

# ornl

ORNL-6594

**OAK RIDGE  
NATIONAL  
LABORATORY**

**MARTIN MARIETTA**

## **Short Rotation Woody Crops Program: Annual Progress Report for 1988**

L. L. Wright  
T. W. Doyle  
P. A. Layton  
J. W. Ranney

Environmental Sciences Division  
Publication No. 3373



OPERATED BY  
MARTIN MARIETTA ENERGY SYSTEMS, INC.  
FOR THE UNITED STATES  
DEPARTMENT OF ENERGY

## **DISCLAIMER**

**This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.**

---

## **DISCLAIMER**

**Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.**

This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from the Office of Scientific and Technical Information, P.O. Box 62, Oak Ridge, TN 37831; prices available from (615) 576-8401, FTS 626-8401.

Available to the public from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Rd., Springfield, VA 22161.  
NTIS price codes—Printed Copy: A05 Microfiche A01

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

ENVIRONMENTAL SCIENCES DIVISION

SHORT ROTATION WOODY CROPS PROGRAM:  
ANNUAL PROGRESS REPORT FOR 1988

ORNL--6594

DE90 004471

L. L. Wright  
T. W. Doyle\*  
P. A. Layton  
J. W. Ranney

Environmental Sciences Division  
Publication No. 3373

---

\*Present address: National Wetlands Research Center, U.S. Fish and  
Wildlife Service, 1010 Gause Blvd., Slidell, LA 70458.

Date Published: October 1989

Prepared for the  
Office of Renewable Energy Technology  
Biofuels and Municipal Waste Technology Division  
EB 24 01 00 0

Prepared by the  
OAK RIDGE NATIONAL LABORATORY  
Oak Ridge, Tennessee 37831-6285  
operated by  
MARTIN MARIETTA ENERGY SYSTEMS, INC.  
for the  
U.S. DEPARTMENT OF ENERGY  
under contract DE-AC05-84OR21400

## CONTENTS

	<u>Page</u>
LIST OF FIGURES . . . . .	v
LIST OF TABLES . . . . .	vii
EXECUTIVE SUMMARY . . . . .	ix
ABSTRACT . . . . .	xiii
1. INTRODUCTION . . . . .	1
2. SHORT-ROTATION WOODY CROPS PRODUCTIVITY . . . . .	6
3. GENETIC COMPONENTS OF PRODUCTIVITY . . . . .	11
3.1 BREEDING AND GENETIC IMPROVEMENT . . . . .	11
3.2 PHYSIOLOGICAL RESEARCH . . . . .	17
3.2.1 Nutrition Research . . . . .	17
3.2.2 Crown Architecture and Carbon Allocation . . . . .	19
3.2.3 Root Morphology and Physiology . . . . .	27
3.3 BIOTECHNOLOGY . . . . .	28
3.3.1 Cell and Tissue Culture . . . . .	29
3.3.2 Somaclonal Variation . . . . .	31
3.3.3 Gene Transfer . . . . .	31
4. ENVIRONMENT-RELATED FACTORS OF PRODUCTIVITY . . . . .	33
4.1 COMPETITION AND SPACING RELATIONSHIPS . . . . .	33
4.2 EFFECTS OF COPPICE MANAGEMENT . . . . .	35
4.3 MIXED-SPECIES CULTURES . . . . .	37
4.4 SITE AND SPECIES ADAPTABILITY . . . . .	39
4.5 CLIMATE CHANGE AND GLOBAL ISSUES . . . . .	41
5. MONOCULTURE VIABILITY TRIALS . . . . .	44
REFERENCES . . . . .	53
APPENDIX I - CONVERSION FACTORS . . . . .	59
APPENDIX II - LATIN AND COMMON NAMES OF WOODY SPECIES . . . . .	65

LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
1 Short Rotation Woody Crops Program project locations . . . . .	4
2 Locations of river drainages from which collections were made for <i>Populus trichocarpa</i> and the test plantations . . . . .	14
3 Biomass productivity; its components and their manipulation .	18
4 Net photosynthetic rate and stomatal conductance of nitrogen-treated <i>Platanus occidentalis</i> trees over the growing season . . . . .	21
5 Total chlorophyll concentration of nitrogen-treated <i>Platanus occidentalis</i> trees over the growing season . . . . .	22
6 In vivo leaf nitrate reductase activity of nitrogen-treated <i>Platanus occidentalis</i> over the growing season . . . . .	23
7 Comparison of stem volume height of two hybrid <i>Populus</i> clones and one clone of each parental species with the development of their leaf area index during their first three growing seasons . . . . .	25
8 ECOPHYS model validation of <i>Populus deltoides</i> clone Ill-005 total aboveground biomass grown in Puyallup, Washington, and a graphical display of the predicted tree twice during the growing season . . . . .	26
9 Diagram of <i>Populus</i> somatic embryo development from callus to germinated microplantlet . . . . .	30
10 Example of height at the end of the first growing season of a hybrid <i>Populus</i> tree grown in southern Minnesota. . . . .	47
11 Height growth of clone NE308 grown in South Dakota at the end of the second growing season . . . . .	48
12 <i>Platanus occidentalis</i> at the end of the first growing season in a 120-ha SRWC plantation established in 1988 in southern Alabama by Scott Paper Company for energy purposes. . . . .	50

LIST OF TABLES

<u>Table</u>		<u>Page</u>
1	Short Rotation Woody Crops Program projects . . . . .	2
2	Short Rotation Woody Crops Program research status and goals by region . . . . .	7
3	Most recent Short Rotation Woody Crops Program yield data (as of March 1988)--experimental yields based on a treatment plot with approximately 225 or more trees (including border trees) . . . . .	8
4	Most recent Short Rotation Woody Crops Program yield data as of March 1988--exploratory yields based on less than 225 trees per treatment plot (including border trees) . . . . .	9
5	Early-, mid-, and late-season leaf area and stem dry weight of nitrogen-treated <i>Platanus occidentalis</i> trees . . . . .	20
6	Hybrid <i>Populus</i> biomass yields from first and second rotations by management strategy . . . . .	36
7	Survival of planted trees by site and cultural treatment for 1980 planting (taken from Bowersox et al. 1988) . . . . .	38
8	Effect of mix (pure vs mixed cottonwood/alder) on yield and basal area of Field Trial 1-b . . . . .	40
9	Yield of pure cottonwood vs mixed cottonwood alder in the second rotation of Field Trial 1-b . . . . .	40
10	Costs of short-rotation woody crops plantation establishment . . . . .	51

## EXECUTIVE SUMMARY

The Short Rotation Woody Crops Program (SRWCP) reached the benchmark age of 10 years in 1988. Its primary charge since its inception has been to develop the technology required for supplying the United States with an adequate and dependable supply of renewable wood feedstocks for energy conversion at a low cost. The most promising avenue of research identified early in the program was the use of selected clones or families of hardwood species in short-rotation woody crops (SRWC) systems. SRWC refers to well-maintained, weed-free, cultivated tree stands harvested every 3 to 10 years at spacings of 0.5 to 3.0 m between trees. Yields in the range of 8 to 16 dry  $\text{Mg}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$  are now being observed in trials all over the United States. The program's productivity goal of 20 dry  $\text{Mg}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$  has been achieved and exceeded in a few small plot trials. Widespread attainment of high yields in SRWC plantations depends on the development of genetically improved hardwood clones with characteristics of rapid juvenile growth, pest and disease resistance, and drought tolerance, in addition to favorable site quality and adaptability. Obtaining a wood quality that facilitates conversion to liquid fuels could be important in reducing the overall costs of biofuel production. Projects funded through the SRWCP are making progress in developing the technology required to make SRWC a success.

