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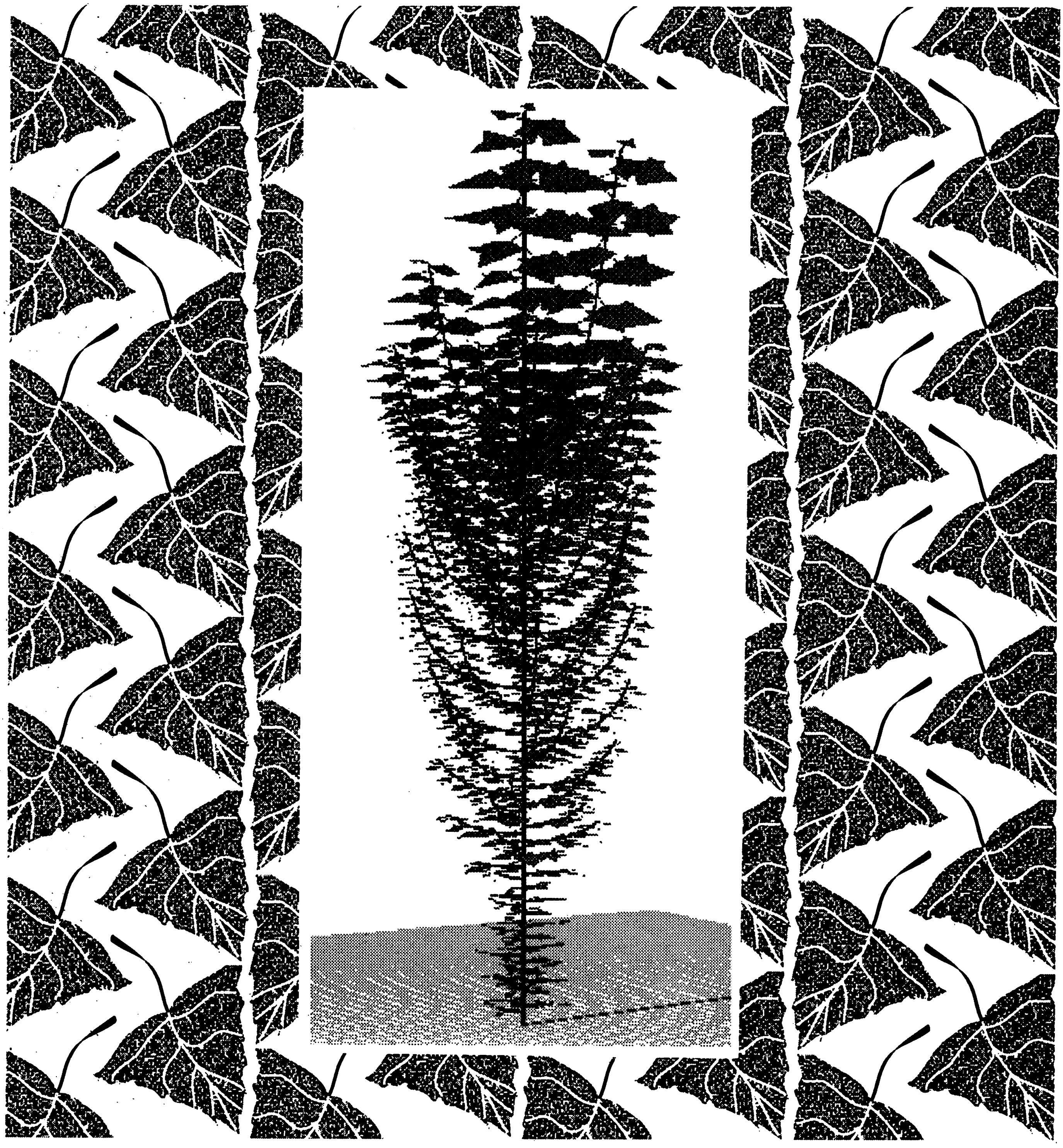

