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The Productivity & Sustainability of Southern Forest Ecosystems in a Changing Environment
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22. Predictions and Projections of Pine Productivity and Hydrology in Response to Climate Change Across the Southern United States

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The southeastern United States is one of the most rapidly growing human population regions in continental United States, and as the population increases, the demand for commercial, industrial, and residential water will also increase (USWRC, 1978). Forest species type, stand age, and the climate all influence the amount of water use and yield from these areas (Swank et al., 1988). Because forests cover approximately 55% of the southern United States land area (Flather et al., 1989), changes in water use by forests could significantly change water yields and potentially lead to water shortages within the region. Hence, estimates of future water supply from forested areas are needed and this will require a model that can accurately predict potential change in forest wateruse at the regional scale.

In addition to water resources, an accurate estimate of future loblolly pine forest productivity is essential to the development of a management plan to provide enough timber to meet consumer demand. At present, it is uncertain if the southern forests will be able to maintain (or increase) present-day levels of productivity. For example, Zahner et al., (1988) recorded a decrease in radial growth of loblolly pine (*Pinus taeda*) during the years from 1949 to 1984 in Piedmont stands.

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 et al., 1989). The magnitudes of these changes are expected to vary both temporally and spatially, and they may have profound effect on forest productivity (Melillo et al., 1993) and wateruse. Although some of these changes may directly affect the physiology of trees, others may increase fire, insect damage, and flooding. Thus, environmental changes and stresses have the potential to alter not only the function of forest ecosystems but also the structure and composition of forests.

Models of forest response to environmental change will be useful tools to help manage our nation's forest resources into the next century. We will need detailed plant physiology models that operate at small spatial and temporal scales to integrate our mechanistic understanding of forest responses to environmental changes at a detailed level. In a dramatically changing environment, we will also need to manage forest resources at regional and national scales both over decades and over centuries. This will require forest ecosystem models that operate at larger spatial and temporal scales. These large-scale models must be realistically demanding in both computational capacity and the information needed to initialize and run the models. As an example of this type of large-scale model,PnET–IIS is a regional scale model developed to predict hydrology and productivity across a range of climate scenarios (McNulty et al., 1994; McNulty et al., 1996a). The objective of this chapter is to validate the use of a regional scale process-based wateruse and productivity model (PnET–IIS) using historic data, and to then predict how climate change could affect pine forest wateruse and productivity across the southern United States.

Model Structure

A derivation of the PnET–II model developed by Aber et al., (1995) to predict forest hydrology and productivity in the northeastern United States (McNulty et al., 1994; McNulty et al., 1996b, 1997), PnET–IIS utilizes site-specific soil-water-holding capacity (SWHC), four monthly climate parameters (i.e., minimum and maximum air temperature, total precipitation, and solar radiation) and species-specific process coefficients to predict evapotranspiration (ET), water drainage and net primary productivity (NPP) from the stand level (< one hectare (ha)) to a 0.5° × 0.5° grid cell resolution (approximately 50 × 75 km) across the southern United States (Aber et al., 1992, 1995; McNulty et al., 1994, 1996a, 1997). The model calculated the maximum amount of leaf area that could be supported on a site based on the soil, the climate, and the parameters specified for the vegetative type. Leaf area is a major component in calculating NPP and water use. The model that we used, PnET–IIS, assumed that all stands were fully stocked and that leaf area was equal to the maximum amount of foliage that could be supported as a result of soil and climate limitations. Predicted NPP was defined as total gross photosynthesis minus growth and maintenance respiration for leaf, wood and root compartments. The respiration was calculated by PnET–IIS as a function of the present and prior month's minimum and maximum air temperature. The optimum temperature for net photosynthesis varied from 23 to 27 °C, and the maximum air temperature for gross photosynthesis ranged from 30 to 43 °C (Strain et al., 1976). As air temperature became elevated beyond the optimum photosynthetic temperature, the respiration rate increased and gross photosynthesis either increased slightly or decreased, and therefore, proportionally less net carbon per unit leaf area was fixed (Daniel et al., 1979; Kramer, 1980). Total gross photosynthesis was a function of both gross photosynthesis per unit leaf area and leaf area. Changes in water availability and plant-water demand placed limitations on the amount of leaf area produced, hence, as vapor-pressure deficit and air temperature increased above optimum levels, leaf area and total gross photosynthesis decreased.

Annual transpiration was calculated from a maximum potential transpiration that was modified by plant-water demand (a function of gross photosynthesis and water use efficiency). In the model, water interception loss was a function of leaf area and total precipitation, and ET was equal to transpiration plus interception loss. Drainage was calculated as water in excess of ET and SWHC. In PnET–IIS, plant-water demand depended on monthly precipitation and the amount of water stored in the soil profile. If precipitation inputs exceeded plant-water demand, the soil was first recharged to the SWHC and if water was still available, water was output as drainage. Monthly drainage values were summed to provide an estimation of annual water outflows.