The genus *Populus* (poplar) has demonstrated the highest productivity gains and potential of all model species studied to date for SRWC applications in the continental United States. *Populus* hybrid clones have demonstrated production levels of 10 to 15 dry  $\text{Mg}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$  in both establishment and coppice rotations in several regional studies. A few exceptional clones have achieved considerably higher experimental yields (20 to 30 dry  $\text{Mg}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$  in the first rotation and up to 43 dry  $\text{Mg}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$  in a coppice rotation). These clones are receiving intensive study to determine the physiological, morphological, and phenological characteristics that account for their exceptionally high yields. Thus far, traits that appear to be highly correlated include early bud break and late leaf fall, development of very large terminal

leaves, ability to grow day and night, good stomatal control in response to drought stress, and relatively more allocation of carbohydrates to leaves rather than roots during the first year or two of growth. In-depth comparative evaluations of high- and low-yielding *Populus* clones are being made to develop a suite of traits that are observable in the first year or two of growth, and can be used as selection indexes in genetic improvement programs.

The SRWCP now supports two genetic improvement programs for poplars. In the Pacific Northwest, a 10-year-old breeding program has produced in excess of 25,000 hybrid seedlings, of which 1900 different clones are now being tested in 12 field sites in the region. Several industries and public agencies are engaged in cooperative trials testing these hybrid clones, and a production nursery is now making available cuttings of the best hybrids to landowners in the region. This exceedingly successful genetic improvement program cannot address the needs of the whole United States, however. Thus, a second genetic improvement project was initiated at Iowa State University in 1988 specifically to breed and select high-yielding poplar clones for the north-central region that are resistant to *Septoria* canker and other diseases.

In SRWC of *Populus*, competition control is imperative to ensure survival of cuttings and rapid early growth. Application of herbicides after leaf expansion risks damage to the trees because most hardwoods are quite sensitive to herbicides. Biotechnological approaches are being used to demonstrate that herbicide resistance can be transferred to hybrid poplar clones. Two approaches are currently under investigation. Although herbicide resistance is a desirable goal, the development of the techniques is more significant because biotechnology can be used to transfer other desirable traits to clones selected for high productivity.

Stand dynamics and the costs associated with different spacings, clones, and cultural treatments are also being studied. Results reported from two trials this past year suggest that high-density coppice stands do not always produce higher yields than do lower-density stands of single-stemmed trees. The trends shown in these

results support other studies, which have led to the current silvicultural recommendation of establishment densities of 2500 to 4000 trees per hectare with planned rotation ages of 5 to 8 years.

Progress has been made in identifying and improving several species other than *Populus* for use as energy feedstocks in the United States. Improvement of alternate "adaptive" species is considered necessary to allow use of a broader range of sites, to offer alternatives to growers and energy conversion facilities, and to hedge against possible risks from disease and pest problems that may be associated with the widespread use of poplars. The alternate species that have received the most work with respect to both silviculture and genetic improvement include eucalypts (*Eucalyptus* spp.), alders (*Alnus* spp.), sweetgum (*Liquidambar styraciflua*), sycamore (*Plantanus occidentalis*), silver maple (*Acer saccharinum*), and black locust (*Robinia pseudoacacia*). Vegetative propagation techniques, including tissue culture procedures, have been developed for all of the species, but improvements are still being made. Genetic and physiological studies aimed at identifying early selection criteria that can be used for genetic improvement are just beginning, but they are severely limited by low budgets.

Nutrient use has been identified as an important area for research to reduce production costs and avoid possible adverse environmental effects associated with fertilizer runoff and leaching. Studies are under way with *Plantanus occidentalis*, a species with high nitrogen demands, to evaluate the degree to which the timing of nitrogen applications affects tree growth and leaching. Investigators are monitoring the trees to search for the most reliable indicators of nitrogen deficiency. The goal is to develop reliable procedures for prescribing nutrient amendment schedules.

