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Potential Climate Change Effects on Loblolly Pine Forest Productivity and Drainage across the Southern United States

PnET-IIS, a well validated, physiologically based, forest ecosystem model combined soil and vegetation data with six climate change scenarios. The model predicted annual net primary productivity and drainage on loblolly pine sites in the southern US states of Texas, Mississippi, Florida and Virginia. Climate scenario air temperature changes were +2°C to +7°C > historic (1951 to 1984) values and climate scenario precipitation changes were −10% to +20% > historic values. Across the sites, increasing air temperature would have much greater impact on pine forest hydrology and productivity than would changes in precipitation. These changes could seriously impact the structure and function of southern United States forests by decreasing net primary productivity and total leaf area. Water use per unit area would increase, but total plant water demand would decrease because of reduced total leaf area, thus increasing regional pine forest drainage. An average annual air temperature increase of 7°C, caused a considerable reduction in the loblolly pine range.

INTRODUCTION

Half the more than 76 mill. ha of commercial timberland in the southern United States (US) are planted with southern pine species (i.e., loblolly (*Pinus taeda*), shortleaf (*Pinus echinata*), longleaf (*P. palustris*) and slash (*P. elliotti*) pine. These species provide important commercial products because over 110 million m^3 of softwood timber (40% of the US total) are harvested annually from this region (1). Continued productivity of these species is vital to the regions development and economic stability. Therefore, reductions in growth could have serious economic implications.

The southeastern US also has one of the most rapidly growing human populations in North America. As the population increases, the demand for commercial, industrial and residential water increases (2). Typically, more than 50% of the precipitation received by southern forests is returned to the atmosphere through evapotranspiration (ET) (3). Forest species type, stand structure (e.g., leaf area, density) and climate influence drainage from forested areas (4). Because forests occupy approximately 55% of the land area in the southern US (5), changes in forest structure and water use could significantly change drainage across the region.

Despite the importance of southern pines, little research has been conducted across their range to evaluate the potential implications of climate change on forest productivity and drainage. Climate change can be divided into spatial and temporal changes in weather (e.g., precipitation and air temperature) and changes in atmospheric chemistry (e.g., CO_2, O_3, NO_x, and SO_x). In this study, we examined two weather-related aspects of climate change, precipitation and air temperature. Changes in atmospheric chemistry influence how changes in precipitation and air temperature affect forest hydrology and productivity. As we better understand how atmospheric chemistry changes over time and how these factors influence forest function, atmospheric chemistry influences can be incorporated into forest function models.

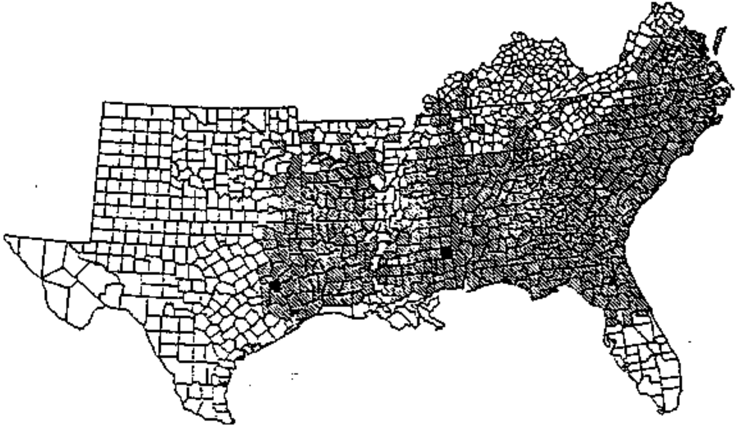

Figure 1. Black shaded counties indicate location of four loblolly pine sites selected for PnET-IIS assessment of changes in net primary productivity (NPP) and hydrology across the southern US: Bradford, Fla.; Gloucester, Va.; Walker, Tex.; and Wayne, Miss. Gray shaded counties indicate the geographic range of loblolly pine.

