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Made in United States of America
Reprinted from Journal of the American Water Resources Association
Vol. 33, No. 5, October 1997

JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION
VOL. 33, NO. 5 AMERICAN WATER RESOURCES ASSOCIATION OCTOBER 1997

McNulty, Steven G.; Vose, James M.; Swank, Wayne T. 1997. Regional hydrologic response of loblolly pine to air temperature and precipitation changes. Journal of the American Water Resources Association. 33(5): 1011 - 1022.

REGIONAL HYDROLOGIC RESPONSE OF LOBLOLLY PINE TO AIR TEMPERATURE AND PRECIPITATION CHANGES[1]

Steven G. McNulty, James M. Vose, and Wayne T. Swank[2]

ABSTRACT: Large deviations in average annual air temperatures and total annual precipitation were observed across the southern United States during the last 50 years, and these fluctuations could become even larger during the next century. We used PnET-IIS, a monthly time-step forest process model that uses soil, vegetation, and climate inputs to assess the influence of changing climate on southern U.S. pine forest water use. After model predictions of historic drainage were validated, the potential influences of climate change on loblolly pine forest water use was assessed across the region using historic (1951 to 1984) monthly precipitation and air temperature which were modified by two general circulation models (GCMs). The GCMs predicted a 3.2°C to 7.2°C increase in average monthly air temperature, a -24 percent to +31 percent change in monthly precipitation and a -1 percent to +3 percent change in annual precipitation. As a comparison to the GCMs, a minimum climate change scenario using a constant 2°C increase in monthly air temperature and a 20 percent increase in monthly precipitation was run in conjunction with historic climate data. Predicted changes in forest water drainage were highly dependent on the GCM used. PnET-IIS predicted that along the northern range of loblolly pine, water yield would decrease with increasing leaf area, total evapotranspiration and soil water stress. However, across most of the southern U.S., PnET-IIS predicted decreased leaf area, total evapotranspiration, and soil water stress with an associated increase in water yield. Depending on the GCM and geographic location, predicted leaf area decreased to a point which would no longer sustain loblolly pine forests, and thus indicated a decrease in the southern most range of the species within the region. These results should be evaluated in relation to other changing environmental factors (i.e., CO_2 and O_3) which are not present in the current model
(KEY TERMS: forest hydrology; climate change; evapotranspiration; drainage; soil water stress; model; PnET-IIS.)

INTRODUCTION

During the next century, substantial changes are expected to occur in a variety of environmental variables including temperature and precipitation (Melillo *et al.*, 1989; Mitchell, 1989). The magnitude of these changes are expected to vary temporally and spatially. Most general circulation models (GCMs) estimate a 3°C to 7°C increase in average annual air temperature and changes (both positive and negative depending on the GCM) in precipitation (Cooter *et al.*, 1993). It is unclear how much of an impact climate change could have on forest hydrology. Forest species type, stand age, and climate all influence the water use and yield from these areas (Swank *et al.*, 1988). Because forests cover approximately 55 percent of the southern United States land area (Flather *et al.*, 1989), changes in forest water use could significantly change water yield within the region.

Models of forest response to environmental change will be useful tools in managing our nation's forest resources into the 21st century. PnET-IIS is a regional scale model developed to predict forest growth and hydrology across a range of historic climates (McNulty *et al.*, 1994, 1996b, 1997). The objective of this paper is to use PnET-IIS to assess the impact of changing precipitation and air temperature on loblolly pine forest hydrology.

[1]Paper No. 96075 of the *Journal of the American Water Resources Association* (formerly *Water Resources Bulletin*). Discussions are open **until June 1, 1998.**
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METHODS

Model Structure

PnET-IIS utilized site specific soil water holding capacity (SWHC), four monthly climate parameters (minimum and maximum air temperatures, total precipitation, and solar radiation) and loblolly pine specific values (Table 1) to predict hydrology and net primary productivity (NPP) from the stand level (< 1 ha) to a approximately 50 x 75 km grid cell resolution across the southern United States (i.e., east of central Texas and south of Kentucky) (McNulty et al., 1994, 1996b). PnET-IIS was derived from the PnET-II model developed by Aber *et al.* (1995). Model descriptions and validation of the PnET-II (Aber *et al.*, 1995), and the PnET-IIS model descriptions (McNulty et al., 1996b), sensitivity analysis (McNulty et al., 1996c), and validation (McNulty *et al.*, 1996b, 1997) have been published, so this paper provides a general overview of model inputs, transfers, and outputs of PnET-IIS (Figure 1).