A major SRWCP accomplishment is the planting of three monoculture viability scale-up trials. Plantations 20 to 40 ha in size have been or are being established in Minnesota, North Carolina, and Iowa to evaluate the costs and risks of monocultures. Species being tested include *Populus* hybrids, *Liquidambar styraciflua*, and *Acer saccharinum*. The drought conditions existing in 1987 and 1988 have reduced survival

success, but significant information on clones and techniques that result in high survival and growth under drought conditions has been obtained.

Efforts are under way to define the wood qualities desirable for biofuel conversion technologies. Preliminary results from literature surveys and actual trials with different woods suggest that wood quality is important for both biochemical and thermochemical conversion processes. A consistent system of measurement and analysis of wood qualities is being developed through cooperation with other programs in the Department of Energy's Biofuels and Municipal Waste Technology Division and the International Energy Agency's biomass programs.

It is a measure of the SRWCP's progress that learning how to grow the trees is no longer a major concern. Research now focuses on how to further modify the genetics and cultural conditions of plantings to produce specialized feedstocks that will enhance conversion processes. SRWC advancements discussed in this report have brought about exceptional production rates at reduced costs capable of providing an economically viable biofuel feedstock. While the SRWC concept will need to be adapted to suit specific conditions around the country, current results clearly demonstrate the potential for SRWC research and technology to supplement the energy needs of the United States.

## ABSTRACT

WRIGHT, L. L., T. W. DOYLE, P. A. LAYTON, and  
J. W. RANNEY. 1989. Short Rotation Woody  
Crops Program Annual Progress Report for  
1988. ORNL-6594. Oak Ridge National  
Laboratory, Oak Ridge, Tennessee. 86 pp.

This report synthesizes the technical progress of research projects in the Short Rotation Woody Crops Program (SRWCP) for the year ending September 30, 1988. The program is sponsored by the U.S. Department of Energy's Biofuels and Municipal Waste Technology Division and has the goal of developing a viable technology for producing renewable feedstocks for conversion to biofuels. The most significant accomplishment has been the attainment of outstanding productivity rates by a *Populus* hybrid in the Pacific Northwest ( $43.5 \text{ Mg}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$ ), highlighting the potential gains achievable with breeding. Genetic improvement studies are broadening species performance within geographic regions and under less-than-optimum site conditions. Advances in physiological research are identifying key characteristics of species productivity and response to nutrient applications. Recent developments utilizing biotechnology have achieved success in cell and tissue culture, somaclonal variation, and gene-insertion studies. Productivity gains have been realized with advanced cultural studies of spacing, coppice, and mixed-species trials. The implications of global warming and climate-change effects on SRWC technology and applications are discussed. The early success of several monoculture viability trials is also presented.

## 1. INTRODUCTION

This report is a summary of the technical progress and achievements made in the Short Rotation Woody Crops Program (SRWCP) during FY 1988. This research program, sponsored by the Biofuels and Municipal Waste Technology Division, U.S. Department of Energy (DOE), has as its primary goal to develop the technology for producing renewable feedstocks for energy conversion in the form of biofuels. The SRWCP completed its first decade of research activities focused on increasing productivity of woody-crop plantations and the cost efficiency of cultivation and conversion to energy. The use of fast-growing short-rotation woody crops (SRWC) that have excellent coppice and cloning potential has long been the central means for achieving program goals. The advent of biotechnology and improved breeding measures have brought about productivity gains beyond initial program expectations. Yields of 8 to 16 Mg<sup>1</sup>·ha<sup>-1</sup>·year<sup>-1</sup> have now become commonplace and in recent studies have reached as high as 43.5 Mg·ha<sup>-1</sup>·year<sup>-1</sup>.

The SRWCP represents an integrated research program in both scientific initiatives and institutional involvement. Twenty-three universities and government agencies participate with private cooperators nationwide in research and technology transfer activities (Table 1; Fig 1). Administration of program subcontracts and synthesis is accomplished by management staff in the Environmental Sciences Division at the Oak Ridge National Laboratory (ORNL). The progress reported herein represents some of the accomplishments completed by program staff and subcontractors for the annum 1988.

