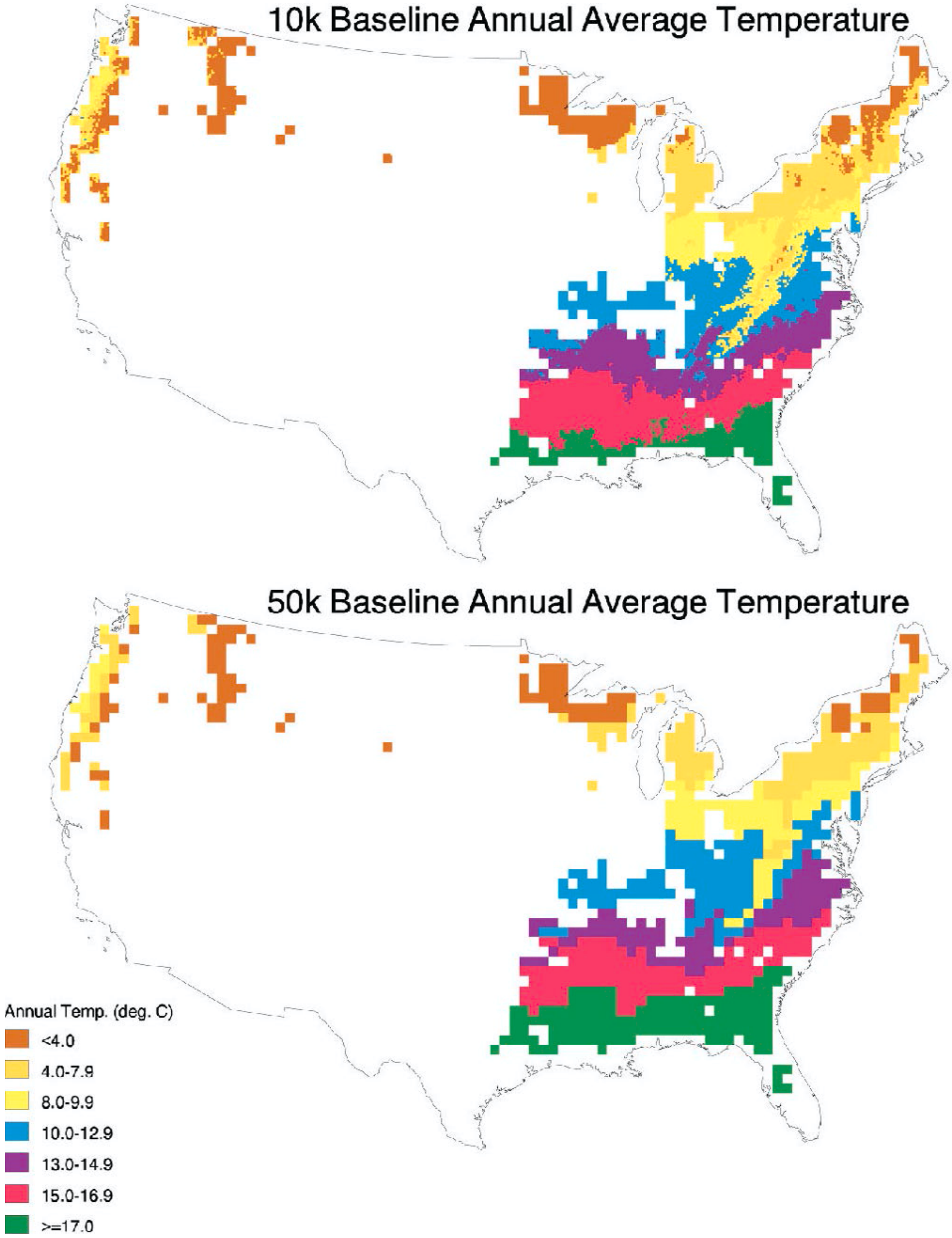


Figure 3.4—Baseline annual average temperature at 50 km and 10 km scales.

was digitized from the 1975 map (Küchler 1975) at 10 km resolution (Steve Hodge, personal communication) and was reclassified to TEM vegetation types. For the 50 km × 50 km input data, the fine scale input data set for vegetation were aggregated to the 50 km × 50 km resolution through the use of the majority rule (proportional aggregation method of Costanza and Maxwell 1994). While the coarse resolution grids include six vegetation types (fig. 3.5), a seventh type, temperate evergreen broadleaf, appeared in only three grid cells at the fine resolution. All forest types that comprised greater than 10 percent of the total area within the 10-km grids retained at least 93 percent of their total area when aggregated to the 50 km grid size. The rarer forest types, boreal, wet boreal, temperate forest wetland, and temperate broadleaf evergreen, lost from 28 to 100 percent of their area under the proportional aggregation rule. Rare types dispersed across the landscape were most likely to be lost in the aggregation. For example, the boreal grid cells in New England disappear at the 50-km scale (fig. 3.5). Similarly, some of the forested boreal wetland forests in the northern Midwest are lost at the 50-km scale.

An aggregation error was computed as the difference of the 10-km estimate of NPP and the 50-km estimate of NPP divided by the 10-km estimate of NPP. This aggregation error was computed for the baseline runs (baseline climate and CO_2 levels of 355 meq/l):

$$E_B = 100 * \left(\overline{NPP_{10}} - NPP_{50}\right) / \overline{NPP_{10}} \tag{1}$$

where E_B is the relative aggregation error and $d_{GQ50} =$ is the average of the mean annual NPP in gC/m^2/yr estimates for the 25 fine grid cells, and NPP_{50} is the estimate of the NPP at the coarse grid scale.