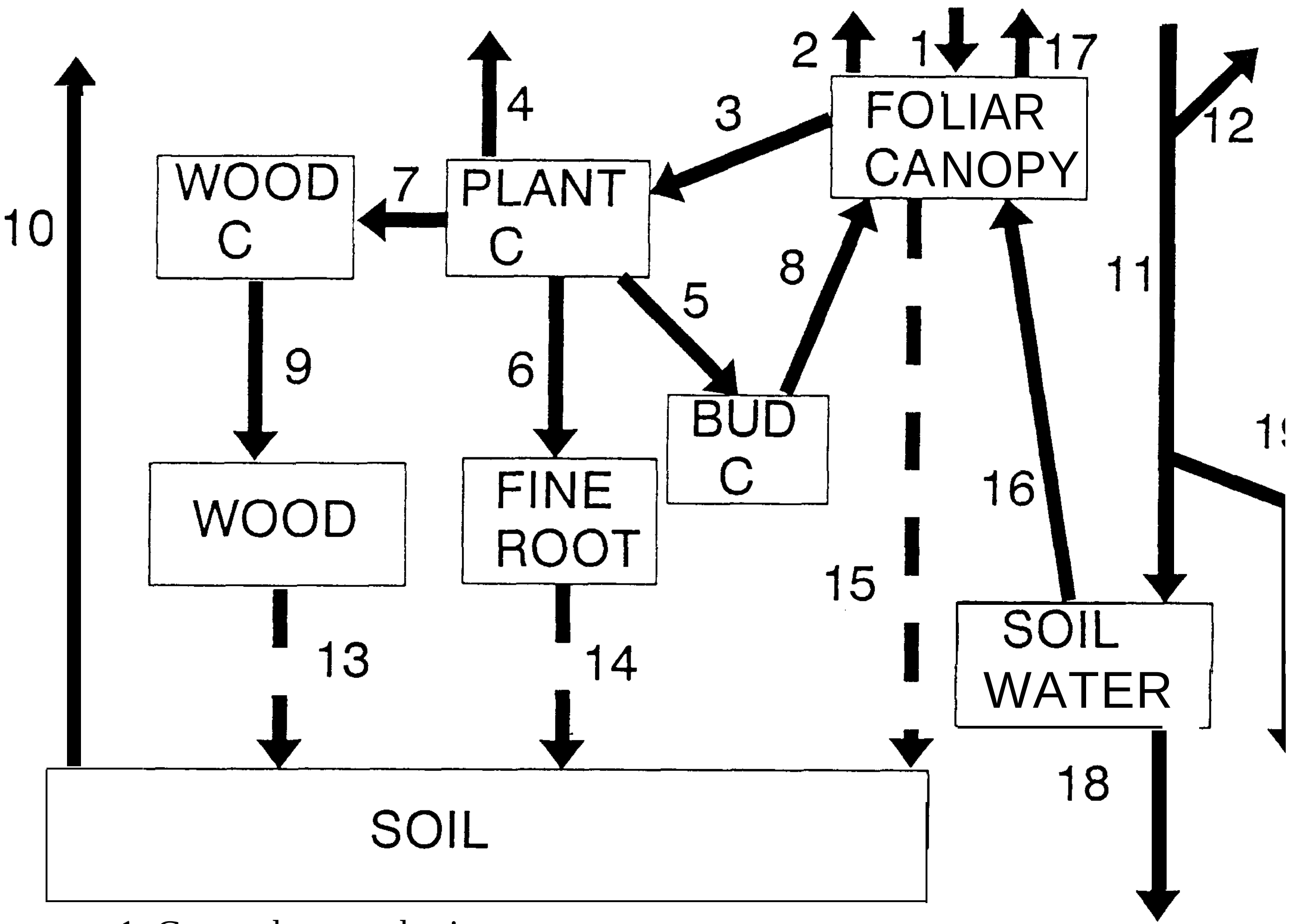
TABLE 1. PnET-IIS Model Values for Loblolly Pine.

Parameter Name	Parameter Abbreviation	Model Value
Light Extinction Coefficient	k	0.5
Folar Retention Time (years)		2.0
Leaf Specific Weight (g)		9.0
NetPsnMaxA (slope		2.4
NetPsnMaxB (intercept)		0
Light Half Saturation ($J m^2 sec^{-1}$)	HS	70
Vapor Deficit Efficiency Constant	VPDK	0.03
Base Leaf Respiration Fraction		0.10
Water-Use-Efficiency Constant	WUEC	10.9
Evaporation Fraction		0.18
Soil Water Release Constant	F	0.04
Maximum Air Temperature for Photosynthesis (°C)	TMAX	Variable
Optimal Air Temperature for Photosynthesis (°C)	TOPT	Variable
Change in Historic Air Temperature (°C)	DTEMP	0
Change in Historic Precipitation (percent difference)	DPPT	0

PnET-IIS calculated the maximum amount of leaf-area which can be supported on a site based on the soil, the climate and parameters specified for the vegetative type (Aber *et al.*, 1995; McNulty *et al.*, 1996b). The model assumed that leaf area was equal to the maximum amount of foliage that could be supported due to soil water holding capacity, species, and climate limitations (Table 1). The model did not account for differences in sites due to insect, disease, or management activities (i.e., burning, thinning, harvesting, or fertilizing).

Predicted NPP equalled total gross photosynthesis minus growth and maintenance respiration for leaf, wood, and root compartments (Figure 1). PnET-IIS calculated respiration as a function of the current and previous month's minimum and maximum air temperature. Changes in water availability and plant water demand also placed limitations on leaf area produced, so total leaf area decreased as vapor pressure deficit and air temperature increased above optimal levels. Reduced leaf area decreased total carbon fixation and altered ecosystem hydrology.

PnET-IIS predicts three hydrologic outputs: water drainage, evapotranspiration and soil water stress. Transpiration was calculated from a maximum potential transpiration modified by plant water demand that was a function of gross photosynthesis and water use efficiency (Aber *et al.*, 1995). Evaporation loss due to plant and soil interception was derived by Swank et al. (1972) for 30-year old South Carolina Piedmont loblolly pine stands and set at 18 percent of the total precipitation. Evapotranspiration was equal to plant transpiration, plus plant and soil interception loss. Drainage was calculated as precipitation in excess of evapotranspiration and soil water holding capacity (SWHC). Maximum water storage capacity was determined by SWHC to a depth of 102 cm (Marx, 1988). Monthly evapotranspiration was a function of leaf area, plant water demand, and climate (i.e., air temperature, vapor pressure deficit). If precipitation inputs exceeded plant water demand, the soil was first recharged to the SWHC and excess water was output as drainage. Monthly drainage values were summed to estimate seasonal or annual drainage. Growing season soil water stress (GSSWS) was equal to [1.0 - (average growing season soil water/SWHC)]. Average monthly soil water for the growing season equaled the sum of monthly calculated soil water, which is ≤ SWHC, divided by the number of months in the growing season. Growing season and annual soil water stress could range from 0.00 (no water stress) to 1.00 (maximum water stress).