Climate, Vegetation, and Soil Input Data

The model PnET–IIS required site-specific soils and climate data, as well as species-specific vegetation information. To predict monthly loblolly pine growth and wateruse, climate data from 1951 to 1984 were used as model inputs. The 900+ cooperative climate station point databases were interpolated on a $0.5° \times 0.5°$ grid across the southern United States (Marx, 1988). The gridded databases of minimum and maximum air temperature, relative humidity, and precipitation were compiled into a single database and were used to calculate average monthly solar radiation (Nikolov and Zeller, 1992). Solar radiation values were then combined with monthly maximum and minimum air temperatures, and total monthly precipitation as input for PnET–IIS.

No site-specific vegetation indices were required to run PnET–IIS. Instead, loblolly pine-specific vegetation coefficients were used (Table 22.1). These coefficients were largely derived from the published literature (Aber and Federer, 1992; Aber et al., 1995; McNulty et al., 1994, 1996b).

Soil-water holding capacity was the only soil parameter needed to run PnET–IIS. The data were derived from a geographic information systems (GIS)-based soils atlas compiled by the Soil Conservation Service (SCS) (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 would have been averaged within the same grid cell to produce a cell with a pseudoaverage SWHC that appeared suitable for pine growth. To eliminate this source of input error, we used forest inventory and analysis (FIA) data, which consisted of stand volume, growth, and species composition information remeasured at more than 21,000 permanent plots across the

Table 22.1. PnET–IIS Default Coefficients[1] Used for Model Predictions and Parameter Coefficients Used in Sensitivity Analysis

Parameter name	Parameter abbreviation	Model default value	Sensitivity analysis values
Light extinction coefficient	k	0.5	0.4, 0.5*, 0.6
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	60, 70*, 80
Vapor deficit efficiency constant	VPDK	0.03	0, 0.03*, 0.05
Base leaf respiration fraction		0.10	
Water use efficiency constant	WUE C	10.9	10, 10.9*, 12.0
Canopy evaporation fraction		0.15	
Soil-water release constant	F	0.04	0.03, 0.04*, 0.05
Maximum air temperature for photosynthesis (°C)	TMAX	variable*	35, 45
Optimum air temperature for photosynthesis (°C)	TOPT	variable*	17, 23
Change in historic air temperature (°C)	DTEMP	0	+2, −2
Change in historic precipitation (% difference)	DPPT	0	+10, −10

[1] Default coefficients are listed with an *.

southern United States. A database that contained plot locations of loblolly pine FIA plots across the southern United States was selected. A GIS was used to layer regional scale map of SWHC over FIA plot locations of loblolly pine. The pine stands were located on FIA plots and SWHC ranged from 3.8 to 15.8 cm H_2O for soil depths of 102 cm (McNulty et al., 1994).

Using the selected range of SWHC where loblolly pine grow, the 0.5° × 0.5° grid cell was placed over the region and a weighted average of all remaining SWHC polygons within each grid cell was computed. This GIS database formed the basis for the soils input to the PnET–IIS model.

Model Validation

Model validation is often overlooked in large geographic scales. Because models designed for use in large spatial scales are based on numerous assumptions about forest structures and functions as soil-water storage and stand stocking, for a specific forest stand, one or more of the assumptions may be inaccurate. Depending on the degree and type, inaccurate assumptions may result in erroneous model predictions of wateruse and productivity for any particular site. Therefore, regional scale models should not be expected to accurately predict annual wateruse and productivity for all sites and all years. However, the model should generally correlate with site wateruse and productivity, across numerous sites occupying a wide geographic range. If general relationships are not found between predicted