The NPP results for the 10 km reflect finer scale patterns than the 50 km results (fig. 3.6), but these patterns are not sufficient to generate large aggregation errors at the national, forest type, or grid cell scale. The NPP estimate for all forests at the national extent differed by less than 1 gC/m^2 between the fine and coarse resolution scales, 675.8 versus 676.7 gC/m^2 (table 3.7). Aggregation error based on these 815 grid cells is very small and negative (–0.4%). Estimates of NPP at the 50-km grid scale differed from the corresponding average for the 10-km grid cells by less than 10 percent across most of the historic range of temperate forests. The smallest aggregation error was found generally throughout the East and Southeast, as well as in the western mountains. Rarely were aggregation error differences greater than 20 percent at the individual grid cell level. These larger aggregation errors occurred around the Great Lakes, in northern New England, and in the Rocky Mountains. By forest type, the aggregation errors were still small, less than 2 percent. Estimates of NPP differed by less than 10 gC/m^2 in most cases (table 3.7). The largest aggregation error occurred in boreal and forested boreal wetland forests, with positive values of 11.8 and 9.6 percent, respectively. Estimates of NPP for boreal forest at the 50-km grid scale were less than the 10-km estimate by approximately 37 gC/m^2 (table 3.7).

Table 3.7—Net primary production (NPP) for baseline climate. Values are net primary production in gC/m2; reported values are means and standard deviations are in parentheses followed by ranges. The "(n)" is the number of coarse resolution grid cells in each forest type.

Forest Type (n)	Resolution	NPP	
Boreal (9)	Fine	312.4 (48.8)	206–380
	Coarse	275.2 (42.6)	163–297
Forested boreal wetland (4)	Fine	319.0 (36.6)	291–372
	Coarse	285.0 (9.8)	271–291
Mixed temperate (409)	Fine	696.1 (124.9)	339–893
	Coarse	691.0 (113.8)	346–863
Conifers (91)	Fine	344.7 (96.3)	158–540
	Coarse	349.4 (97.9)	181–551
Deciduous (260)	Fine	751.5 (66.3)	483–877
	Coarse	761.3 (60.7)	600–909
Temperate forested wetland (42)	Fine	838.5 (61.0)	751–1046
	Coarse	846.6 (62.0)	790–1058
ALL FORESTS (815)	Fine	675.8 (167.9)	158–1046
	Coarse	676.7 (165.3)	163–1058

The climate change scenarios (temperature, precipitation) at the 10 km scale were based on two GCMs used in the last RPA analysis: the Geophysical Fluid Dynamics Laboratory Q-flux (GFDL-Q) (Manabe and Wetherald 1987) and Oregon State University (OSU) models (Schlesinger and Zhao 1989). Using the same protocol as for baseline climate, fine resolution climate input data were averaged within a coarse grid to serve as coarse resolution inputs to TEM. Values for forest type, elevation, and soils remain unchanged from the baseline simulation. The climate change scenarios included a CO_2 concentration of 625 ppmv. Aggregation error in NPP for the two climate change scenarios was computed in the same manner as the baseline aggregation error.

Grid-level response of net primary productivity to the climate change scenarios were calculated as:

$$d_{OS10} = 100 * \left(\overline{NPP_{OS10}} - \overline{NPP_{10}}\right) / \overline{NPP_{10}}, \tag{2}$$

$$d_{OS50} = 100 * \left(NPP_{OS50} - NPP_{50}\right) / NPP_{50}, \tag{3}$$

$$d_{GQ10} = 100 * \left(\overline{NPP_{GQ10}} - \overline{NPP_{10}}\right) / \overline{NPP_{10}}, \text{ and} \tag{4}$$