To address the question of how temporal and spatial changes in precipitation and air temperature affect forest hydrology and productivity, we used the model PnET-IIS. The physiologically based model combines climate, soil and vegetation data, to predict annual soil water stress, drainage and productivity on four loblolly pine sites in the southern US (Fig. 1). The sites were located in the states of Texas (TX), the driest site, Mississippi (MS), the wettest site, Florida (FL), the hottest site, and Virginia (VA), the coolest site. We used historic climate data and six climate change scenarios in the model. These sites were chosen because they represent the climatic extremes of loblolly pine and because historic measurements of growth on the sites and drainage across the region were previously well correlated with PnET-IIS predictions (6–8).

METHODS

Model Structure

PnET-IIS used site specific soil water holding capacity (SWHC) and four monthly climate parameters (minimum and maximum air temperature, total precipitation and solar radiation) to predict hydrology and productivity (6–9). When vegetative information is combined with the site specific climate and soil parameters, PnET-IIS predicted loblolly pine net primary productivity (NPP) and drainage across its natural range. Predicted NPP equalled defined as annual gross leaf photosynthesis minus growth and maintenance respiration for leaf, wood and root compartments (9). Gross photosynthesis rates were largely driven by solar radiation, while respiration was a function of air temperature.

Gross photosynthesis was a function of gross photosynthesis per unit leaf area and leaf area index (LAI). Changes in water availability and plant water demand placed limitations on the amount of leaf area produced (9). As vapor pressure and air temperature increased. LAI and net photosynthesis decreased.

Net photosynthesis in loblolly pine was related to the length of time that the trees had to acclimate to changes in air temperature. As the length of acclimation time increased, gross foliar respiration rates decreased, especially at high air temperature (> 30°C) (10). PnET-IIS calculated respiration as a function of the current and previous months minimum and maximum air temperature. The optimal temperature for net photosynthesis varied from 23° to 27°C, and the maximum air temperature for gross photosynthesis varied from 30° to 43°C (10). As temperature increased beyond the optimal photosynthetic temperature, the respiration rate increased, while gross photosynthesis increased slightly or decreased, so proportionally less net carbon per unit leaf area was fixed (11–13).

PnET-IIS predicted productivity and hydrology including ET and drainage. Annual transpiration was calculated from a maximum potential transpiration modified by plant water demand (a function of gross photosynthesis and water-use efficiency). Interception loss was a function of leaf area and total precipitation. Evapotranspiration was equal to transpiration and interception loss. Drainage was calculated as water in excess of ET and SWHC. Soil water storage was determined by SWHC, monthly ET, LAI and climate. Plant water demand was dependent on monthly precipitation and water stored in the soil profile. If precipitation inputs exceeded plant water demand, the soil was recharged to the SWHC. If water was still available, water was output as drainage. Monthly drainage values are summed to estimate annual water outflows.

Input Data

PnET-IIS required site specific soils and climate data and species specific vegetation attributes.

Soils Data

SWHC was the only soil variable required to run PnET-IIS. Two soil pits were dug on each of the four sites. In each soil pit, two 785-cm^3 soil cores were extracted at each horizon to a depth of 102 cm. The cores were returned to the laboratory, and weighed at field capacity. Soils were placed on a pressure plate at -10 MPa for 48 hours and reweighed. Differences between pre- and post-pressure weights were converted into centimeters of water for that horizon sample. Waterholding capacity of the sample was factored over the total soil horizon depth, and all waterholding capacities for each horizon were summed to estimate total water-holding capacity for the profile.

Vegetation Data

No site specific vegetation data were needed to parameterize the PnET-IIS model. Instead, PnET-IIS used vegetation variables (e.g., growing degree days to start and stop of leaf and wood production, light extinction coefficient) specifically developed for southern pine tree species (13, 14) (Table 1). These variables remained fixed across all sites and model runs.

Climate Data

PnET-IIS required four monthly climatic drivers: minimum and maximum air temperatures, precipitation and solar radiation. The Forest Health Atlas provided climate data from 1951 to 1984, which were originally acquired from the National Climatic Data Center (NCDC) (15). Because these data have error rates between 5 and 40% (15), many data points were removed before usage. After being checked for accuracy, the database was interpolated on a 0.5° • 0.5° grid across the southern US (15). Climate data from 1985 to 1990 were entered from NCDC microfiche by averaging each of the four climate variables using the three climate stations closest to each site. The minimum and maximum air temperatures, relative humidity and precipitation for each site were compiled into a single database and run through a program to calculate monthly solar radiation (16). Solar radiation values were then combined with average monthly maximum and minimum air temperatures and total monthly precipitation into a single database.