1. Gross photosynthesis
2. Foliar Respiration
3. Transfer to Mobile C
4. Growth and Maint. Resp.
5. C Allocation to Buds
6. C Allocation to Fine Roots
7. C Allocation to Wood
8. Foliar Production
9. Wood Production
10. Soil Respiration
11. Precipitation
12. Interception
13. Wood Decomposition
14. Fine Root Decomposition
15. Foliar Decomposition
16. Uptake
17. Transpiration
18. Drainage
19. Fast Flow

Figure 1. Model Structure of PnET-IIS.

Input Data

Vegetation Data. No site specific vegetation indices were required to run PnET-IIS. Loblolly pine specific values were used as inputs to PnET-IIS (Table 1). These coefficients were largely derived from field measurements and from the published literat (Aber and Federer, 1992; McNulty *et al.*, 1994; A et *al.*, 1995).

Soils Data. Soil water holding capacity was only soil parameter needed to run PnET-IIS. The d were derived from *The Soils Atlas* compiled by

Soil Conservation Service (Marx, 1988). In developing a coverage of average SWHC, soils unsuitable for growing loblolly pines were excluded from the data set. If all SWHC were averaged across a grid cell, very low and high SWHC areas might be averaged within the same grid cell to produce a cell with an average SWHC that appears suitable for pine growth. To eliminate this source of input error, we used USDA Forest Service Forest Inventory and Analysis (FIA) data, which consisted of stand volume, growth, and species composition information remeasured at 21,000 permanent plots across the southern United States (Kelly, 1991). The database contained the location of loblolly pine FIA plots across the southern U.S. The ARC-INFO@ geographic information system (GIS) was used to combine data coverages and perform geographic analysis for soil series and FIA plot locations within the region. This information provided the soil series and associated range of SWHC where the pines were growing. The pine stands were located on FIA plots with a SWHC ranging from 3.8 to 15.8 cm H_2O for soil to a depth of 102 cm (Figure 2a).

Using the selected range of SWHC where loblolly pine grew, the 0.5" x 0.5" grid cell was placed over the region and a weighted average was computed for all remaining SWHC polygons within each grid cell. This GIS database was the only soils input to the PnET-IIS model.

Climate Data. To predict loblolly pine growth and hydrology, monthly climate data from 1951 to 1984 were used as model inputs. The 900+ meteorology station point databases were interpolated on a 0.5" x 0.5" grid across the southern U.S. (Marx, 1988). The gridded databases of minimum and maximum air temperature, relative humidity, and precipitation were compiled into a single database and run through a program to calculate average monthly solar radiation (Nikolov and Zeller, 1992). Solar radiation values were then combined with monthly maximum and minimum air temperature, and total monthly precipitation as input for PnET-IIS.

Climate Change Scenarios

Three climate change scenarios were developed using historic climate data bases in conjunction with two GCMs and a third scenario that assumed a constant moderate increase in air temperature and precipitation. The United Kingdom Meteorological Office (UKMO) (Wilson and Mitchell, 1987) and Goddard Institute of Space Studies (GISS) (Hansen *et al.*, 1983) GCMs were selected because of their common application and wide range of climate change predictions. The two GCMs were added to historic (1951 to 1984) average monthly minimum and maximum air temperature or multipled by historic monthly precipitation to produce 34 years of climate change scenario data for each grid cell. A 2°C increase in average monthly air temperature represented a conservative estimate of global temperature change under doubled atmospheric CO_2 (King *et al.*, 1992). Many GCMs predict increased precipitation across the southern U.S. (Cooter *et al.*, 1993). We used a static 20 percent increase in precipitation multipled by historic (i.e., 1951 to 1984) monthly precipitation and added 2°C to historic monthly maximum and minimum air temperature for each grid cell to create a third minimum climate change (MCC) scenario.

RESULTS AND DISCUSSION

Model Validation

Ecosystem model validation is often an overlooked aspect of model testing, especially at large spatial scales. Models designed for use at large spatial scales are based on numerous assumptions about forest structure and function such as soil water storage and stand stocking, and for a specific forest stand, one or more of the assumptions may be inaccurate. Because numerous assumptions were built into large scale models, regional scale models should not be expected to accurately predict hydrologic components (e.g., evapotranspiration, soil water stress) for all sites and all years. However, the model should generally correlate with hydrologic components from many widely located sites. If general relationships were not found between predicted and measured hydrologic components across a wide range of site conditions, the model logic is flawed. In PnET-IIS, productivity was related to plant water use. Both productivity and water use increased with increased leaf area. Therefore, it is important to validate both the water use and productivity predictions to gain confidence in model outputs across broad climatic conditions and geographic areas.

Predictions of forest NPP (t $ha^{-1} yr^{-1}$) were compared with measured annual basal area growth (cm^2 $tree^{-1} yr^{-1}$) for 12 loblolly pine stands located across the southern U.S. These sites were selected because the trees on each site most closely characterized natural loblolly pine stands and had not been substantially impacted by insects, disease, or forest management practices (i.e., burning, fertilizing, thinning, or harvesting). The sites also represent a wide range of air temperature, precipitation, and soil conditions (McNulty *et al.*, 1997). PnET-IIS was run on each of the 12 sites using site specific climate data from 1951