$$d_{GQ50} = 100 * \left(NPP_{GQ50} - NPP_{50}\right) / NPP_{50} \tag{5}$$

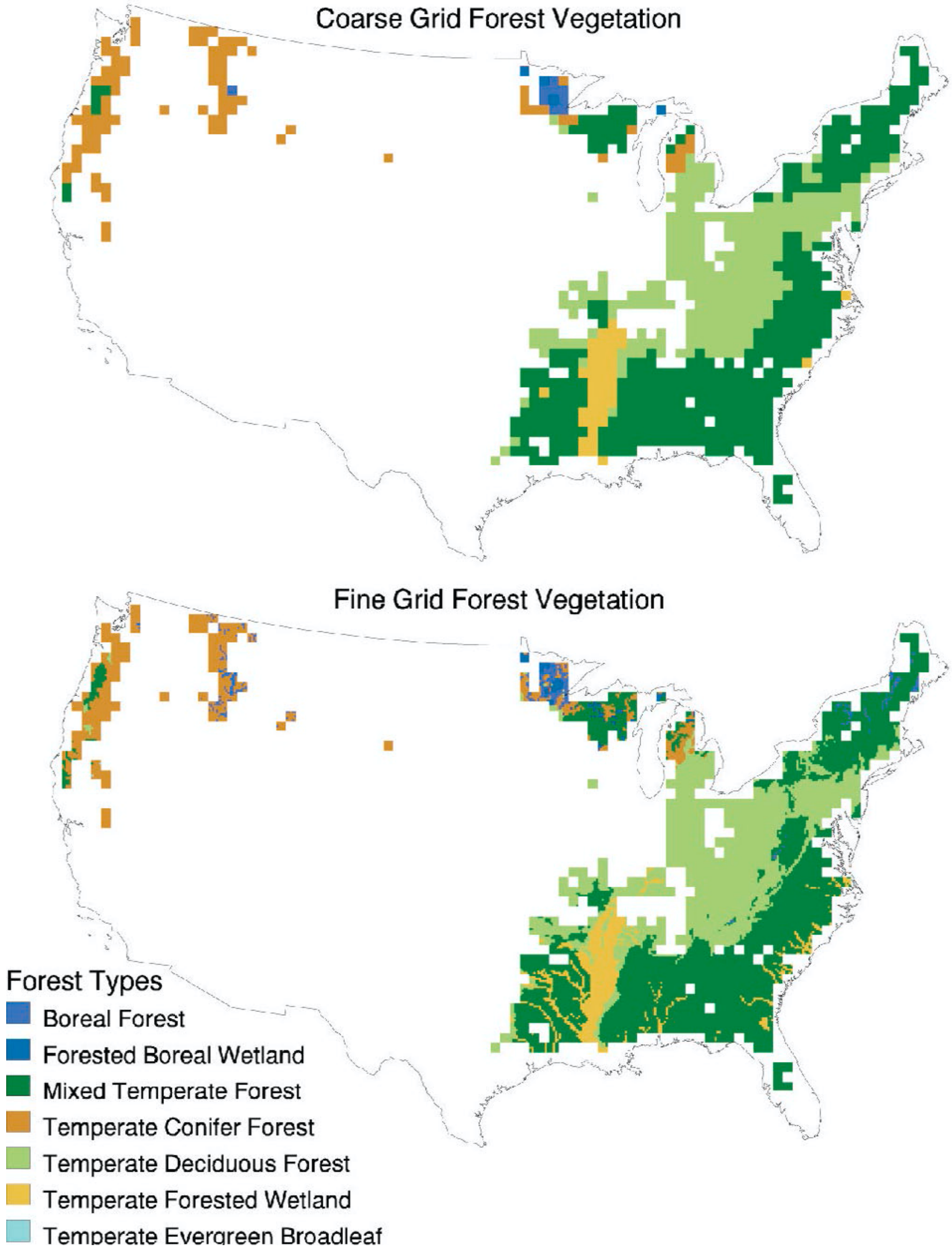


Figure 3.5—Vegetation types mapped at 50 km and 10 km scales.

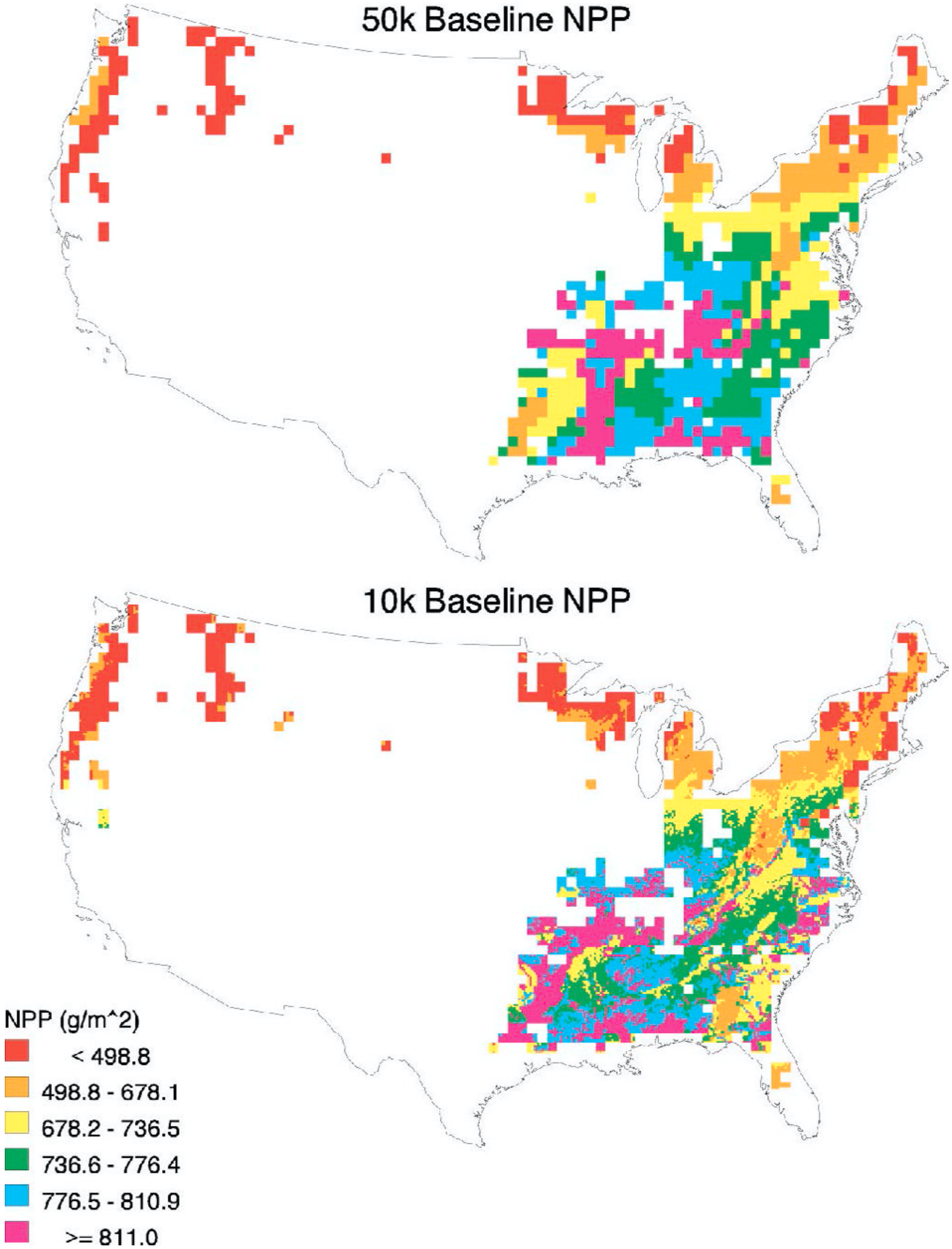


Figure 3.6—Baseline net primary productivity (NPP) at 50 km and 10 km scales.

where d_{OS10}, d_{OS50}, d_{GQ10}, and d_{GQ50} are NPP responses for each fine (d_{-10}) and coarse (d_{-50}) resolution grid to the OSU and the GFDL-Q climate scenarios. This metric is the delta that is passed to the forest sector model and used to modify timber volume increases in the inventory model.

Net primary productivity for all forests increased under both climate change scenarios at both resolutions. Under the OSU climate, NPP of all forests increased approximately 30 percent above the baseline NPP response, whereas under the GFDL-Q climate, NPP of all forests increased less than 13 percent (fig. 3.7). Within each climate change scenario, the response to climate change at the coarse resolution differed by less than 1 percent from the response at the finer resolution. Aggregation error for all forests for the OSU climate (–0.5 percent) was similar to the error for the GFDL-Q climate (–0.8 percent) and both results were similar to the aggregation error of the baseline climate (–0.4 percent). The spatial patterns of these aggregation errors were similar between the two climate scenarios and the baseline across the historic range of temperate forests.