Climate Change Scenarios

Only changes in precipitation and air temperature were considered in the climate change scenarios. Two types of climate change scenarios were developed to assess altered temperature and precipitation patterns on loblolly pine productivity and drainage. The first type of climate change scenario increased the historic (1951 to 1990) monthly averages of daily minimum and maximum temperatures by 2°C (H2TEMP Scenario). A 2°C increase in average monthly air temperature represents a conservative estimate of global temperature change by the year 2100 (17). Because most general circulation models (GCMs) predict increased precipitation across the southern US (18), a second scenario increased historical (1951 to 1990) total monthly precipitation by 20% (H2OPPT Scenario) for all sites and months. The relatively conservative estimates of temperature increases and a liberal estimate of precipitation increases were combined in a Mild Climate Change Scenario (MCC Scenario).

A second series of climate change scenarios combined historic climate databases and three GCMs. The Oregon State University (OSU) (19), Goddard Institute for Space Studies (GISS) (20), and United Kingdom Meteorological Office (UKMO) (21), were selected from 19 GCMs because they share common applications and ranges of climate change predictions. All GCMs predict variation in monthly temperature and precipitation, based on a doubling of atmospheric CO_2. Each of the three GCMs monthly climate change data were added to historic (1951 to 1990) average monthly minimum and maximum air temperatures or multiplied by historic monthly precipitation to produce 40 years of climate change scenario data.

Previous Validation of Productivity Predictions

Predictions of productivity (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 US. These sites represent a wide range of climates (i.e., hot, moderate and relatively cool average annual air temperature, and high, moderate and low average annual precipitation) and soil conditions (7). PnET-IIS was run on each of the 12 sites using site specific climate data from 1951 to 1990. Across all sites and years, predicted NPP was significantly ($r^2 = 0.30$, $P < 0.005$, $n = 165$) correlated with annual basal area growth, and average annual basal area growth was highly correlated ($r^2 = 0.66$, $P < 0.005$, $n = 12$)

Table 1. PnET-IIS model values. (*) values are derived specifically for loblolly pine. All other parameters are general vegetative values.

Parameter name	Parameter Abbreviation	Model value
Light extinction coefficient	k	0.5
Foliar 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	WUE C	10.9
Canopy evaporation fraction		0.15
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 (% difference)	DPPT	0

with average annual predicted NPP (7). The four sites selected for assessment of climate change impacts on forest hydrology and productivity were selected from these 12 sites.

Previous Validation of Hydrology Predictions

The USGS has more than 6000 stream gauging stations across the continental United States, some of which were used in model validation of regional drainage (8). Average annual measured runoff for the southern US was calculated from gauge station data from 1951 to 1980 (8). A 0.5° x 0.5° grid cell was placed over an isopleth map of the southern US and a weighted average of mean cell run-off was calculated based on the area size and value of all isopleths within each cell. PnET-IIS predictions of drainage correspond to measured USGS annual runoff data collected from 1951 and 1980 ($r^2 = 0.64$, $P < 0.0001$, n = 502) (8). Measured average annual precipitation was less well correlated with measured USGS average annual runoff ($r^2 = 0.42$, $P < 0.0001$, n = 502).

RESULTS AND DISCUSSION

Historical Climatic and Soil Characteristics

Across the region, the 1950s and 1980s contained some of the hottest and driest years on record (15). The annual variation in air temperature and precipitation equaled or exceeded the range of change applied to the PnET-IIS model under the climate change scenarios. Besides intra-site climate variability, climatic conditions also varied among sites (Table 2). The MS site received the highest average annual precipitation, while the TX site received the lowest. The highest average annual site temperatures were recorded in FL and the lowest in VA (Table 2). Average SWHC was 11.2 cm, but ranged from 6 cm in the FL site to 16 cm in the MS site.

Table 2. Historic climate and soils data for loblolly pine sites in four southern US states used to predict productivity change under various climate change scenarios. Standard errors (SE) are shown in parentheses.