Research projects supported by the SRWCP have demonstrated notable productivity gains through ongoing genetic improvement and advanced cultural studies this year. In the following sections, the productivity accomplishments for the different regions and research activities are reviewed. The report also considers the realized and potential yields

---

<sup>1</sup>Metric units are used throughout this report; conversion factors are provided in Appendix I.

Table 1. Short Rotation Woody Crops Program projects

Institution	Investigator	Title
Amana Society <sup>a</sup>	D. Shoup L. Gnewikow	Monoculture viability trial of woody crops for energy production
BioEnergy Development Corporation	T. B. Crabb	<u>Eucalyptus</u> plantations for energy in Hawaii
Energy/Development International	S. Hale, Jr. D. C. Deardorff R. D. Kirmse	Species screening and genetic selection at sites in Arizona, New Mexico, and Texas
Fisk University	M. Gunasekaran	Influence of N fertilization on glutamine synthetase activity in mycorrhizal and nonmycorrhizal sycamore plants
University of Florida	D. L. Rockwood	Woody species for biomass production in Florida
University of Georgia	B. C. Bongarten L. R. Boring R. O. Teskey	Optimizing energy yields in black locust through genetic selection
Institute of Paper Chemistry	R. J. Dinus	Review and summary of efforts to alter the composition of woody plants
Iowa State University	R. B. Hall E. Hart H. S. McNabb, Jr.	Selection and breeding of pest-resistant clones of <u>Populus</u> for biomass energy production in the North Central region
Kansas State University	W. A. Geyer	Great Plains energy forest research program
Michigan State University	D. I. Dickmann K. S. Pregitzer	Net assimilation and photosynthate allocation of <u>Populus</u> clones grown under short-rotation intensive culture: physiological and genetic responses regulating yield
Mississippi State University	S. B. Land	Early selection criteria and clonal propagation methods for increased productivity of sycamore in short-rotation energy systems
North Carolina State University	D. J. Frederick R. C. Kellison	Silvicultural and harvesting systems for producing fuels from woody biomass in the Southeast
North Carolina State University <sup>d</sup>	R. Lea	Short-rotation sweetgum plantations: establishment and care in the southeastern United States
Northern States Power Company <sup>c</sup>	E. Hansen	Short-rotation woody crops trials for energy producing in north central United States

Table 1. (continued)

Institution	Investigator	Title
Oak Ridge National Laboratory	D. W. Johnson R. J. Norby	Optimum nitrogen nutrition in short-rotation sycamore plantations
Oklahoma State University	C. G. Tauer	Evaluate <u>Populus</u> selections for fuelwood (U.S.-India Science and Technology Initiative)
Pennsylvania State University	P. R. Blankenhorn T. W. Bowersox C. H. Strauss	Economic analyses for producing <u>Populus</u> hybrids under four management strategies
Southern Illinois University	W. C. Ashby J. E. Preece P. L. Roth	Genetic biomass and growth analyses of clonal silver maple ( <u>Acer saccharinum</u> L.) in several locations
Tennessee Valley Authority	D. T. Curtin	Short-rotation woody crops harvesting and field handling
Tuskegee University, Carver Research Foundation	A. Weaver	Nutrient optimization research
USDA FS North Central Forest Experiment Station	J. G. Isebrands E. A. Hansen B. E. Haissig	Increasing yields of <u>Populus</u> energy plantations
USDA FS Pacific Northwest Forest and Range Experiment Station	D. S. DeBell	Increasing the biomass M. A. Radwan production of alder and cottonwood plantations in the Pacific Northwest
USDA FS Pacific Southwest Forest Experiment Station	C. D. Whitesell	<u>Eucalyptus</u> plantations for energy production in Hawaii
University of Washington/ Washington State University	R. F. Stettler T. M. Hinckley P. E. Heilman	Evaluate <u>Populus</u> selections for fuelwood (US-India Science and Technology Initiative)

<sup>a</sup>Other institutions cost sharing the Amana Society contract include Iowa State University, the Iowa Department of Natural Resources (DNR) Energy and Geological Resources Division, and the Iowa DNR Forestry Division.