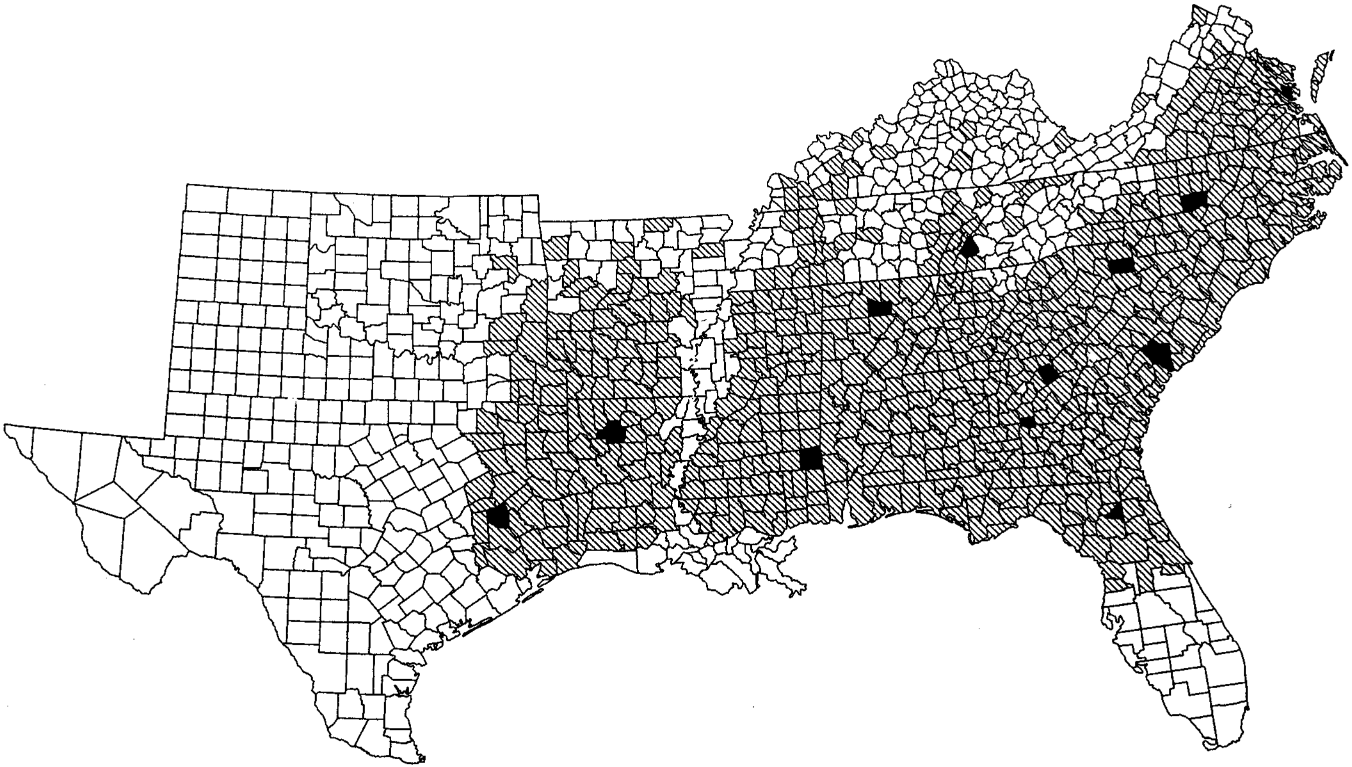

Figure 22.1. Site locations of the twelve pine sites sampled (in black), overlaid on range map of loblolly pine (in grey).

and measured wateruse and productivity across sites, the model logic is flawed or the model has too many incorrect assumptions to produce accurate predictions.

Net Primary Production Validation

Predicted productivity (t ha^{-1} yr^{-1}) was compared with measured basal area growth (cm^2 $tree^{-1}$ yr^{-1}) for twelve loblolly pine stands located across the southern United States (Figure 22.1). These sites represented a wide range of climate and soil conditions (Table 22.2), as well as meeting the following selection criteria: 1) stands were fully stocked at the time of sampling; 2) more than 95% of the stand basal area contained loblolly pine; 3) the site had not been thinned, burned, fertilized, or heavily damaged by insect or disease; 4) all sites were on relatively level terrain ($<$ 10% slope). PnET–IIS was run on each of the twelve sites using climate data from 1951 to 1990.

Forest Growth Measurements

Two tree core samples were collected 1.4 m above the forest floor (diameter at breastheight (DBH)) from each of twenty trees per site. The selected trees were randomly located within the plot, but represented the dominant or codominant size class. The first core was selected at a random azimuth, and the second core was extracted at 90° to the first core. Cores were returned to the laboratory, mounted, and sanded prior to ring-width measurements. The cores were the cross-dated, and ring width was measured using a Model 3 increment measurer (Fred C. Henson Co.), which has an accuracy of 0.01 mm. All cores were measured twice and if the difference in measured annual ring width was $>$ 10% between the two readings, the core was measured a third time and an average of the three measurements was used. Annual basal growth (cm^2) was calculated as $\pi \times$ (tree radius) of the present year ring area $- \pi \times$ (tree radius) of the prior year ring area.