Site	Latitude (°)	Growing season average air temperature (°C)	Annual average air temperature (°C)	Growing season average total precipitation (cm H_2O)	Annual Average total precipitation (cm H_2O)	Soil water holding capacity (cm H_2O 102 cm^{-1} soil)
FL	30.0	25.3 (0.2)	20.2 (0.2)	80(2)	130 (3)	6
VA	37.5	22.0 (0.2)	15.0 (0.3)	62 (4)	117 (7)	12
TX	31.0	25.3 (0.3)	19.5 (0.2)	55 (2)	114 (7	11
MS	31.6	24.1 (0.2)	18.2 (0.2)	72 (3)	149 (6)	16

Table 3. Variation in general circulation model (GCM) predictions of growing season and annual average air temperature and total precipitation for loblolly pine forests In four southern US states. Standard errors are represented in (SE).

Site	Average annual air temperature	Average growing season air temperature	Average annual precipitation	Average growing season precipitation
TX	+4.3 (0.23)	+3.9 (0.32)	-5 (8)	+12 (9)
VA	+3.9 (0.33)	+3.6 (0.42)	+11 (6)	+18 (9)
MS	+4.3 (0.26)	+4.0 (0.24)	−2 (7)	+14 (5)
FL	+3.1 (0.19)	+3.4 (0.25)	−5 (7)	−1 (9)
Avg	+3.9 (0.30)	+3.7 (0.34)	−1 (6)	+2 (8)
OSU GCM				
TX	+3.3 (0.17)	+3.6 (0.20)	−2 (6)	−3 (8)
VA	+3.2 (0.24)	+3.0 (0.19)	+16 (6)	+20 (9)
MS	+3.5 (0.21)	+3.5 (0.17)	+5 (9)	+3 (12)
FL	+3.4 (0.15)	+3.4 (0.11)	+11 (3)	+17 (4)
Avg	+3.4 (0.20)	+3.4 (0.20)	+7 (7)	+8 (10)
UKMO GCM				
TX	+6.1 (0.33)	+5.9 (0.56)	0 (6)	+3 (10)
VA	+7.3 (0.28)	+6.7 (0.26)	+4 (4)	+3 (4)
MS	+8.0 (0.21)	+7.9 (0.40)	-19 (5)	-14 (7)
FL	+4.8 (0.80)	+4.9 (0.07)	+11 (3)	+17 (4)
Avg	+6.5 (0.44)	+6.3 (0.61)	-1 (6)	+2 (8)

Climate Change Scenarios

GCM predictions of precipitation and air temperature under a doubled CO_2 environment vary widely (18). The OSU, GISS and UKMO GCM models predict between a 3.0°C and 7.9°C increase in inter-site growing season temperature and between a 3.1°C and 8.0°C change in inter-site average annual temperature (Table 3). Overall, the three GCM'S agreed that growing season and annual air temperature would increase most on the MS site and the least on the FL site (Table 3). The OSU GCM predicted the smallest increase in growing season and annual air temperature, while the UKMO GCM predicted the largest increase in air temperature.

The GCMs agreed less on which sites would experience the largest change in precipitation. GCM predictions of inter-site changes in precipitation ranged from 81% to 116% of historic average total annual precipitation and from 86% to 120% of historic average total growing season precipitation (Table 3). Across the four sites, average annual precipitation and growing season precipitation differed little from historic averages in the GISS and UKMO GCM, while the average increase in precipitation was approximately 8% in the OSU GCM.

The GISS and OSU GCMs predicted that average annual precipitation would have the highest decrease in the TX and/or FL site and the largest increase in VA. The UKMO predicted that average annual precipitation would have the largest decrease on the MS site and largest increase on the FL site (Table 3). The GISS and OSU GCMs predicted that average growing season precipitation would have the largest decrease on the FL and/or TX sites, respectively, and the largest increase on the VA site. The UKMO GCM predicted that the largest decrease in growing season precipitation would occur on the MS site and the largest increase on the FL site.

Historic Net Primary Productivity

Using historic climate data for these four sites, predicted annual inter-site NPP ranged from 0.5 to 18.7 t ha^{-1} yr^{-1}, with an average of 11.2 t ha^{-1} yr^{-1}. Predicted annual NPP was highest on the MS site (13.1 t ha^{-1} yr^{-1}) and lowest on the TX site (9.3 t ha^{-1} yr^{-1}). Net primary productivity decreased as growing season temperature increased across the region. Average growing season air temperatures in FL, TX and MS were at or above optimal levels for photosynthesis using historic climate data (Table 2).