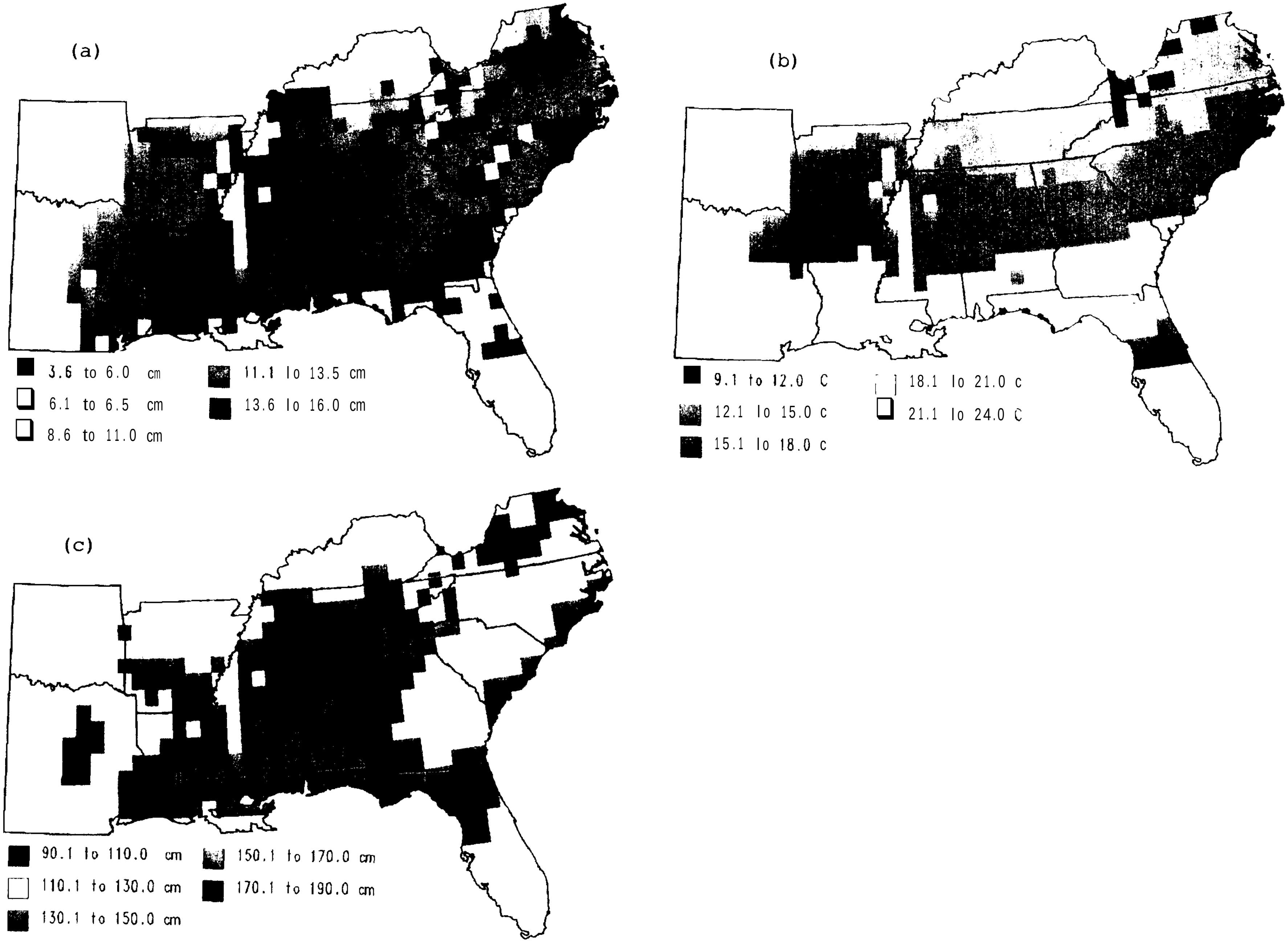


Figure 2. (a) Measured Average Soil Water Holding Capacity, (b) Measured Average Annual Historic (1951-1980) Air Temperature, and (c) Measured Average Annual Historic (1951-1980) Precipitation.

to 1990. Across all sites and years, average annual basal area growth was significantly correlated with average annual predicted NPP (r^2=0.66, P < 0.005, n = 12) (McNulty et al., 1997).

Researchers have long used United States Geologic Survey (USGS) stream flow data for hydrologic modeling (Moody *et al.*, 1986), but traditionally the emphasis was on model calibration (Dawdy *et al.*, 1972). Basin stream flow data are useful in broad-scale modeling, calibration, and validation because measurements integrate ecosystem water input, movement, and, usage. The USGS used 5,900 stream gauging stations across the continental U.S. to produce a map of average annual stream flow from 1951 to 1980 (Krug *et al.*, 1989). A 0.5" x 0.5' grid cell was placed over the map and a weighted average of mean stream flow was calculated based on the area size and value of all isopleths within each cell. The gridded map of stream flow was then overlaid on a map of the spatial extent of loblolly pine. The resulting map represents measured stream flow across the geographic range of loblolly pine (Figure 3a).

PnET-IIS predicted that the lowest drainage will occur in eastern Texas and along the coastal plain while the highest drainage will occur in the high elevation Appalachian Mountains in southwestern North Carolina and northeastern Georgia (Figure 3a). Although stream flow is most strongly determined by precipitation, other factors affect stream flow, some of which are not accounted for in model predictions of regional stream flow. Nationally, 8 percent of all stream flow is removed for industrial, commercial, and residential purposes (USGS, 1992) but the regional location and proximity to population centers will affect the percentage of diverted stream flow. The other principle factor affecting stream flow is vegetation. Forests evapotranspire 20 to 75 percent of the annual precipitation (Waring *et al.*, 1981). Species type, age, and morphology all influence ET rates. Although some of these factors are not accounted for by PnET-IIS, historic (1951 to 1980) rates of predicted annual drainage generally agreed with the gridded USGS stream flow maps of the region (r^2=0.64, P < 0.0001, n = 502). By comparison, measured annual precipitation was less well correlated with measured USGS average annual stream flow (r^2 = 0.42, P < 0.0001, n = 502) (McNulty *et al.*, 1996a).