Predicted Forest Growth by PnET–IIS

The years of record (YOR) that basal area growth could be compared to predicted NPP varied between sites, because plantation establishment times and rates of canopy closure differed (Table 22.2). The shortest record of basal area growth (eight years) was from the site at Chester County, SC, and the longest (twenty-eight years) was from the site at Wayne County, MS. Predicted average annual NPP was greatest on both the sites at Colleton County, SC and Wayne County, MS, and smallest at the site in Wilkinson County, GA (Table 22.2). The Colleton County, SC site had the largest average annual basal area growth, and the Dooly County, GA site had the smallest average annual basal area growth (Table 22.2). PnET–IIS predicted NPP ranged from 2 to 18 t biomass ha^{-1} yr^{-1}, with an average annual value of 11.3 t biomass ha^{-1} yr^{-1}, and average annual basal area growth was highly correlated ($r^2 = 0.66$, $P < 0.001$, $n = 12$) with average annual predicted NPP (Figure 22.2). Predicted growth rates were within the general range of forest growth measured by others. Teskey et al., (1987) measured a range of

Table 22.2. Climatic Data for Twelve Measured Loblolly Pine Sites[1]

SITE	YOR[1]	Lat.[2] (°)	Growing season avg. solar radiation[3] ($j\ m^{-1}\ sec^{-1}$)	Annual avg. temp. (°C)	Annual avg. PPT (cm H_2O)	GIS SWHC[4] (cm H_2O)[5]	Predicted NPP (t biomass $ha^{-1}\ yr^{-1}$)	Avg. basal area growth[6] ($cm^2\ yr^{-1}$)[7]
Bradford, FL	21	30.0	465 (10)	20.2 (0.2)	130 (3)	6	11.4 (0.9)	11.4 (0.5)
Bienville, LA	15	32.3	446 (5)	18.0 (0.2)	149 (9)	14	10.2 (0.7)	11.3 (0.9)
Chatham, NC	14	35.6	414 (6)	15.0 (0.2)	117 (6)	14	10.8 (0.9)	11.8 (0.5)
Chester, SC	8	34.8	432 (10)	16.2 (0.3)	120 (6)	13	10.3 (1.3)	13.1 (0.4)
Colleton, SC	11	32.9	436 (6)	18.7 (0.2)	121 (4)	13	12.8 (1.2)	21.1 (1.3)
Gloucester, VA	13	37.5	400 (7)	15.0 (0.3)	117 (7)	12	10.8 (0.9)	11.7 (0.7)
Dooly, GA	11	32.1	466 (8)	20.2 (0.3)	108 (4)	14	9.4 (0.8)	8.7 (0.8)
McMinn, TN	14	35.5	417 (9)	14.8 (0.2)	134 (9)	9	9.3 (0.8)	11.3 (0.7)
Morgan, AL	10	34.5	424 (9)	15.0 (0.2)	136 (5)	14	11.9 (0.9)	13.6 (0.4)
Walker, TX	12	31.0	477 (8)	19.5 (0.2)	114 (7)	11	9.9 (0.8)	14.2 (1.6)
Wayne, MS	28	31.6	432 (4)	18.2 (0.2)	149 (6)	16	13.1 (0.5)	17.4 (0.7)
Wilkinson, GA	14	32.8	449 (6)	17.9 (0.2)	111 (4)	13	9.1 (0.8)	11.4 (0.6)

[1] YOR = years of record since canopy closure.
[2] Lat. = latitude.
[3] Growing Seas. Avg. Solar Radiation = growing season solar radiation.
[4] GIS SWHC = site soil-water-holding capacity derived from a Soil Conservation Service map of the soils on each site.
[5] Per 102 cm soil.
[6] Avg. basal area growth = average annual basal area growth for the measured trees on each site.
[7] Standard errors are included in ().