This range and average NPP is within the range of values measured by others. Teskey et al. (13) measured a range of aboveground NPP between 2 and 10 t dry matter ha^{-1} yr^{-1} on loblolly pine sites. Other studies have estimated that belowground production equaled approximately 40% of aboveground NPP (22, 23). Multiplying Teskey et al., (13) measurements of aboveground NPP by 1.4 (60% aboveground NPP/ 40% below ground NPP) yielded a measured range of total (above- and belowground) NPP between 2.8 and 14.0 t biomass ha^{-1} yr^{-1}, with most site NPP (aboveground only) > 8.5 t biomass ha^{-1} yr^{-1} (13).

Climate Change Scenario Effects on NPP

Increasing average monthly air temperature in the climate change scenario produced a range of NPP responses across the sites. In the H2TEMP and MCC Scenarios, average monthly air temperature exceeded the optimal range for photosynthesis

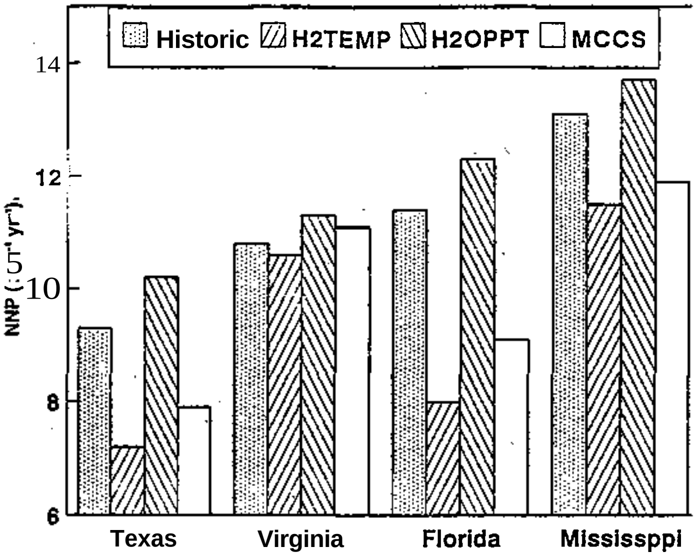

Figure 2. Predicted changes in net primary productivity (NPP) across selected loblolly pine sites in four southern US states. Historic = historic site climate from 1951 to 1990, H2TEMP = historic air temperature + 2°C increase in average annual air temperature, H20PPT = 120% of historic precipitation, and MCC Scenario's = historic site climate + combined increases In air temperature and precipitation.

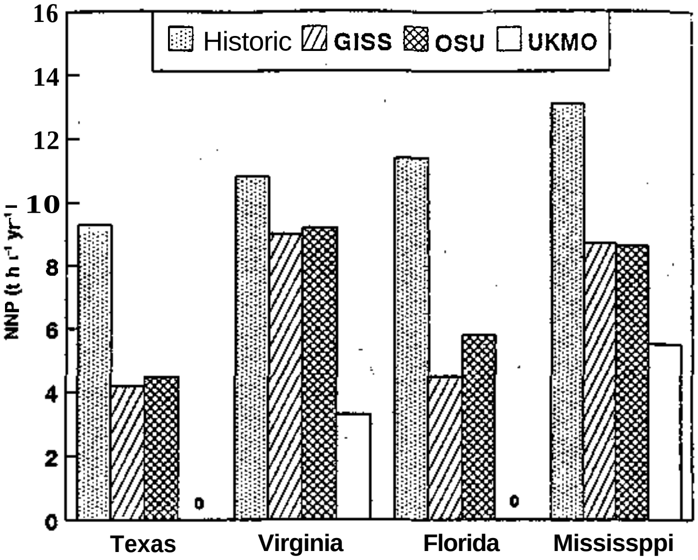

Figure 3. Predicted changes in net primary productivity (NPP) across selected loblolly pine sites in four southern US states. Historic = historic site climate from 1951 to 1990, GISS Scenario = historic climate + GISS GCM, OSU Scenario = historic climate + OSU GCM, UKMO Scenario = historic climate + UKMO GCM.