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Modeling the Effects of Climatic Extremes on Early Growth of Poplar Under Short Rotation Intensive Culture

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Change in seasonal weather patterns is one of the most prominent aspects of anticipated global climate change. Light and temperature regimes in particular are important determinants of the geographic range of species as well as their productivity. At the individual plant level, diurnal changes in incoming solar radiation and temperature affect the rates of photosynthesis and subsequent growth of different plant components. Many current plant or forest growth models, such as ECOPHYS (Rauscher *et al.* 1990), TREGRO (Weinstein *et al.* 1992), and PnET (Aber and Federer 1993), include light and temperature as primary driving variables.

Because of scale differences, simulating global change effects on individual trees is difficult. Outputs from General Circulation Models (GCM's) have been used to drive landscape and patch scale models (e.g., BIOME, GEM, CENTURY; Smith *et al.* 1994), but the generation of the hourly data required to drive individual tree models from GCM's involves the introduction of potential error at several scales. Similarly, the creation of artificial data sets designed to simulate global change effects at high temporal resolution (hourly) can be problematic: should temperature be raised uniformly by some fraction of a degree, or should proportions of colder and warmer days be substituted into a real data set? Because of the uncertainties in predicting light and temperature with GCM's or artificial data sets, it would be informative to determine the magnitude of model responses to weather extremes from actual high resolution data from hourly recording stations.

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The use of actual weather data from extreme years provides a means of assessing effects of climate on photosynthesis and growth without the complications of simulated data. In the Lake States, the growing seasons for 1988 and 1992 represent the warmest and coldest years, respectively, in 100 years of climatic records (Bowser 1992). To study effects of these conditions on individual tree growth, we obtained seasonal weather traces for these years from the University of Wisconsin's North Temperate Lakes Long-term Ecological Research Weather Station (Bowser 1992), located near Rhinelander, Wisconsin. These data were used as input to ECOPHYS, a mechanistic individual tree growth process model for juvenile poplar. ECOPHYS uses hourly light and temperature in conjunction with leaf area and several physiological parameters to predict carbon assimilation; carbon is then transported to various growth centers within the tree and converted to increased biomass and dimensional growth. The model is described in detail in Rauscher *et al.* (1990).

ECOPHYS was developed for poplar growing under short rotation intensive culture conditions (SRIC), in which moisture and nutrients are maintained at optimal levels. Currently, operational poplar plantations in the United States often include irrigation, fertilization, and weed control, particularly during the establishment year (Hansen *et al.* 1983). In this study, we used the ECOPHYS model to assess differences in photosynthesis and growth of hybrid poplar under SRIC given observed extremes in light and temperature. Although the model does not currently incorporate the effects of drought stress, it does provide a means of quantifying plant response given extremes in light and temperature in systems where moisture is maintained at adequate levels. Industry is currently doing this routinely. In addition, these real world data provide a surrogate for the types of effects predicted under global climatic change scenarios. ECOPHYS has been subjected to extensive validations both in terms of photosynthesis (Host *et al.* 1990) and in regional predictions of biomass production (Host and Isebrands 1994).

MATERIALS AND METHODS

Location and Clonal Materials

In this study, we simulated the growth of two hybrid poplar clones growing in Rhinelander, Wisconsin, under short rotation intensive culture conditions, as described in Michael *et al.* (1988). *Populus* 'Eugenei' is a *P. deltoides* x *P. nigra* hybrid that exhibits a strongly vertical leaf display and has a relatively long growing season (time until bud set). P. 'Tristis', a *P. tristis* x *P. balsamifera* hybrid, is characterized by a relatively short growing season and a predominantly horizontal leaf display (Michael *et al.* 1988). Tristis has higher instantaneous photosynthetic rates than Eugenei (table 1), and allocates proportionately more carbon to the root system in the late growing season (Isebrands and Nelson 1983, Nguyen *et al.* 1990).