Historic Climate

Across the southern U.S. there is a strong north-south average annual air temperature gradient (Figure 2b). The annual precipitation gradient is more complex. The highest rates of annual precipitation occur in the southern Appalachian Mountains and along the central section of the Gulf of Mexico Coast (Figure 2c). The lowest rates of precipitation occur along the far western and far northeastern range of loblolly pine (Figure 2c). The variation in inter-annual monthly air temperature and precipitation from 1951 to 1984 equals or exceeds the range of change applied to the PnET-IIS model under the GCM climate change scenarios.

Climate Change Across *the Southern U.S.*

The GISS GCM predicted above average precipitation from May to August, and below average annual precipitation from October to January (Table 2). The GISS GCM predicted that annual precipitation would increase by 3 percent compared to historic values, and that average annual precipitation would have the largest decrease in the central portion of the region and the largest increase along the Atlantic coast. The UKMO GCM predicted a slight decrease in average annual precipitation (-1 percent of historic precipitation), with a predicted increase during March to May, but a decrease from June to November, except September which was higher (Table 2). The UKMO GCM predicted that annual precipitation would have the largest decrease in the central and southwestern portion of the region and the largest increase along the southern Atlantic coast.

Across the southern U.S., the GISS GCM consistently predicted smaller increases in air temperature compared to the UKMO GCM (Table 2). Within the region, the GISS GCM predicted above average temperature from September to November and the largest increase in March (Table 2). The summer months, although still much warmer than historic air temperatures, were predicted to increase by the least amount. The UKMO GCM predicted a relatively constant increase in average monthly temperatures, which were higher than the GISS GCM predicted air temperature increase (Table 2).

Climate Change Scenario Effects On Hydrology

Predicted average annual ET, soil water stress and drainage using historic climate varied widely across the region. Historically, low annual precipitation and high annual air temperature combine to give the eastern Texas and central Georgia the lowest predicted rates of annual water drainage (Figure 3a) and high soil water stress (Figure 5a). Conversely, cooler temperatures and high rates of precipitation combine to make the southern Appalachian mountains in western North Carolina the area of highest predicted

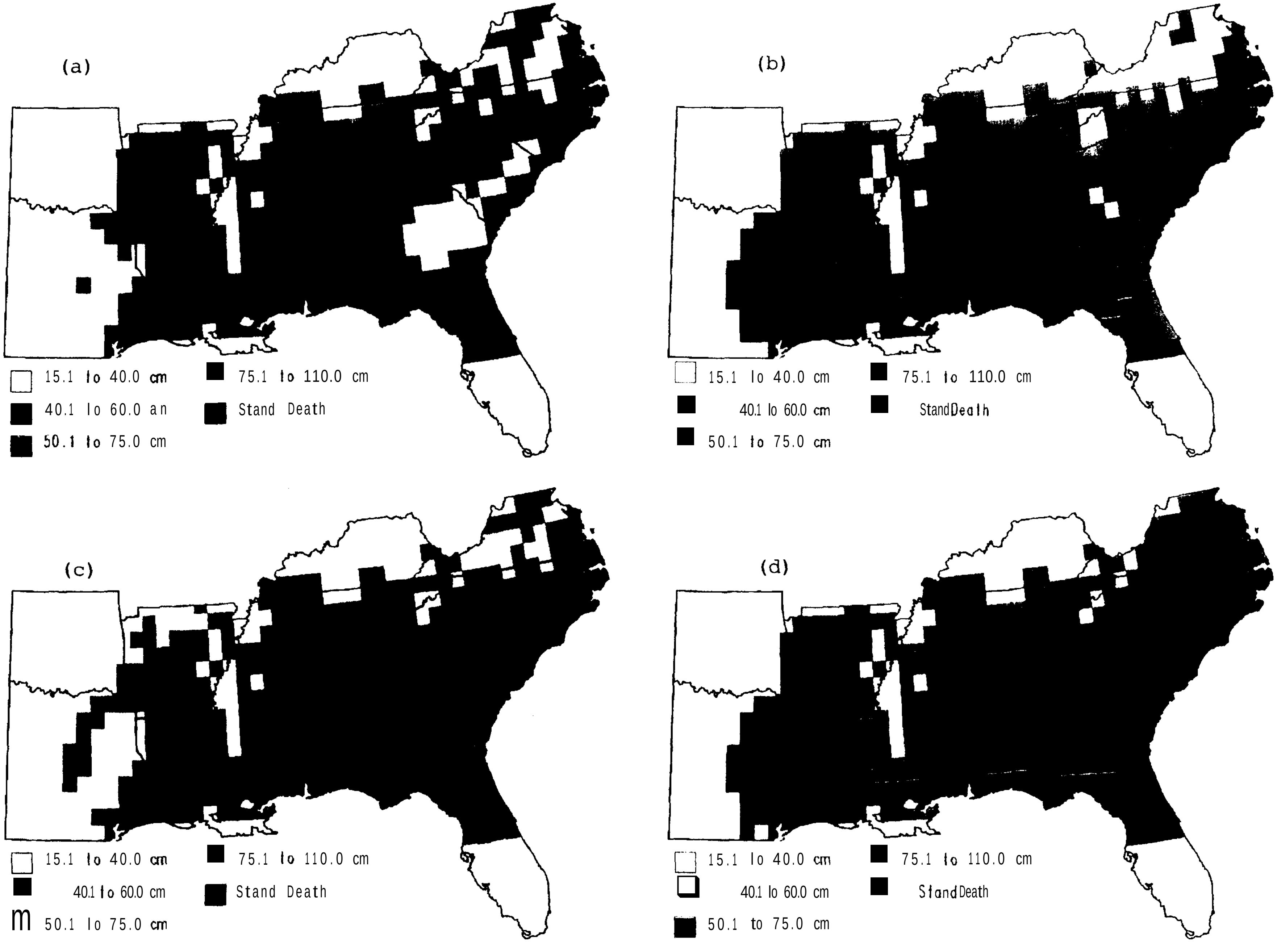


Figure 3. (a) PnET-IIS Predicted Average Annual Water Drainage Using the Historic (1951-1980) Climate Data, (b) the UKMO Climate Scenario, (c) the GISS Climate Scenario (c), and (d) the MCC Scenario.