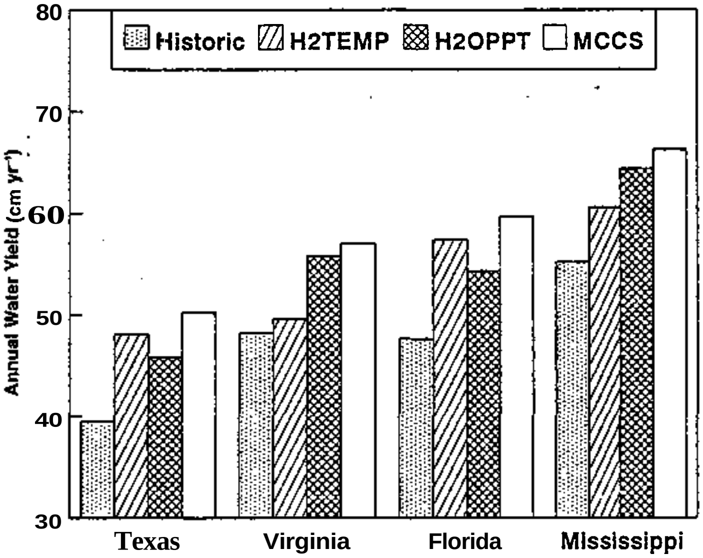

Figure 4. Predicted changes in annual drainage across selected loblolly pine sites In four southern US states using historic, H2TEMP, H20PPT and MCC Scenarios. Historic = historic site climate from 1951 to 1990, H2TEMP Scenario = historic air temperature + 2°C increase in average annual air temperature, H2OPPT Scenario= 120% of historic precipitation, and MCC Scenario = historic site climate + combined Increases In air temperature and precipitation.

during the growing season at all sites except VA. NPP decreased as gross photosynthesis remained constant (VA Site) or decreased (MS, TX and FL sites), and plant respiration increased. Therefore, the H2TEMP Scenario caused a 30% decrease in predicted NPP in the FL site but only a 2% decrease in predicted NPP in the VA site (Fig. 2).

A 20% increase in monthly precipitation using the H2OPPT Scenario increased predicted NPP at all sites, with the TX site showing the largest response. Because the wettest site (MS), and the coolest site (VA) were less water stressed under historic conditions, predicted NPP only increased 5% at both sites in the H2OPPT Scenario. The MCC Scenario predicted that NPP at the VA site would increase, while predicted NPP at the three other sites decreased. The MCC Scenario for the VA site did not increase average growing season air temperature beyond optimal levels for photosynthesis (10), and increased precipitation reduced water stress. Conversely, the effects of increased temperature at the FL and TX sites were not offset by increased precipitation, so NPP decreased. Finally, the MS site, which had the highest precipitation and intermediate air temperature, showed the smallest increase in NPP when precipitation was increased by 20% and exhibited a moderate reduction in NPP under the MCC Scenario.

For all sites, the reductions in NPP due to increasing air temperature by 2°C (H2TEMP Scenario) seem greater than the increase in NPP due to increasing average annual precipitation by 20% (H20PPT Scenario). Therefore, the GCM scenarios should have an even greater impact on NPP since the temperature changes in each scenario are > 2°C and the changes in average annual precipitation are < 20% (Table 3).

The NPP predictions using the GISS or OSU GCMs were similar, while predicted NPP using the UKMO Scenario was substantially different. The GISS and OSU GCMs predicted similar and less dramatic increases in air temperature, compared to the UKMO GCM (Table 3). Predicted NPP at the TX and FL sites were reduced the most when compared to historic conditions. In the extreme GCM scenario (UKMO GCM), predicted NPP for the FL and TX sites were reduced by 100% of historic NPP suggesting that the climate in these states would no longer be suitable for growing loblolly pine. The GCM scenarios predicted less severe reductions in NPP for the VA and MS sites (Fig. 3). When the OSU or GISS GCM Scenarios were calculated for VA, the climate was very similar to the historic climate at the TX site; consequently, predicted NPP for the VA site was similar to the historic predicted NPP for TX.