Weather Data

To provide climatic inputs to the simulation, we obtained hourly weather traces of air temperature and solar radiation for 1988 and 1992 from the nearby North Temperate Lakes Long-term Ecological Research Weather Station (Bowser 1992). Data were screened for errors and formatted for the ECOPHYS model. Temperature and radiation data were summarized as daily averages and seasonal degree-day accumulation, using a base temperature of 4° C; below this temperature, plants are relatively inactive in terms of light or temperature response (Larcher 1980).

Simulation Methods

The ECOPHYS model requires that "initial trees" be established to begin the model run (Rauscher *et al.* 1990). Model runs were initiated with 15 and 20 leaf trees on July 9 (Julian Date 190) for Eugenei and Tristis, respectively. These initial trees represented the typical developmental state of the tree at that date; Tristis is characterized by higher initial growth and leaf initiation rates, that decline early in the growing season (Michael *et al.* 1988). Simulations were run through September 3 (Julian date 246). Model predictions of whole-tree photosynthesis, defined in terms of assimilated carbon (mg CO_2 d^{-1}), total

Table 1.—*Morphological and physiological characteristics of hybid poplar clones P. 'Eugenei' and P. 'Tristis'*

	P. Eugenei	**P. Tristis**
Leaf characteristics		
Midrib angle°	100	90
Lamina angle°	60	90
Specific leaf area (mg cm^{-2})	0.200	0.137
Photosynthetic characteristics - recently mature leaves		
Pmax (μmol CO_2 m^{-2} s^{-1})	22.5	29.5
Pe (mol mol^{-1})	0.16	0.16
Rd (μmol CO_2 m^{-2} s^{-1})	2.46	2.27
Phenological characteristics		
Leaf initiation rate (h)	35	56
Bud set date (Julian Date)	244	228

leaf area (cm^2), height (cm), and total biomass (g), were recorded daily.

RESULTS AND DISCUSSION

Microclimatic Differences

The mean daily temperatures recorded during the summer of 1988 were approximately 2° C warmer than those during the summer of 1992 (fig. 1a). Cumulative degree-days were 12 percent greater in 1988 than in 1992. Cumulative solar radiation, defined in terms of photosynthetically-active photon flux density (PPFD), for 1988 at this location was 30 percent higher than in 1992, with consistently high light levels throughout the 1988 growing season (fig. 1b).

Carbon Assimilation

Whole-tree photosynthate production, the principal driving variable for growth in the ECOPHYS model, is a function of light, temperature, leaf area, and parameters of the photosynthesis/light response model. The total seasonal whole tree photosynthesis (WTP) for Eugenei was 85 percent greater in 1988 than in 1992 (fig. 2a). The difference in daily WTP between these years increased through the growing season as a result of a positive feedback induced by increasing leaf area providing further increases in photosynthesis (fig. 2b). Tristis showed a 66 percent increase in total seasonal WTP in 1988; the daily patterns were similar to Eugenei but less pronounced.

Plant Development

Leaf area development closely tracked daily photosynthesis (fig. 2b). Leaf area development and height growth showed large differences between the two years. The end-of-season total leaf area for Eugenei in 1988 was 70 percent greater than in the 1992 simulation run (3,185 cm^2 in 1988 compared with 1,834 cm^2 in 1992). Tristis showed a 41 percent increase between the two years. The slower rate of leaf area development in Tristis is due in part to the fact that Tristis has a longer leaf initiation period than Eugenei (56 compared with 35 hours), as well as a lower specific leaf area, resulting in a greater carbon cost for synthesizing leaf tissue. The increases in leaf area and photosynthesis translated into a 40-percent increase in height at budset for Eugenei and a 14 percent increase for Tristis (fig. 2c). Height growth and leaf area expansion for Tristis ceased on August 16 (Julian date 228) following budset. In the 1988 growing season, total biomass increased 56 percent and 32 percent for Eugenei and Tristis, respectively (fig. 2d).