Within forest types, NPP increased from 2.3 to 48.3 percent varying by climate scenario. The NPP response for boreal forests and forested boreal wetlands was 4 to 7 percent greater under the GFDL-Q climate than under the OSU climate. However, for mixed temperate, deciduous, and temperate forested wetland, NPP under the OSU climate was 18 to 40 percent greater than under the GFDL-Q climate. Within each climate scenario, forest NPP responses at the coarse scale differed by less than 2 percent from the NPP response to climate change at the finer resolution for all forest types except conifer, which differed by less than 6 percent. The error in all three climate scenarios was highest in the boreal forests and forested boreal wetlands (11.8 and 10.4 percent, respectively). The absolute value of the aggregation error for the other forests was less than 5.5 percent. Geographically, aggregation error for both OSU and GFDL-Q is concentrated in the same areas as that of baseline climate: around the Great Lakes, in New England, and in the Rocky Mountains. The smallest aggregation error, less than 10 percent, was found in the South and the Mid-Atlantic, an area that had the greatest differences in the NPP response to climate change, –17 to 82 percent.

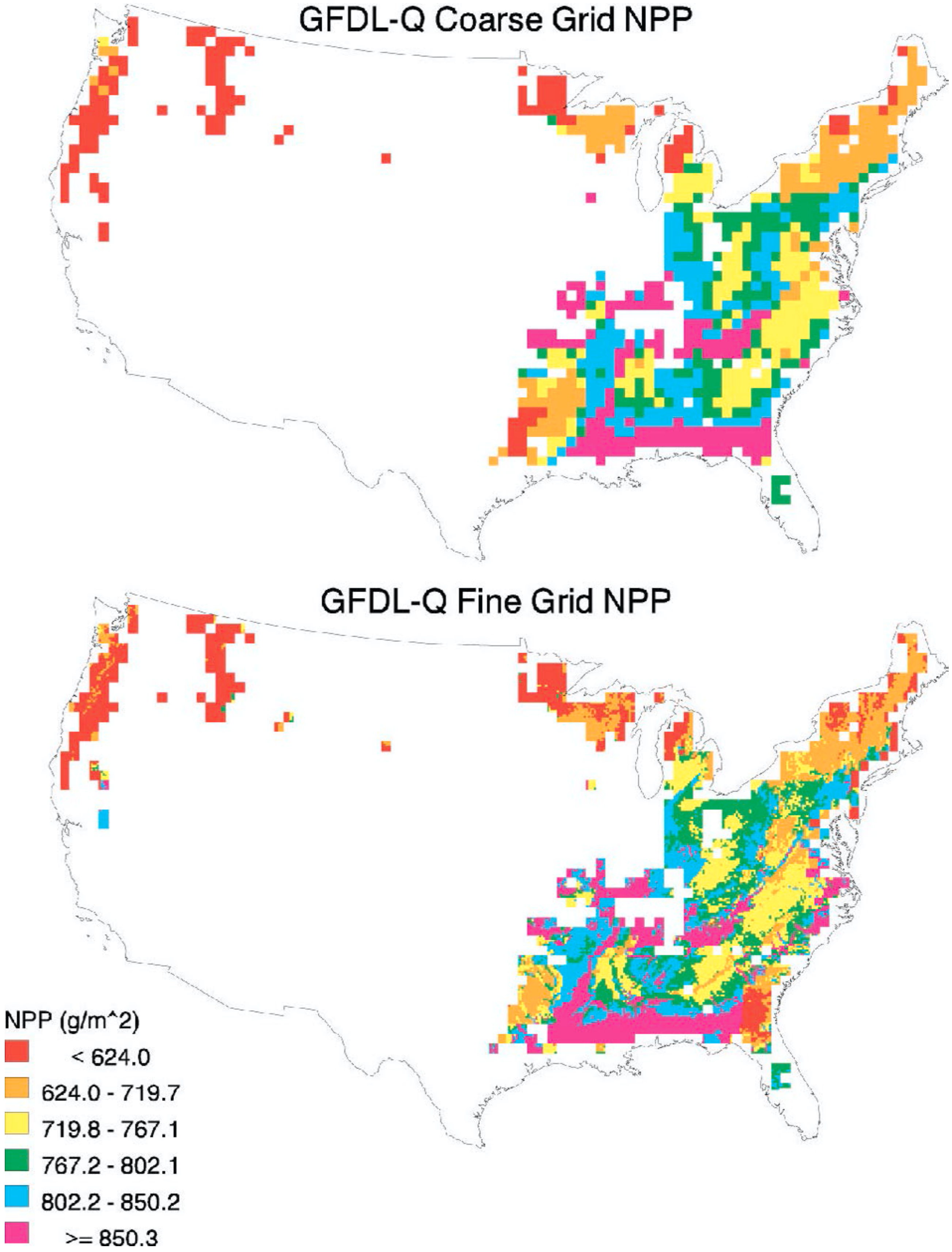
Relative to the baseline, the percent increases or decreases in NPP are similar across the fine and coarse resolutions within a climate change scenario but differ significantly across scenarios (fig. 3.8). Percent increases in NPP were similar under both climate scenarios in the West, but the responses in the South and Mid-Atlantic forests were dramatically different. For the GFDL-Q climate, the southern and mid-Atlantic forest NPP declined up to 17 percent relative to the baseline NPP whereas under the OSU climate these forests increased in NPP from 10 to 82 percent.