<sup>b</sup>Industries cost sharing the monoculture viability trial work led by North Carolina State University include Federal Paper Board Company, Inc. and Scott Paper Company.

<sup>c</sup>A cost-sharing cooperator on the Northern States Power (NSP) Company project is the USDA Forest Service, North Central Forest Experiment Station. NSP will withdraw from the project April 1989.

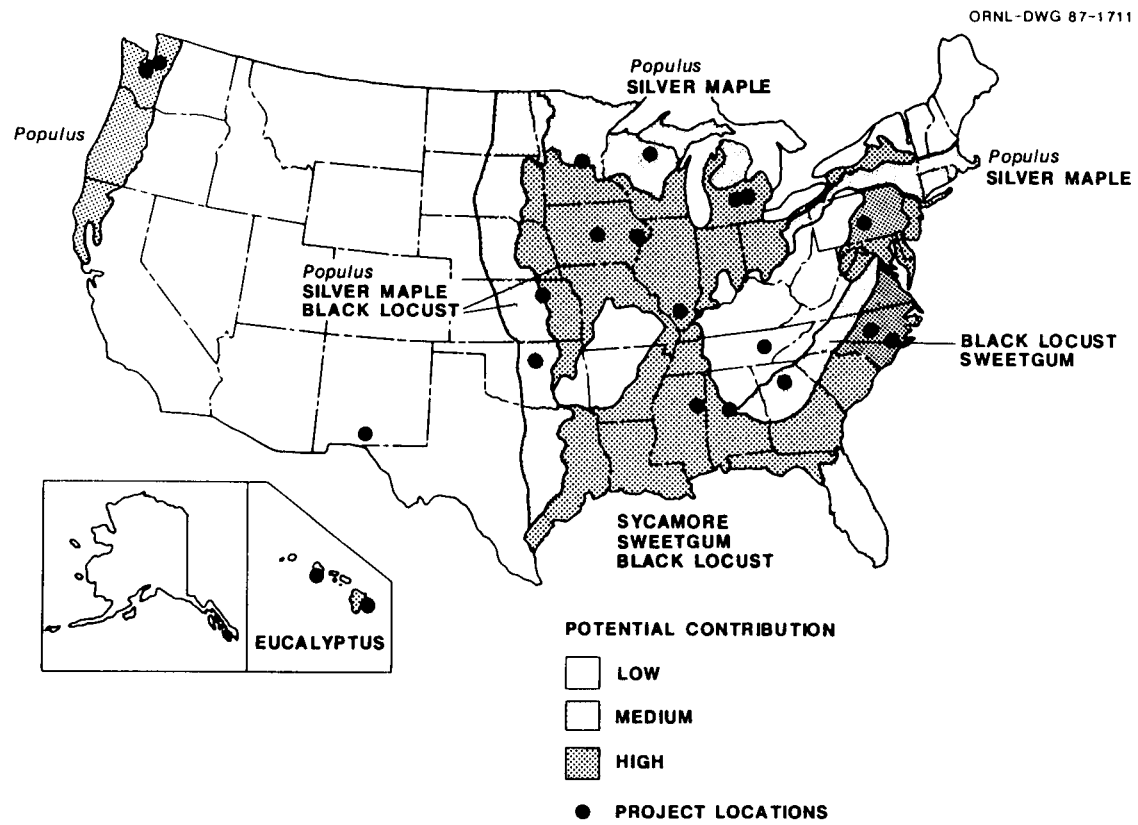


Fig. 1. Short Rotation Woody Crops Program project locations.

from manipulating the intrinsic qualities of various model species by exploiting diverse gene pools, physiological traits, and biotechnology advances. Similarly addressed are some research efforts that contend with the complex environmental influences and cultural interventions that affect the sustained yield of biomass plantations. And finally, the encouraging results of technology transfer of several successful monoculture viability trials are discussed.