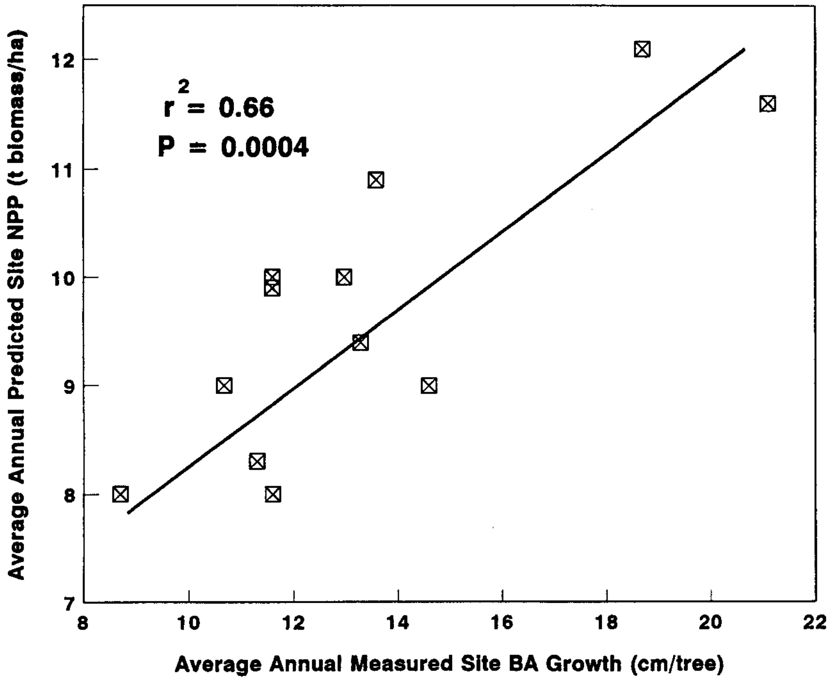

Figure 22.2. Average annual predicted NPP vs average annual measured basal area growth for all twelve loblolly pine sites.

aboveground NPP between 2 and 10 t dry matter ha^{-1} $year^{-1}$ on loblolly pine sites. Other studies have estimated that belowground production equals approximately 40% of aboveground NPP (Nadelhoffer et al., 1985; Whittaker and Marks, 1975). Multiplying Teskey et al., (1987) measurements of aboveground NPP by 1.4, which represents the approximate 30% additional NPP that occurs belowground, yielded a measured range of total (aboveground 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} (Teskey et al., 1987). The NPP predicted by PnET–IIS fell within this measured range of NPP.

Wateruse Validation

Although runoff is related to precipitation, numerous factors affect the amount of runoff from a basin. Nationally, 8% of all runoff is removed for industrial, commercial, and residential purposes (USGS, 1992). The other principle factor affecting runoff is vegetation. Approximately 50% of precipitation either evaporates from leaf surfaces or transpires through plant stomates (Swift et al., 1975). Species type, age, and morphology all influence ET and, therefore, the rates of runoff. Researchers have long used United States Geologic Survey (USGS) streamflow data for hydrologic modeling, but traditionally, the emphasis was on model calibrations (James, 1972; Dawdy et al., 1972; Magette et al., 1976). Basin streamflow data are useful in broad-scale modeling, calibration, and validation because measurements integrate ecosystem water input, movement, and usage. The USGS has more than 6,000 stream-gauging stations across the continental United States (USGS, 1992), some of which were used in model validation of regional drainage (McNulty et al., 1994). Average annual runoff data for the southern United States was calculated from gauge-station data from 1951 to 1980 (Moody et al., 1986). The 0.5° × 0.5° grid cell was placed over an isopleth map and a weighted average of mean cell runoff was calculated that was based on the area size and value of all isopleths within each cell. Historic rates of predicted average annual drainage varied widely across the region. Low rates of average annual precipitation and elevated annual air temperatures combined to give the eastern Texas and central Georgia the lowest measured rates of annual water drainage (Figure 22.3a). Conversely, cool temperatures and high rates of precipitation combined to make southern Appalachian mountains in western North Carolina the area of highest predicted drainage. PnET–IIS predicted that the lowest drainage would occur in eastern Texas and along the coastal plain, and the highest drainage would occur in the high elevation Appalachian Mountains in southwestern North Carolina and northeastern Georgia (Figure 22.3a). Predicted drainage corresponded with measured USGS annual runoff data collected from 1951 and 1980 ($r^2 = 0.64$, $P < 0.0001$, $n = 502$) (Figure 22.4). Measured average annual precipitation was not as well correlated with measured USGS average annual runoff ($r^2 = 0.42$, $P < 0.0001$, $n = 502$).

Climate Change Scenarios

After model-predicted wateruse and productivity estimates were validated against historic measurements, PnET–IIS was used to predict the potential influence of climate change on southern pine forest wateruse and productivity. Only changes in precipitation and air temperature were considered in the climate change scenarios. Other such potential atmospheric changes as carbon dioxide (CO_2), ozone (O_3), or sulfur oxides (SO_x), which may be important to future forest growth, are not addressed in this chapter.

Two climate change scenarios were developed using historic climate databases in conjunction with two GCMs. The Oregon State University (OSU) (Schlesinger and Zhao, 1989), and United Kingdom Meteorological Office (UKMO) (Mitchell, 1989), were selected because of their common application and range of climate change predictions. All of the GCMs predicted variation in monthly temperature and precipitation, based on a doubling of atmospheric CO_2 by the year 2050 (Cooter et al., 1993). The predicted monthly degree (°C) changes in air temperature and percent changes in precipiation by GCMs were projected onto a 0.5° × 0.5° grid across the southern United States. Because predictions of climate change by GCMs are static between years, historic monthly air temperature and precipitation data (1951 to 1984) were combined with predicted changes in air temperature