The 50-km grid-cell resolution is most relevant to stand-level forest managers. Aggregation error at this scale is less than 9 percent (two standard deviations), which is within the 20 percent precision that stand-level NPP is measured. Our analyses indicate that aggregation error is the largest in transition regions and in regions with substantial variability in air temperature. Aggregation error is primarily associated with the representation of a mosaic of forest types with a single forest type at 50-km resolution. This source of aggregation error can easily be minimized by making NPP estimates for each forest type within a 50-km grid cell and aggregating estimates based on the proportion of each forest type within the grid cell. This approach has been used by Bonan (1995) as a means of representing vegetative heterogeneity for estimating carbon, water, and energy exchange in the surface boundary layer of general circulation models. Pierce and Running (1995) also found that averaging temperature substantially influenced aggregation error in regions of complex terrain. It may be possible to achieve computational efficiency at 50-km resolution by aggregating temperature for a limited number of elevation bands, making NPP estimates for each elevation band, and aggregating estimates based on the proportion of each elevation band within the grid cell (Nungesser et al. 1999).

The resolution of forest types is most relevant to country-specific economic assessments of the impacts of climate change on timber resources. For example, relative climatic responses of NPP for different forest types in different regions were used as inputs for the last RPA (Joyce et al. 1995). Except for boreal forests and forested boreal wetlands, the mean aggregation error of baseline NPP estimates is less than 2 percent for each forest type. In contrast, aggregation error for boreal forests and forested boreal wetlands is approximately 10 percent. This level of error is caused primarily by the over-representation of boreal and boreal wetland forests and under-representation of more highly productive forests in the 50-km simulation.

In comparison to the baseline simulations, mean aggregation error for the absolute estimates of each forest type in the climate change simulations is similar except for temperate conifer forest (–3.7 percent for OSU and –5.5 percent for GFDL vs. –1.6 percent for baseline climate). Similar to aggregation error, the relative responses of NPP at each resolution are similar except for conifer forests (2.9 and 5.6 percent lower response for the fine resolution OSU and GFDL simulations). The negative aggregation errors and lower responses for temperate conifer forests are associated with the averaging of temperature in the complex terrain in the northern Rocky Mountains and in western Washington, Oregon, and California. Because differences between the responses of NPP at different resolutions are small compared with the responses to different climate scenarios, they could be ignored in impact assessments that evaluate sensitivities to different climate change scenarios.

The national resolution is most relevant to global economic assessments of the impacts of climate change on



GFDL-Q Coarse Grid NPP

GFDL-Q Fine Grid NPP

Figure 3.7—Net primary productivity at 50 km and 10 km scales from the GFDL-Q climate scenario.

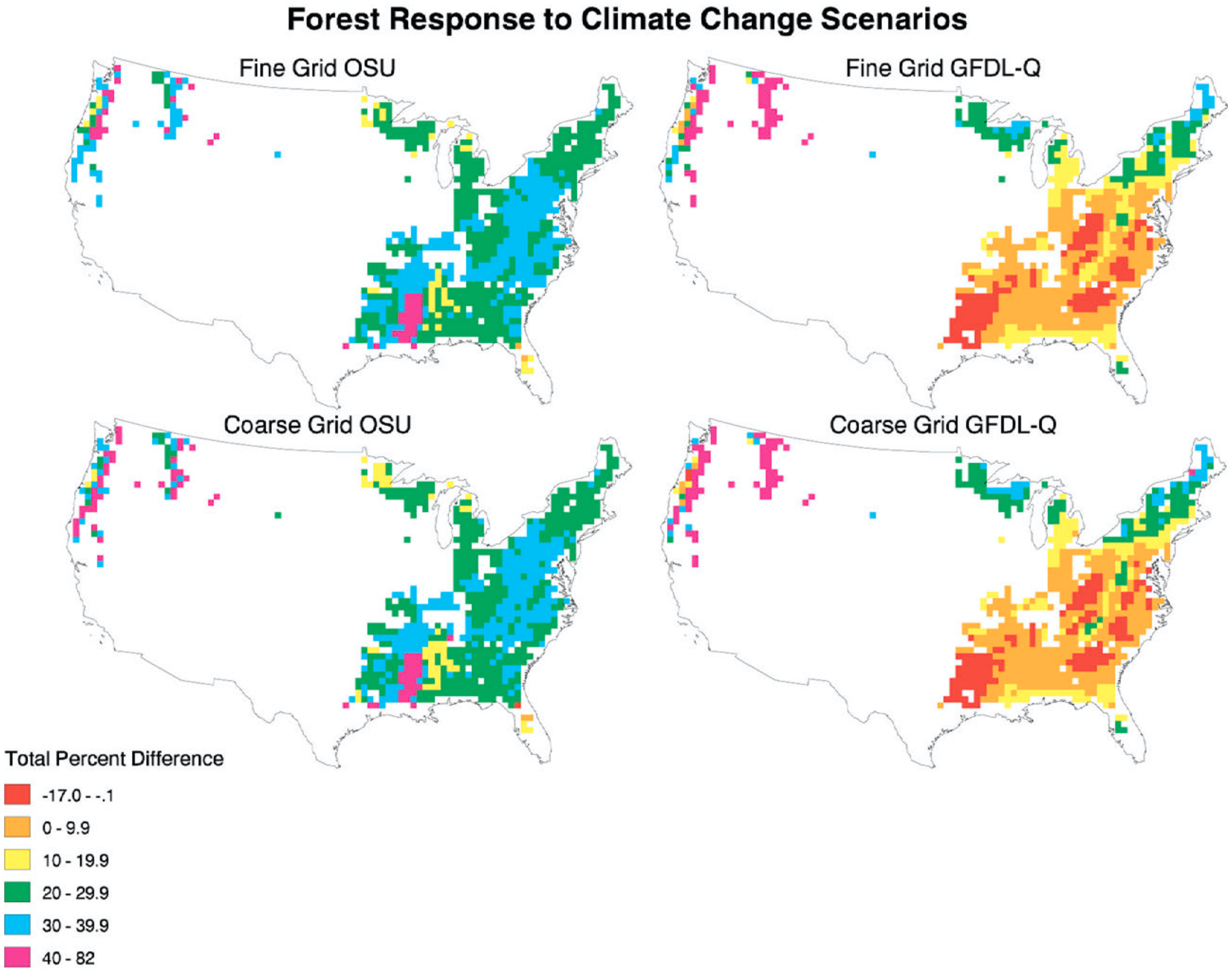


Figure 3.8—Forest responses to two climate change scenarios (OSU, GFDL-Q) at 10 km (fine grid) and 50 km (coarse grid) scales.

timber resources. The relative climatic responses of NPP of hardwoods and softwoods for different regions were used as inputs for a national assessment (Perez-Garcia et al. 1998). For the conterminous United States, aggregation error was 0.4 percent in the baseline simulation, 0.5 percent in the OSU simulation, and 0.8 percent in the GFDL simulation. Responses of NPP across the two spatial scales were 0.3 and 0.7 percent lower for the OSU and GFDL simulations. Because these differences are minuscule in comparison to the national NPP responses, they can be ignored in impact assessments that evaluate sensitivities to different climate change scenarios.