TABLE 2. Average Percentage Change in Total Monthly Precipitation and Average Monthly Change in Air Temperature for Southern U.S. as Predicted Using the United Kingdom Meteorological Office (UKMO) General Circulation Model (GCM) and the Goddard Institute of Space Studies (GISS) GCM, and the Minimum Climate Change (MCC) Scenario.

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Average (s.e.)
Average Total Monthly Precipitation (cm) Across the Southern United States (1951 to 1980)													
Average	**10.9**	**10.7**	**12.9**	**10.9**	11.9	11.2	12.8	11.2	10.6	8.2	9.2	11.5	11.0 (0.4)
Scenario	Percentage Change from Historic Values												
MCC	+20	+20	+20	+20	+20	+20	+20	+20	+20	+20	+20	+20	+20 (0.00)
UKMO	-19	+5	+9	+18	+8	-1	-9	-5	+3	-20	-7	+6	-1 (0.03)
GISS	-15	+31	-9	+1	+22	+27	+31	+5	+0	-16	-24	-18	+3 (0.05)
Average Monthly Air Temperature (°C) Across the Southern United States (1951 to 1980)													
Average	6.4	8.2	12.2	17.1	21.1	24.7	26.4	26.0	23.2	17.7	12.1	8.2	16.9 (2.2)
Scenario	Additive Change to Historic Values (°C)												
MCC	+2.0	+2.0	+2.0	+2.0	+2.0	+2.0	+2.0	+2.0	+2.0	+2.0	+2.0	+2.0	+2.0 (0.0)
GISS	+3.8	+3.8	+5.8	+4.2	+3.8	+3.8	+3.5	+3.2	+5.3	+4.6	+5.4	+4.1	+4.3 (0.2)
UKMO	+6.7	+6.6	+7.1	+6.5	+5.6	+6.1	+6.7	+6.9	+6.7	+6.7	+6.6	+7.2	+6.6 (0.1)

drainage (Fig 3a) and the lowest soil water stress (Fig 5a).

When the MCC scenario was run with PnET-IIS, the reduction in leaf area in the relatively cooler northern areas was offset by increased ET per unit leaf area, so annual ET remained constant or increased (Figure 4d). Drainage also increased due to a 20 percent increase in precipitation that was not fully evaporated or transpired (Table 3, Figure 3d) and average regional soil water stress decreased (Table 3, Figure 5d). However, under the MCC scenario, leaf area decreased in the warmest sections of the region, and states such as Florida and Texas did not counterbalance increases in ET per unit of leaf area. Therefore, across the southern most part of the region, total annual ET decreased (Figure 4d), total annual drainage increased (Figure 3d) and average annual soil water stress decreased (Figure 5d).

Using the GISS GCM, predicted annual ET (Figure 4c) and average annual soil water stress increased in the central, northwestern and northeastern areas, and decreased across the southern and eastern portions of the region (Figure 5c). Compared to historic drainage, the GISS scenario predicted an average annual drainage decrease of 1 percent across the southern U.S. (Table 3).

The UKMO scenario predicted the largest deviation in predicted ecosystem hydrology compared to historic climatic conditions. In areas where PnET-IIS predicted that loblolly pine leaf area equaled zero, we assumed that the pine ecosystem could no longer survive. Predicted pine ET was zero, and drainage was equal to precipitation minus soil transpiration (Figures 3b and 4b). The UKMO scenario predicted increased drainage throughout the region, except along the cooler Appalachian Mountains where drainage decreased due to increased ET (Figure 4b). Compared to historic drainage, the UKMO scenario average annual drainage increased by 66 percent across the region (including areas of forest death) (Table 3). If only areas where loblolly pine NPP > 0 were included, drainage increased by **10** percent compared to historic levels (Table 3).

Influence of Species Migration and Replacement

PnET-IIS predictions of water use assume that if loblolly pine losses leaf area, as occurs in some part of the region with both GCM scenarios, no other vegetation will replace the loblolly pine. Using ZELIG in conjunction with the GISS GCM, Urban and Shugart (1989) predicted that future climatic conditions may no longer be suitable for loblolly pine growth across much of the south. Loblolly pine may be replaced by other southern coastal plain pine species [i.e., *Pinus palustris* (longleaf pine), *Pinus serotina* (pond pine), and *Pinus elliotti* (slash pine)] which may be more heat tolerant. However, due to the increased temperature, ZELIG predicted that the replaced species