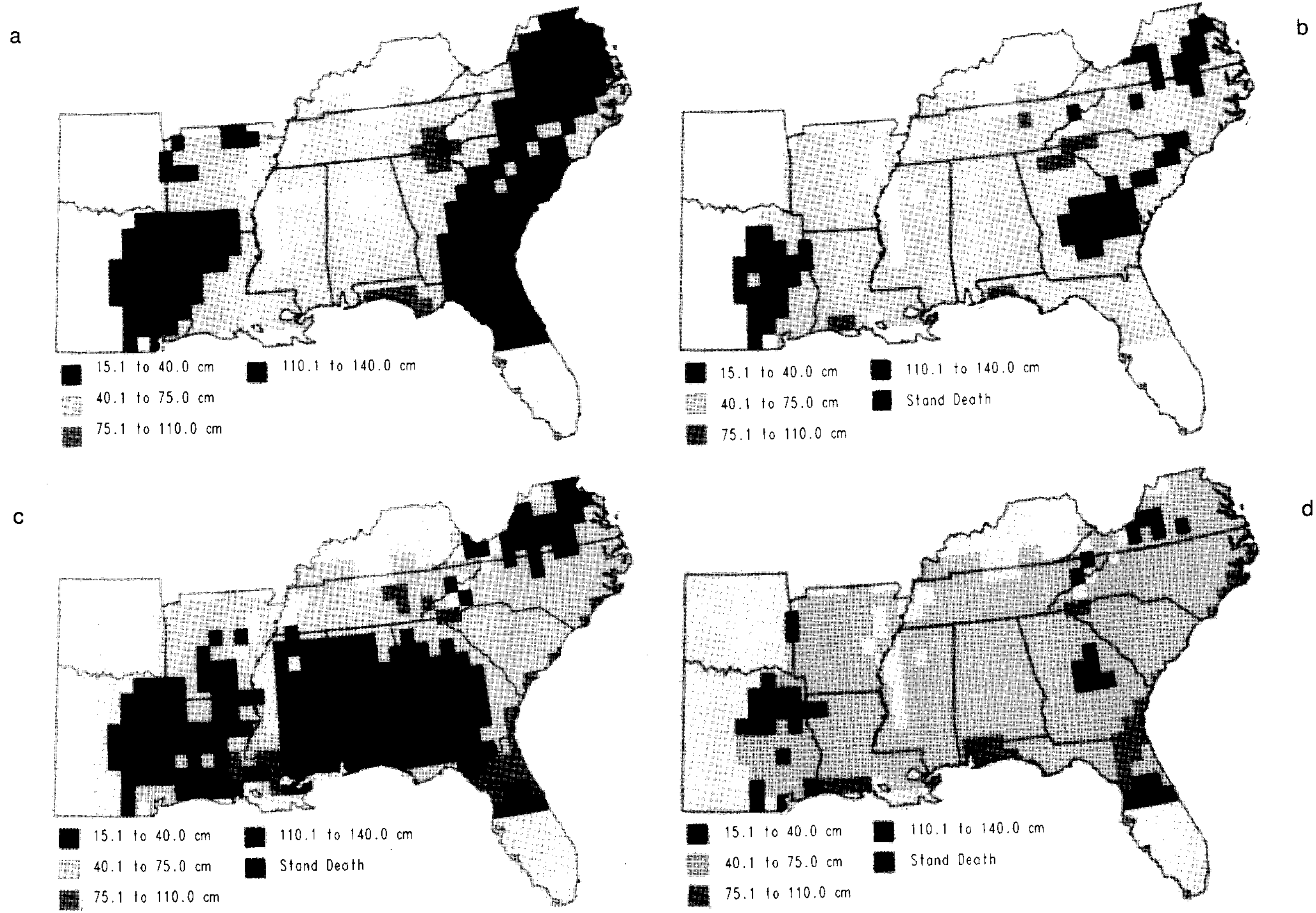

Figure 22.3. Measured USGS average annual historic (1951–1980) drainage (a); PnET–IIS predicted average annual water drainage using the historic (1951–1980) climate data (b); the UKMO climate scenario (c); and OSU climate scenario (d).