In a previous study, we explored the effects of light and temperature on dry matter production of Eugenei independently (Rauscher *et al.* 1988). In that analysis, we created artificial weather traces in which (i) seasonal radiation was held constant but temperature altered, (ii) temperature was held constant and light regime altered, or (iii) both were altered. Data sets were constructed by substituting different proportions of the warmest and coldest days into an observed data set. The results of these independent manipulation of factors was that dry matter was found to increase linearly with increased light, but asymptotically with increased temperatures (Rauscher *et al.* 1988). The net increase in biomass between the extremes in that study was 62 percent, which is comparable with the 56 percent observed in the present study. A criticism of the earlier study, and the impetus for the present approach, is that in nature, light and temperature are actually not independent variables. Although the approach of manipulating factors independently is useful for understanding the physiological responses of plants and for conducting sensitivity analyses, it may not represent conditions that occur in the real world. For example, several GCM's predict that increased temperatures are accompanied by increased cloud cover (with implications for the effects of respiration on growth), while others emphasize the importance of nocturnal warming (Karl *et al.* 1991). Thus, the use of actual data as we have here provides the opportunity to assess physiological responses under conditions that occur in nature.

Clearly, changes in moisture availability, through changes in precipitation patterns, are a component of global change not reflected in this modeling approach. However, there are currently 25,000 ha of hybrid poplars in the Western United States and 4,000 ha in the Eastern States that are managed under irrigation and fertilization systems; our former validation study indicates that the model