## 2. SHORT-ROTATION WOODY CROPS PRODUCTIVITY

Delivery of plantation-grown wood energy feedstocks at prices that are competitive with coal, gas, and oil requires that very high productivity goals be achieved (Table 2). The major focus of the SRWCP is to develop the research base (i.e., definition of cultural requirements and genetic improvement strategies) needed to meet those high productivity rates. This information is largely being developed on relatively small plots, which can only provide an estimate of operational productivity in large monoculture plantations. Our summary of best and average research yields will provide guidelines for further research investments necessary in order for the private sector to produce competitive energy feedstocks from wood. The expected date of availability of the research base given in Table 2 provides an optimistic estimate of when ORNL believes that an adequate research base will be available for private sector adoption of the technology.

The best and average production yields given in Table 2 are selected values from research results most representative of current technology by geographical region. Table 3 summarizes the most recent yield results from SRWCP experimental production trials by region, species, and test design. In some cases reported results are from 1985 or 1986 projects or trials that have been discontinued. The yields clearly indicate that SRWC applications can result in obtainable yields 2 to 5 times those from unmanaged natural forest stands.

The exploratory yields given in Table 4 point the way to the exciting future of SRWC of hardwoods. Exceptionally high yields have been obtained by second-rotation *Populus trichocarpa* x *deltoides*<sup>2</sup> hybrids in the Pacific Northwest. The top yield of 43.5 Mg·ha<sup>-1</sup>·year<sup>-1</sup> (which is averaged over a 4-year coppice growth cycle) approaches the theoretical maximum limit of growth. Incremental (or current annual) growth in the third or fourth year is likely to have been between 60 and 80 Mg·ha<sup>-1</sup>. Maximum, current annual-production rates reported by Jarvis

---

<sup>2</sup>Latin names are used throughout this report; common names are provided in Appendix II.

Table 2. Short Rotation Woody Crops Program research status and goals by regions

Current research status			Program goals			
Best dry Mg·ha <sup>-1</sup> ·year <sup>-1</sup>	Average dry Mg·ha <sup>-1</sup> ·year <sup>-1</sup>	Average \$/GJ	Regions	Average dry Mg·ha <sup>-1</sup> ·year <sup>-1</sup>	Average \$/GJ	Expected date of availability of research base
33	17	2.28	Pacific Northwest	27	2.00	1992
22	17	2.28	Subtropics	27	2.00	1990
12	9	3.14	Lake States/ Midwest	20	2.00	1996
9	7	3.52	South	18	2.00	1996
13	11	3.14	Northeast	18	2.40	1994

Table 3. Most recent Short Rotation Woody Crops Program yield data (as of March 1988)--experimental yields used on a treatment plot with approximately 225 or more trees (including border trees)