Historic Hydrology

Based on historic climate data, predicted average annual ET and drainage varied widely across sites. Low average annual precipitation and high ET combined to give the TX site the lowest annual drainage (Fig. 4). The MS site, which received the highest precipitation and had a lower ET, had the highest average annual drainage (Fig. 4).

Climate Change Scenario Effects on Hydrology

Under the H2TEMP Scenario, predicted drainage increased for all sites (Fig. 4), due to a reduction in ET. Generally, the warmer the site, the larger the increase in drainage per unit increase in

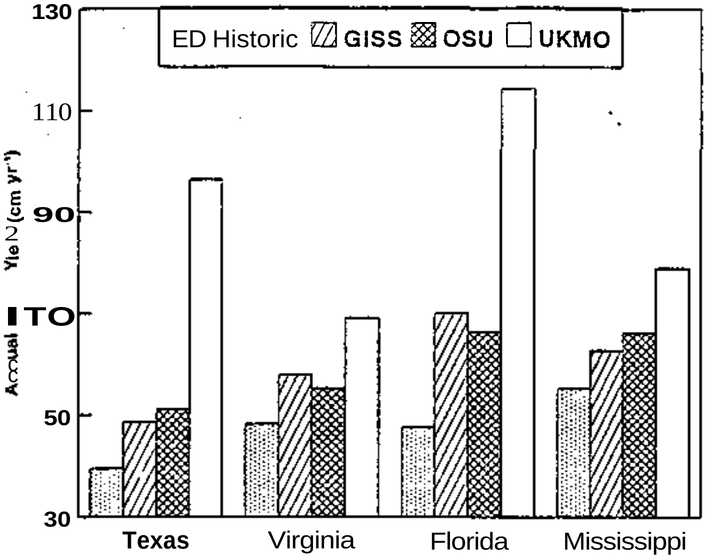

Figure 5. Predicted changes in annual drainage across selected loblolly pine sites in four southern US states using historic, GISS, OSU, and UKMO scenarios.

air temperature. Under the H2OPPT Scenario, most of the increased precipitation was output as drainage (Fig. 4) and not increased ET.

The MCC Scenario accentuated the individual influence of the H2TEMP and H2OPPT Scenarios for predictions of drainage across all sites (Fig. 4). When the MCC Scenario was run with PnET-IIS on the relative cooler sites (i.e., VA and MS), the reduction in LAI was off-set by increased ET per unit leaf area, so annual drainage and total ET remained constant relative to increased in precipitation alone (i.e., using the H2OPPT Scenario) (Fig. 4). Under the MCC Scenario, decreases in leaf area on the warmest sites (i.e., TX and FL) did not counterbalance increases in ET per unit of leaf area and total ET decreased, while drainage was substantially increased.

Although all the GCM Scenarios predicted increased drainage across all sites, the UKMO Scenario had the largest impact on hydrology. Using the UKMO Scenario, PnET-IIS predicted that climatic conditions would no longer support southern pine species in the TX and FL sites, so predicted transpiration was zero and drainage equaled precipitation minus evaporation (Fig. 5). The OSU and the GISS Scenarios predicted similar drainage across sites when input to PnET-IIS. Both the GISS and OSU Scenario's predicted a decrease in annual drainage (Fig. 5) for the TX and MS sites.

CONCLUSIONS

Climate change could significantly reduce NPP and increase drainage across many forested areas in the southern US. Forests located in the warmest sections of the present range of loblolly pine are more susceptible to changes in productivity and hydrology than forests located in wetter or cooler areas. Given the MCC Scenario, the most conservative GCM applied to PnET-IIS, NPP would be reduced by 60% in FL, 55% in TX, 35% in MS and 15% in VA. These projections have serious potential implications for southern US forest production. Using the GCM scenarios across the region, annual drainage may increase by 10% to 240% (when predicted forest death is assumed to have no species replacement), as ET is altered.

Additional research is needed to assess the effects that other atmospheric changes (e.g. CO_2, O_3, NO_x, and SO_x), weather changes (e.g. solar radiation), and genetics or species replacement may have on forest processes before a complete assessment of climate change effects on forest productivity and drainage can be made. However, despite the preliminary nature of these results, these findings should be added to the growing body of knowledge that suggests that severe ecosystem disruption is possible given the existing climate change scenarios.

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