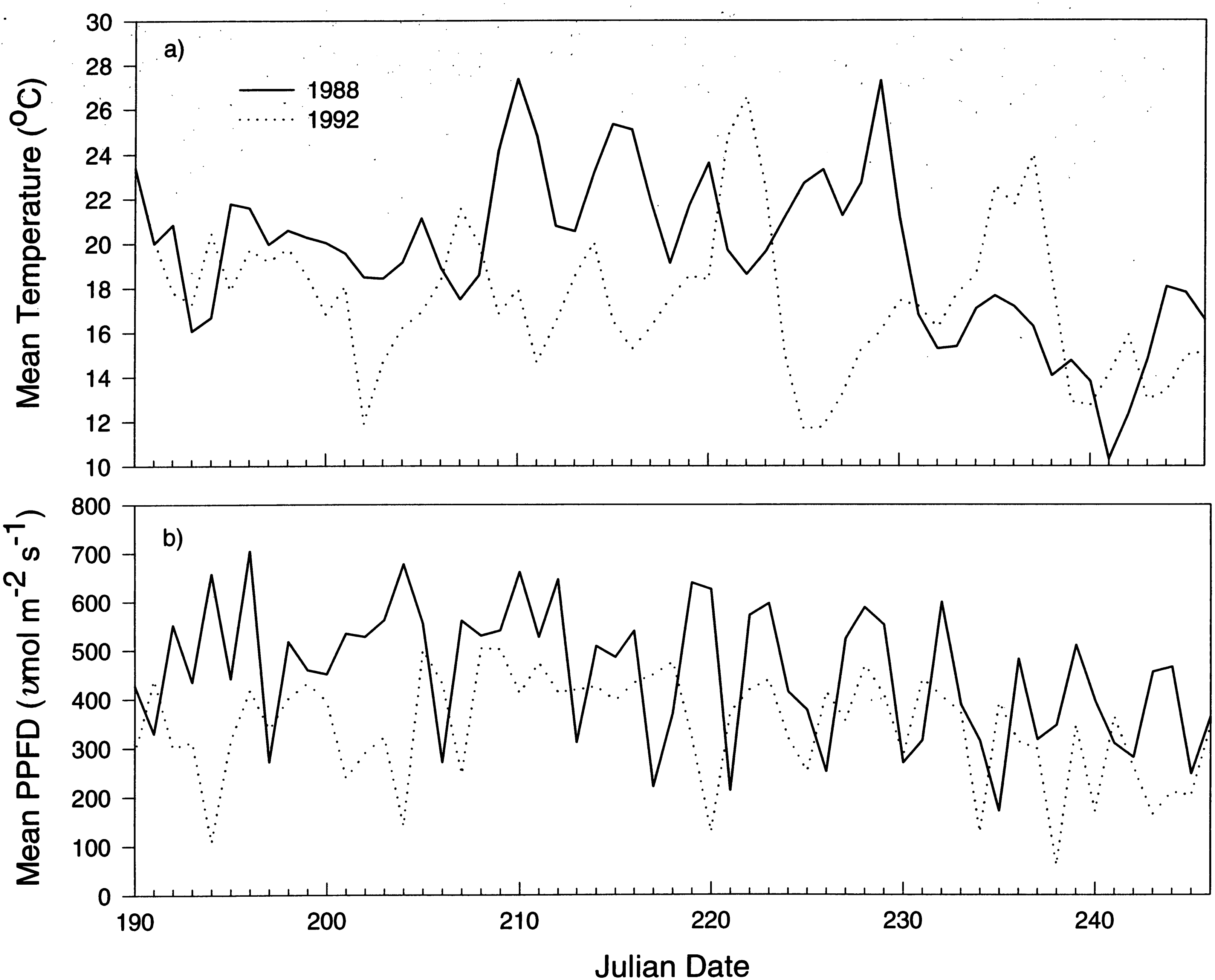

Figure 1.—*Mean daily temperatures and solar radiation (PPFD) for the summers of 1988 and 1992 in Rhinelander, Wisconsin.*