These results indicate that NPP responses of TEM to projected climate change are insensitive to the resolution of inputs, but that aggregation error of absolute NPP estimates is sensitive to the resolution of inputs for some situations. Except for transition areas and regions with substantial temperature variability, these simulations indicate that the use of 0.5° resolution provides an acceptable level of aggregation error at the three scales of analysis in this study.

It is important to recognize that the conclusions in this study are based on two resolutions and one biogeochemistry model. Pierce and Running (1995) used a different biogeochemistry model to simulate NPP for various resolutions ranging from 1 km^2 to 110 km^2 in a region of complex topography. At the coarsest scale, they found coarse-resolution NPP was overestimated by up to 30 percent relative to NPP estimates at the finest resolution. The results of Nungesser et al. (1999) qualitatively agree with those of Pierce and Running (1995).

Because most large-scale biogeochemistry models are parameterized with stand-level data, a systematic analysis of aggregation error with several biogeochemistry models across a range of spatial resolutions from stand to 0.5° (e.g., 100 m^2 to 1 km^2 to 100 km^2 to 2500 km^2) should be undertaken in different forest regions to determine whether our conclusions and those of Pierce and Running (1995) are robust.

Finally, it is important to verify the conclusion about the insensitivity of NPP responses to the resolution of inputs with other biogeochemistry models. By clarifying the scaling issues associated with NPP estimates and responses, these suggested studies would improve impact assessments that rely on the estimates of large-scale ecological models.

Conclusions

Analyses of the impact of climate change on forest productivity, based on experimental research and modeling, would suggest that forest productivity may increase under elevated carbon dioxide, but that the local conditions of moisture stress and nutrient availability will strongly temper any response. Projected increases in productivity from carbon dioxide fertilization appear to be within the same magnitude as potential increases in productivity from timber management treatments. Refinements in the analysis such as analyzing the impact at a finer scale do not appear to alter the results from the last RPA analysis. Incorporating land use changes appears to be a critical next step in the analysis of the impact of climate change on forest productivity.

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Literature Cited

Atkinson, C.J.; Taylor, J.M.; Wilkins, D., [et al.]. 1997. Effects of elevated CO_2 on chloroplast components, gas exchange and growth of oak and cherry. Tree Physiology. 17: 319–325.

Berntson, G.M.; Bazzaz, F.A. 1996. The allometry of root production and loss in seedlings of *Acer rubrum* (Aceraceae) and *Betula papyrifera* (Betulaceae): implications for root dynamics in elevated CO_2. American Journal of Botany. 83(5): 608–616.

Birdsey, Richard A.; Plantinga, Andrew J.; Heath, Linda S. 1993. Past and prospective carbon storage in United States forests. Forest Ecology and Management. 58: 33–40.

Birdsey, R.A.; Heath, L.S. 1995. Carbon changes in U.S. Forests. In: Joyce, L.A., ed. Climate change and the productivity of America's forests. Gen. Tech. Rep. RM-271. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station: 56–70.

Bonan, G.B. 1995. Land-atmosphere CO_2 exchange simulated by a land surface process model coupled to an atmospheric general circulation model. Journal of Geophysical Research. 100: 2817–2831.

Ceulemans, R.; Shao, B.Y.; Jiang, X.N., [et al.]. 1996. First- and second-year aboveground growth and productivity of two *Populus* hybrids grown at ambient and elevated CO_2. Tree Physiology. 16: 61–68.

Ceulemans, R.; Mousseau, M. 1994. Tansley Review No. 71. Effects of elevated atmospheric CO_2 on woody plants. New Phytologist. 127(3): 425–446.

Costanza, R.; Maxwell, T. 1994. Resolution and predictability: an approach to the scaling problem. Landscape Ecology. 9(1): 47–57.

Cramer, W.; Kicklighter, D.W.; Bondeau, A., [et al.]. 1999. Comparing global models of terrestrial net primary productivity (NPP): overview and key results. Global Change Biology. 5(Supplement 1): 1–15.

Curtis, P.S.; Vogel, C.S.; Pregitzer, K.S., [et al.]. 1995. Interacting effects of soil fertility and atmospheric CO_2 on leaf area growth and carbon gain physiology of *Populus* x *euramericana* (Dode) Guinier. New Phytologist. 129(2): 253–263.

Curtis, P.S.; Wang, X. 1998. A meta-analysis of elevated CO_2 effects on woody plant mass, form, and physiology. Oecologia. 113: 299–313.

Daly, C.; Neilson, R.P.; Phillips, D.L. 1994. A statistical-topographic model for mapping climatological precipitation over mountainous terrain. Journal of Applied Meteorology. 33: 140–158.

Davis, M. 1989. Lags in vegetation response to greenhouse warming. Climate Change. 15: 75–82.

DeLucia, E.H.; Callaway, R.M.; Schlesinger, W.H. 1994. Offsetting changes in biomass allocation and photosynthesis in ponderosa pine (*Pinus ponderosa*) in response to climate change. Tree Physiology. 14: 669–677.

Eyre, F.H., ed. 1980. Forest cover types of the United States and Canada. Washington, DC: Society of American Foresters.