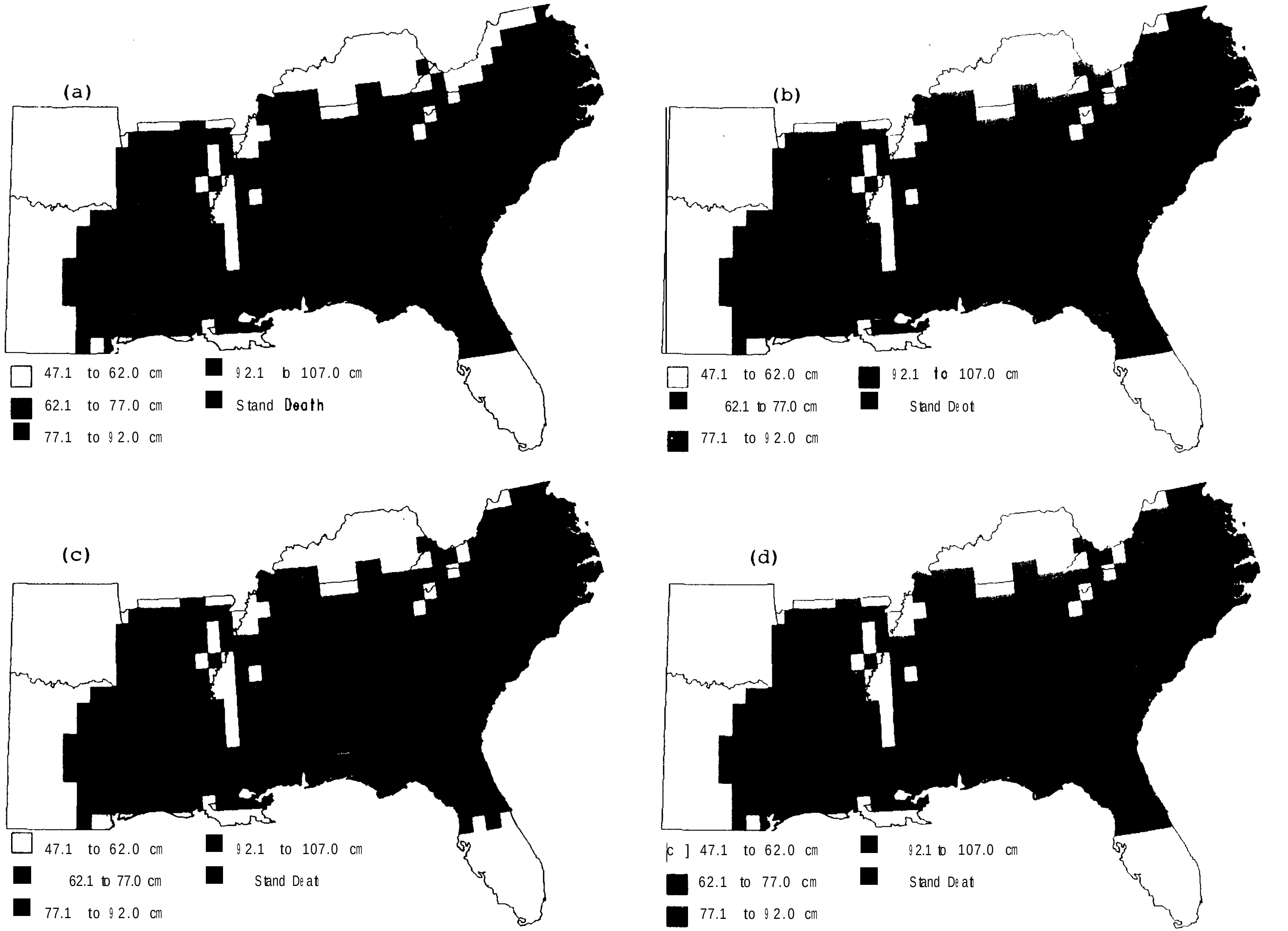


Figure 4. (a) PnET-IIS Predicted Average Annual ET Using Historic (1951-1980) Climate Data, (b) the UKMO Climate Scenario, (c) the GISS Climate Scenario, and (d) the MCC Scenario.