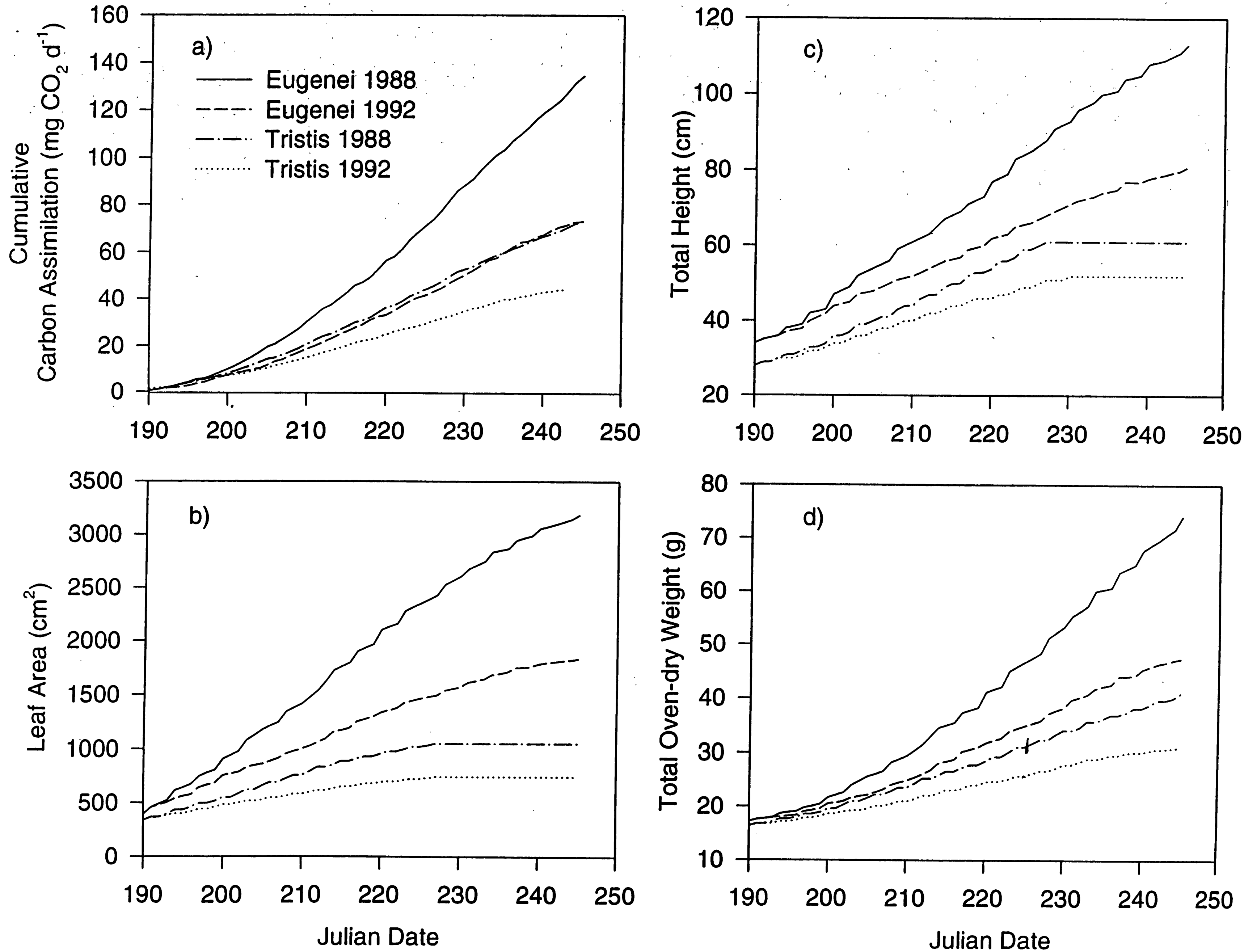

Figure 2.—*ECOPHYS model predictions of a) whole tree carbon assimilation, b) leaf area, c) total height, and d) total ovendry weight for two poplar clones, given hourly temperature and radiation data from 1988 and 1992 in Rhinelander, Wisconsin.*

performs well in both regions (Host and Isebrands 1994). We are currently developing a soil moisture routine to simulate the effects of drought and competition among trees (Host *et al.* 1996) and have integrated this with EPIC, an existing stand-level agronomic model of productivity and soil erosion (Williams *et al.* 1989).

This simulation analysis provides a way to predict the magnitude of individual tree responses to changing climatic conditions. The use of actual weather data showed that the increases in temperature and light regimes experienced in the past decade can cause increases of more than 80 percent in whole tree photosynthesis. These increases in carbon assimilation translate to increases on the order of 50 percent in terms of total biomass production in young poplar trees under short rotation culture. The analyses also show that the magnitude of response will differ by clone (genotype), and that the ability to respond can be related to specific physiological traits. One of the overriding factors between these two clones is the difference in bud set dates, which allows continued leaf area development and aboveground biomass production in Eugenei long after Tristis has set bud.

The alterations of temperature and light regimes are, of course, only two components of global climate change. Changes in atmospheric trace gasses such as CO_2 and tropospheric ozone also impact the growth of plants (Coleman *et al.* 1995), as does the diurnal timing of temperature increases: the pattern of nocturnal warming shown in some data sets (Karl *et al.* 1991) would have a different impact on growth than uniform or daytime temperature increases. Modeling approaches that incorporate the physiological mechanisms that drive plant growth, coupled with field and laboratory experimentation, have the potential to make realistic predictions of plant response to changing global conditions.

ACKNOWLEDGMENTS

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Uses an individual tree growth process model, ECOPHYS, to assess the differences between climate extremes on growth of hybrid poplar.

KEY WORDS: Global change, climate, temperature, light, *Populus*, simulation, modeling.

Our job at the North Central Forest Experiment Station is discovering and creating new knowledge and technology in the field of natural resources and conveying this information to the people who can use it. As a new generation of forests emerges in our region, managers are confronted with two unique challenges: (1) Dealing with the great diversity in composition, quality, and ownership of the forests, and (2) Reconciling the conflicting demands of the people who use them. Helping the forest manager meet these challenges while protecting the environment is what research at North Central is all about.

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