Garrison, G. A.; Bjugstad, A. J.; Duncan, D. A.; Lewis, M. E.; Smith, D. R. 1977. Vegetation and environmental features of forest and range ecosystems. USDA Forest Service Agriculture Handbook No. 475. Washington, DC: U.S. Government Printing Office.

Gorissen, A.; Kuikman, P.J.; Van De Beek, H. 1995. Carbon allocation and water use in juvenile Douglas fir under elevated CO_2. New Phytologist 129(2): 275–282.

Griffin, K.L.; Winner, W.E.; Strain, B.R. 1995**.** Growth and dry matter partitioning in loblolly and ponderosa pine seedlings in response to carbon and nitrogen availability. New Phytologist. 129(4): 547–556.

Heimann, M.; Esser, G.; Hazeltine, A., [et al.]. 1998. Evaluation of terrestrial carbon cycle models through simulations of the seasonal cycle of atmospheric CO_2 - First results of a model intercomparison study. Global Biogeochemical Cycles. 12: 1–24

Henderson-Sellers, A.; McGuffie, K. 1995. Global climate models and 'dynamic' vegetation changes. Global Change Biology. 1: 63–75.

Hibbs, D.E.; Chan, S.S.; Castellano, M., [et al.]. 1995. Response of red alder seedlings to CO_2 enrichment and water stress. New Phytologist. 129(4): 569–577.

Ineichen, K.; Wiemken, V.; Wiemken, A. 1995. Shoots, roots and ectomycorrhiza formation of pine seedlings at elevated atmospheric carbon dioxide. Plant, Cell and Environment. 18: 703–707.

Joyce, L.A., ed. 1995. Productivity of America's Forests and Climate Change. Gen. Tech. Rep. RM-271. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 70 p.

Joyce, L.A.; Mills, J.R.; Heath, L.S., [et al.]. 1995. Forest sector impacts from changes in forest productivity under climate change. Journal of Biogeography. 22: 703–713.

Joyce, L.A.; Birdsey, R.; Mills, J.; Heath, L. 1997. Progress toward an integrated model of the effects of global change on United States forests. In: Birdsey, R.; Mickler, R.; Sandberg, D. [et al.], eds. 1997. USDA Forest Service Global Change Research Program Highlights 1991–1995. Gen. Tech. Rep. NE-237. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station: 93–96.

Kicklighter, D.W.; Bondeau, A.; Schloss, A.L., [et al.]. 1999. Comparing global models of terrestrial net primary productivity (NPP): Global pattern and differentiation by major biomes. Global Change Biology. 5(Supplement 1): 16–24.

King, J.S.; Thomas, R.B.; Strain, B.R. 1996. Growth and carbon accumulation in root systems of *Pinus taeda* and *Pinus ponderosa* seedlings as affected by varying CO_2, temperature and nitrogen. Tree Physiology. 16: 635–642.

Kirschbaum, M.U.F.; Fischlin, A., eds. 1996. Climate change impacts on forests. In: Watson, R.T.; Zinyowera, M.C.; Moss, R.H.; Dokken, D.J., eds. Climate Change 1995: Impacts, Adaptations, and Mitigation of Climate Change: Scientific-Technical Analyses. Intergovernmental Panel on Climate Change. Cambridge, UK: Cambridge University Press: 95–129. Chapter 1.

Küchler, A.W. 1964. Potential natural vegetation of conterminous United States. American Geographic Society. Spec. Publication No. 36. New York. 116 p.

Küchler, A.W. 1975. Potential natural vegetation of the United States. 2nd ed. New York: American Geographic Society.

Küchler, A. W. 1978. Potential natural vegetation of the United States. Washington, DC: USDA Forest Service. RARE II Map B.

Lathrop, R.G., Jr.; Aber, J.D.; Bognar, J.A. 1995. Spatial variability of digital soil maps and its impact on regional ecosystem modeling. Ecological Modelling. 82: 1–10.

Lindroth, R. L; Kinney, K. K.; Platz, C. L. 1993. Response of deciduous trees to elevated atmospheric CO_2: productivity, phytochemistry, and insect performance. Ecology. 74: 763–77.

Lord, D.; Morissette, S.; Allaire, J. 1993. Influence de l'intensite lumineuse, de la temperature nocturne de l'air et de la concentration en CO_2 sur la croissance de semis d'epinette noire (*Picea mariana*) produits en recipients en serres. Canadian Journal of Forest Research. 23: 101–110.

Manabe, S.; Wetherald, R.T. 1987. Large scale changes in soil wetness induced by an increase in carbon dioxide. Journal of Atmospheric Sciences. 44: 1211–1235.

Marks, D. 1990. The sensitivity of potential evapotranspiration to climate change over the continental United States. In: Gocinski, H.; Marks, D.; Turner, D.P., eds. Biospheric feedbacks to climate change: the sensitivity of regional trace gas emissions, evapotranspiration, and energy balance to vegetation redistribution. EPA/600/3-90/078. Corvallis, OR: U.S. Environmental Protection Agency: IV–1 to IV–31.

McGuire, A.D.; Melillo, J. M.; Joyce, L. A.; [et al.]. 1992. Interactions between carbon and nitrogen dynamics in estimating net primary productivity for potential vegetation in North America. Global Biogeochemical Cycles. 6: 101–124.

McGuire, A.D.; Melillo, J.M.; Kicklighter, D.W., [et al.]. 1995a. Equilibrium responses of soil carbon to climate change: empirical and process-based estimates. Journal of Biogeography. 22: 785–796.

McGuire, A.D.; Melillo, J.M.; Joyce, L.A. 1995b. The role of nitrogen in the response of forest net primary production to elevated atmospheric carbon dioxide. Annual Review of Ecology and Systematics. 26: 475–503.

Melillo, J.M.; McGuire, A.D.; Kicklighter, D.W., [et al.]. 1993. Global climate change and terrestrial net primary production. Nature. 363: 234–240.

Miao, S. 1995. Acorn mass and seedling growth in *Quercus rubra* in response to elevated CO_2. Journal of Vegetation Science. 6: 697–700.