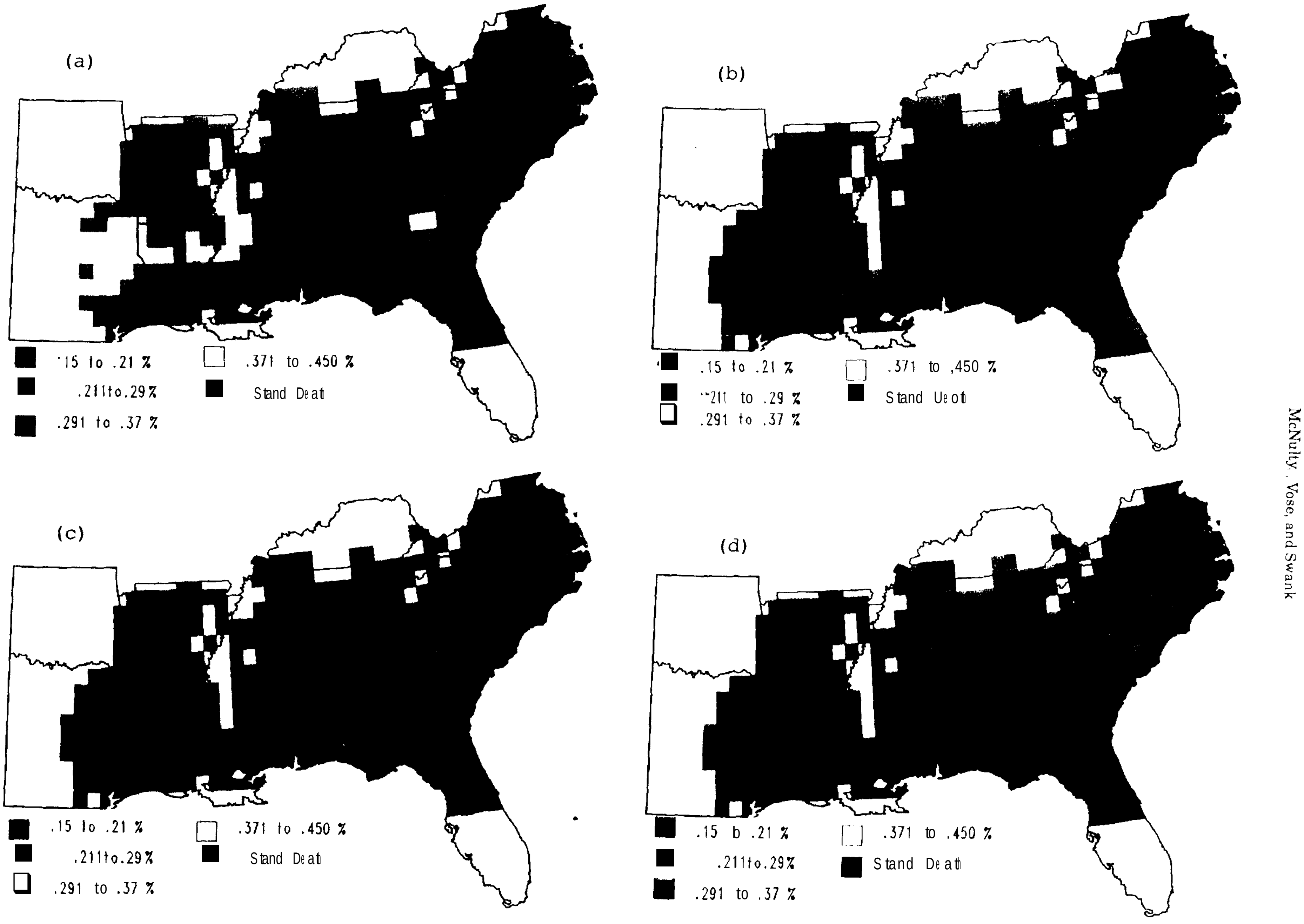


Figure 5. (a) PnET-IIS Predicted Average Annual Soil Water Stress Using Historic (1951-1980) Climate Data, (b) the UKMO Climate Scenario, (c) the GISS Climate Scenario, and (d) the MCC Scenario.

TABLE 3. Predicted Average Changes in Growing Season Drainage (GS Drain), Annual Drainage (Ann. Drain), Growing Season Evapotranspiration (GS ET), and Annual Evapotranspiration (Ann. ET) for Historic Climate (1951 to 1980) and for Three Climate Change Scenarios.

Scenario	Cells	GS Drain (cm)	Ann. Drain (cm)	GS ET (cm)	Ann. ET (cm)
Predicted Hydrology Averaged Over All (502) Cells in Southern U.S.					
Historic	502	16.9 (0.3)	52.5 (0.5)	55.5 (0.2)	79.7 10.4)
MCC	602	25.7 (0.2)	70.3 (0.5)	59.9 (0.2)	88.5 (0.5)
GISS	502	26.2 (0.4	51.9 (0.5)	52.4 (0.3)	80.2 (0.3)
UKMO	502	43.7 (0.8)	87.2 (0.8)	28.7 (0.6)	45.2 (0.5)
Scenario	**Live Cells**	**GS Drain (cm)**	**Ann. Drain (cm)**	**GS ET (cm)**	**Ann. ET (cm)**
Predicted Hydrology Averaged Over All Living Cells in Southern U.S.					
Historic			Same As Above		
MCC			Same As Above		
GISS	491	21.6 (0.6)	56.3 (0.6)	53.5 (0.5)	81.7 (0.4)
UKMO	289	24.3 (0.7)	58.0 (0.8)	49.9 (0.3)	78.5 (0.3)

may not develop into a closed canopy forest. ZELIG predicted that the southern forests could eventually degrade into marginal forests or non-forest vegetation within the next century. The timing of forest replacement would depend on the degree and rate of an air temperature increase. Urban and Shugart (1989) cautioned that the range of climate for which the ZELIG was run was outside the range for which it was developed, so there is some uncertainty associated with the predicted vegetation response.

Influence of Atmospheric CO_2

Although there is general agreement that a doubling of atmospheric CO2 will increase plant photosynthesis, leaf area, water use and efficiency and growth, and reduce leaf conductance and sensitivity to drought (Kickert and Krupa 1990), there is little agreement regarding the size of these changes (Idso and Idso, 1994). Additionally, scaling plant level response to increased atmospheric CO_2 to ecosystems is a complex issue which is only beginning to be addressed by the scientific community (Woodward, 1992). Increases in atmospheric CO_2 are likely to moderate the influence of elevated air temperatures on forest productivity and hydrology, but the level of moderation is unknown at the regional scale. Future research should focus on integrating forest process models with climate change scenarios and atmospheric CO_2 concentration projections to more fully assess regional scale hydrologic response.

CONCLUSIONS

Climate change could significantly alter stream flow across many forested areas in the southern U.S. Forests located in the warmest sections of the present range of loblolly pine were more susceptible to changes in hydrology than forests in wetter or cooler areas. Using the GCM scenarios across the region, predicted annual drainage may decrease by 1 percent to 66 percent (when predicted forest death was assumed to have no species replacement). Most of the increase in drainage associated with the MCC scenario was due to a 20 percent increase in total annual precipitation. The GISS scenario is most closely aligned with the expectations of future climate change (Cooter *et al.*, 1993). Using this scenario, predicted total annual regional drainage would not be significantly different from historic rates, because of increased evapotranspiration per unit leaf area and reduced total leaf area. The UKMO scenario represents the most severe climate change. Although unlikely to occur, this scenario was included because it represents the extreme predicted climate response for the region and demonstrates the range of future climatic conditions. Using the UKMO scenario, PnET-IIS predicts massive mortality across the southern U.S. pine forest. These predictions of water use and yield do not account for increases in atmospheric CO_2 that will likely moderate losses in forest productivity and leaf area due to increased air temperatures. Increased forest leaf area could increase water use and decrease water yields, compared with no CO_2 fertilization effect. However, the influence of increased atmospheric CO_2 on increased water use efficiency needs to be better quantified at the regional scale before the influence of climatic change on regional scale water use and yield can be assessed.

ACKNOWLEDGMENTS

The authors thank Eugene Pape and Adrian Rollans for technical support, Dr. John Aber for assistance in model use and modification, and Dr. Dean Urban and Ms. Marie Louise Smith for manuscript review. Support for this research was provided by the USDA Forest Service Southern Global Change Program.

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