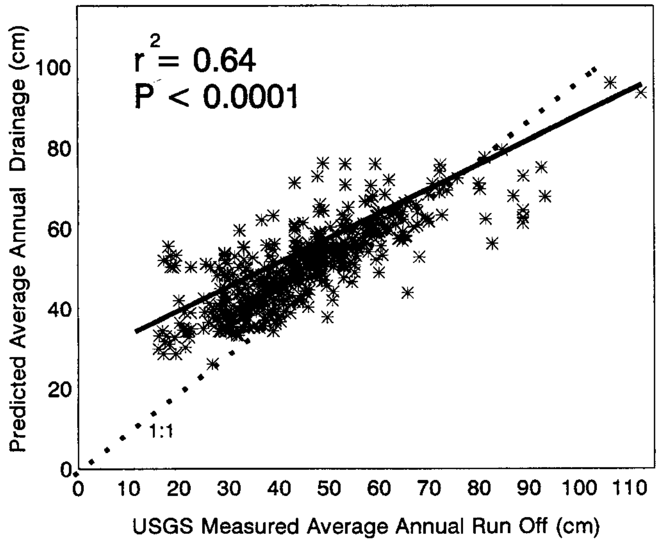

Figure 22.4. Measured USGS average annual historic (1951–1980) drainage v PnET–IIS predicted average annual drainage using historic (1951–1980) climate data on 0.5° × 0.5° grid cells across the southern United States.

and precipitation to provide thirty-five years of dynamic climate change scenario data.

The GCM-predicted precipitation and air temperature change estimates under a doubled CO_2 environment were very different. Across the southern United States, the OSU–GCM predicted a smaller increase (+3 °C) in average annual air temperature compared to the UKMO–GCM (+7 °C). The OSU–GCM also predicted above-average precipitation in the late summer and fall, as well as below historic average levels of precipitation in the late winter and spring. Finally, the OSU–GCM predicted that although the total annual precipitation would decrease in the central portion of the South and would increase along the Atlantic coast, generally across the region average annual precipitation would increase by 3% as compared to historic total annual precipitation. The UKMO–GCM predicted that regional precipitation would be greater than historic amounts during the spring and smaller during the summer and fall; average annual precipitation would decrease in the central and southwestern portion of the region and increase along the southern Atlantic coast, with the total annual precipitation decreasing by 1% region-wide compared to historic levels.

Results and Discussion

Predicted Net Primary Production

When PnET–IIS was run in conjunction with the two climate change scenarios, predicted NPP was reduced across most of the southern United States (except in some high-elevation, mountainous areas) but the severities of the reductions were dependent on the GCM applied. Using the OSU–GCM scenario, PnET–IIS predicted a 26% average reduction in growth across the southern United States, but the envirnomental conditions were not predicted to be severe enough to cause a large reduction in the pine range. PnET–IIS predicted that approximately 2% of the present-day loblolly pine range would be lost across the southern United States. if the OSU–GCM scenario occurred. Predicted NPP generally decreased across the region but would increase in the cooler, mountainous areas of the region (Figure 22.5a), and the model suggested that the range of loblolly pine could shift significantly northward if global climate change should occur. When the OSU–GCM scenario was applied to northern sections of the loblolly pine range, the climate in this area was very similar to historic climate in eastern Texas, and consequently, predicted NPP for the northern loblolly pine range was then similar to the eastern Texas predicted NPP under historic conditions. Future ecosystem research will need to account for shifts in species range resulting from climate change.

In the UKMO–GCM scenario, predicted NPP was reduced by 100% of historic NPP across most of the south-central and southwestern portions of the region including most of Florida, Georgia, Alabama, Mississippi, Louisiana, and Texas (Figure 22.5a), which suggested that the climate in these states would no longer be suitable for growing loblolly pine. The UKMO–GCM predicted less severe reduction in NPP for the northern and eastern portions of the region (Figure 22.5a), because these areas have historically cooler air temperatures and relatively high rates of precipitation. Across the region, average NPP was reduced by 46% and the range of loblolly pine was reduced by 42% when the UKMO–GCM scenario was applied to the model.

Climate Change Scenario Effects on Wateruse

Because drainage was equal to precipitation minus ET, and ET and NPP are a function of leaf area and temperature, the pattern of drainage is similar to NPP. Using the OSU–GCM, predicted drainage decreased in the central and north-central areas, and increased across the southern and eastern portions of the region. Compared to historic drainage, the OSU scenario average annual drainage increased by 6% across the region. The UKMO–GCM scenario caused a larger deviation in predicted ecosystem hydrology. In areas of mortality, predicted ET was zero, and drainage was equal to precipitation. The UKMO scenario predicted increased drainage throughout the region, except along the cooler Appalachian Mountains where drainage decreased. Compared to historic drainage, the UKMO scenario average annual drainage increased by 82% across the region, including areas of mortality where drainage equaled precipitation. If only areas where loblolly pine NPP > 0 are included, drainage increased by only 42% as compared to historic levels.