Neilson, R.P. 1995. A model for predicting continental-scale vegetation distribution and water balance. Ecological Applications. 5(2): 362–385.

Noble, R.; Jensen, K. F.; Ruff, B.S.; Loats, K. 1992. Response of *Acer saccharum* seedlings to elevated carbon dioxide and ozone. Ohio Journal of Science 92: 60–62.

Norby, R.J.; Gunderson, C.A.; Wullschleger, S.D., [et al.]. 1992. Productivity and compensatory responses of yellow-poplar trees in elevated CO_2. Nature. 357: 322–324.

Nungesser, M.K.; Joyce, L.A.; McGuire, A.D. 1999. Effects of spatial aggregation on predictions of forest climate change response. Climate Research. 11: 109–124.

Pan, Y.; Melillo, J.M.; McGuire, A.D., [et al.]. 1998. Modeled responses of terrestrial ecosystems to elevated atmospheric CO_2: a comparison of simulations by the biogeochemistry models of the Vegetation/Ecosystem Modeling and Analysis Project (VEMAP). Oecologia. 114: 389–404.

Parton, W.J.; Schimel, D.S.; Cole, C.V., [et al.]. 1987. Analysis of factors controlling soil organic matter levels in Great Plains grasslands. Soil Science Society of America Journal. 51: 1173–1779.

Parton, W.J.; Scurlock, J.M.O.; Ojima, D.S., [et al.]. 1993. Observations and modeling of biomass and soil organic matter dynamics for the grassland biome worldwide. Global Biogeochemistry Cycles. 7(4): 785–809.

Perez-Garcia, J.; Joyce, L.A.; Binkley, C.S., [et al.]. 1998. Economic impacts of climatic change on the global forest sector an integrated ecological/economic assessment. Critical Reviews in Environment and Technology. 27 (Special): 5123–5138.

Pierce, L.L.; Running, S.W. 1995. The effects of aggregating sub-grid land surface variation on large-scale estimates of net primary production. Landscape Ecology. 10(4): 239–253.

Polle, A.; Pfirrmann, T.; Chakrabarti, S., [et al.]. 1993. The effects of enhanced ozone and enhanced carbon dioxide concentrations on biomass, pigments and antioxidative enzymes in spruce needles (*Picea albies* L.). Plant, Cell and Environment. 16: 311–316.

Rochefort, L.; Bazzaz, F.A. 1992. Growth response to elevated CO_2 in seedlings of four co-occurring birch species. Canadian Journal of Forestry Research. 22:1583–87.

Running, S.W. 1994. Testing FOREST-BGC ecosystem process simulations across a climatic gradient in Oregon. Ecological Applications. 4: 238–247.

Running, S.W.; Coughlan, J.C. 1988. A general model of forest ecosystem processes for regional applications. I. Hydrologic balance, canopy gas exchange and primary production processes. Ecological Modeling. 42: 125–154.

Saxe, H.; Ellsworth, D.S.; Heath, J. 1998. Tansley Review No. 98. Tree and forest functioning in an enriched CO_2 atmosphere. New Phytologist. 139: 395–436.

Schlesinger, M.E.; Zhao, Z. 1989. Seasonal climatic changes induced by doubled CO_2 as simulated by the OSU atmospheric GCM/mixed-layer ocean model. Journal of Climate. 2: 459–495.

Solbrig, O. T. 1994. Plant traits and adaptive strategies: their role in ecosystem function. In Biodiversity and Ecosystem Function, E.-D. Schulze and H. A. Mooney, eds. New York: Springer-Verlag. Page 97–116. Chapter 5

Tissue, D.T.; Thomas, R.B.; Strain, B.R. 1996. Growth and photosynthesis of loblolly pine (*Pinus taeda*) after exposure to elevated CO_2 for 19 months in the field. Tree Physiology. 16: 49–59.

Townend, J. 1995. Effects of elevated CO_2, water and nutrients on *Picea sitchensis* (Bong.) Carr. seedlings. New Phytologist. 130(2): 193–206.

USDA Forest Service. 1994. RPA Assessment of the Forest and Rangeland Situation in the United States—1993 Update. Forest Resource Report No. 27. Washington, DC: U.S. Department of Agriculture, Forest Service. 75 p.

Vasievich, J. M.; Alig, R. J. 1996. Opportunities to increase timber growth and carbon storage on timberlands in the contiguous United States. In: Forests and Global Change. Volume 2: Forest Management Opportunities for Mitigating Carbon Emissions. Sampson, R. N. and Hair, D. eds. Washington, DC: American Forests: pages 91–104.

VEMAP Members. 1995. Vegetation/ecosystem modeling and analysis project: Comparing biogeography and biogeochemistry models in a continental-scale study of terrestrial ecosystem responses to climate change and CO_2 doubling. Global Biogeochemical Cycles. 9(4): 407–437.

Vinton, M.A.; Burke, I. C. 1995. Interactions between individual plant species and soil nutrient status in shortgrass steppe. Ecology 76: 1116–1133.

Wayne, P.M.; Bazzaz, F.A. 1997. Light acquisition and growth by competing individuals in CO_2- enriched atmospheres: consequences for size structure in regenerating birch stands. Journal of Ecology. 85: 29–42.

Wilkins, D.; Van Oosten, J.-J.; Besford, R.T. 1994. Effects of elevated CO_2 on growth and chloroplast proteins in *Prunus avium*. Tree Physiology. 14: 769–779.

Woodward, F. I.; Smith, T. M.; Emanuel, W. R. 1995. A global land primary productivity and phytogeography model. Global Biogeochemical Cycles 9: 471–480.

Xiao, X.; Kicklighter, D.W.; Melillo, J.M., [et al.]. 1997. Linking a global terrestrial biogeochemical model with a 2-dimensional climate model: implications for the global carbon budget. Tellus. 49b: 18–37.

Yakimchuk, R.; Hoddinott, J. 1994. The influence of ultraviolet-B light and carbon dioxide enrichment on the growth and physiology of seedlings of three conifer species. Canadian Journal of Forest Research. 24: 1–8.