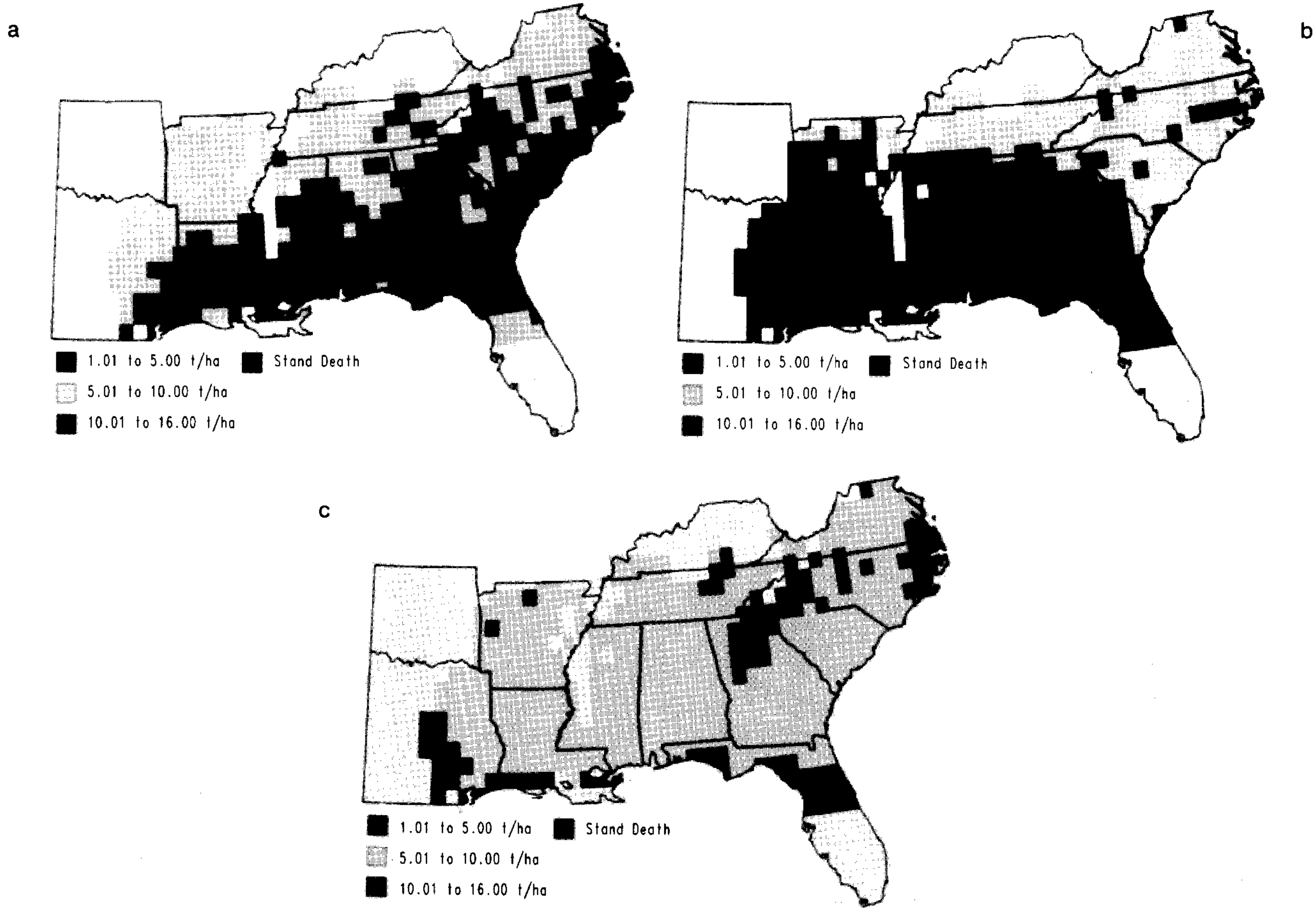

Figure 22.5. PnET–IIS predicted average annual NPP using historic (1951–1980) climate data (a); UKMO (b); and OSU (c) climate scenarios.

Conclusions

Depending on the climate scenario and site location, loblolly pine NPP could be significantly reduced and drainage could be increased across forested areas in the southern United States. Sites located in the warmest sections of the present range of loblolly pine are more susceptible to changes in productivity and wateruse than pine sites located in cooler areas. The model also suggested that the region is much more susceptible to changes in air temperature than changes in precipitation. Depending on the climate scenario, annual NPP could be reduced from 26% to 46%, and drainage could be increased from 6% to 82% across the region. These projections have serious potential socioeconomic implications for the southern United States. However, additional research is needed to assess the effects that other atmospheric changes (e.g., CO_2, O_3, NO_x, SO_x), weather changes (e.g., solar radiation), genetics, and species replacement may have on forest processes, before a complete assessment can be made of potential climate change effects on forest productivity and wateruse.

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