Region	State	Species	Test type	Root age	Stem age	No. treatments	No. replicates	Yield (dry Mg·ha <sup>-1</sup> ·year <sup>-1</sup> )		
								Av	Min	Max
Northeast	PA	<u>Populus hybrids</u>	Culture	8	4	8	3	10.6	9.5	11.3
			Culture	7	3	8	3	11.9	10.0	13.5
Lake States/ Midwest	WI	<u>Populus hybrids</u>	Clone/spacing	7	7	12	2	9.6	7.6	11.5
			Spacing	11	11	2	4	7.6	7.0	8.3
			Rotation length	var	var	4	4	8.8	8.2	9.4
Pacific Northwest	WA	<u>Populus hybrids</u>	0.5 x 0.5 m	2	2	2	3	8.7	7.3	10.1
			1 x 1 m	2	2	2	3	5.7	3.8	7.6
			Woodgrass	2	1	4	3	8.6	7.7	9.7
	WA	<u>Alnus rubra</u>	Spacing	12	12	6	2	7.2	5.3	8.0
Subtropics	HI	<u>Eucalyptus saligna</u>	Spacing	4	4	4	4	8.9	5.4	14.4
			Spacing	8	8	4	5	12.8	11.6	14.0
	HI	Mixed	Species mix	5.4	5.4	3	9	11.2	6.8	17.3
			Species mix	4	4	7	4	23.6	16.7	27.5
South	AL	<u>Liquidambar styraciflua</u>	Spacing	6	6	3	6	6.5	5.0	7.3
				6	3	3	6	5.2	4.3	6.2
	AL	<u>Platanus occidentalis</u>	Spacing	6	6	3	6	6.7	6.5	7.0
				6	3	3	6	6.0	5.4	6.6
	AL	<u>Quercus nigra</u>	Spacing	6	6	3	6	6.7	5.1	8.0
				6	3	3	6	5.4	4.7	6.2
	FL	<u>Pinus elliotii</u>	Fertilizer	8	8	?	3	3.7	3.0	5.6

∞

Table 4. Most recent Short Rotation Woody Crops Program yield data (as of March 1988)--exploratory yields based on less than 225 trees per treatment plot (including border trees)

Region	State	Species	Test type	Root age	Stem age	No. treatments	No. replicates	Yield (dry Mg·ha <sup>-1</sup> ·year <sup>-1</sup> )		
								Av	Min	Max
Subtropics	HI	<u>Eucalyptus saligna</u>	Spacing	4	4	6	4	17.4	12.0	27.0
			Spacing	2	2	4	4	15.4	11.2	23.4
			Fertilizer	6	6	4	4	12.9	2.2	22.8
			Fertilizer	6	6	5	4	12.2	6.5	18.2
			Fertilizer	4.5	4.5	12	4	19.0	11.0	26.6
Pacific Northwest	WA	<u>Populus trichocarpa</u> <u>Populus hybrids</u> <u>Populus/Alnus</u>	Provenance	8	4	51	3	11.3	3.1	32.6
			Clonal	8	4	3	3	32.8	21.5	43.5
			Species mix	8	4	28	3	11.4	-	-
South	FL	<u>Pinus elliottii</u>	Fertilizer	8	8	3	3	14.1	13.5	14.8
			Selection	8	8	-	3	15.2	-	18.4
			Nelder	8	8	-	8	18.2	-	22.7

and Leverenz (1983) for 18 temperate forest stands ranged from 20 to 53  $\text{Mg}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$ . Linder (1985) calculated that if all incident radiation were intercepted and converted into biomass with a conversion efficiency of 6%, that potential biomass production in Australia would range from 80 to 110  $\text{Mg}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$  and for Northern Europe production would be about 50  $\text{Mg}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$ . While the high yields reported in Table 4 have been obtained only in exploratory research experiments, they suggest that we have only begun to tap the genetic potential of hardwoods for high juvenile growth rates. Such results spur us to search for the physiological mechanisms allowing such high production rates and apply that knowledge to developing better SRWC hardwoods for all regions of the United States.

There are many limitations to the current research information base on SRWC yield estimates. For instance, the data that currently represent the Lake States are based on trials in one location (Rhineland, Wisconsin) (Table 3), which is somewhat atypical for the region since it has a shorter growing period. Already the height growth of hybrid poplars established in 12 locations in the Lake States last year suggests that operational yields of the best clones are likely to be higher than yields reported from the Rhineland trials. In the South/Southeast, much of the land that is available for energy crop production and that was first tested under SRWC conditions is nutrient deficient for nitrogen or phosphorus, and yields were consequently relatively low. Those trials were discontinued, and the only current data from the South/Southeast is from Alabama and Florida. These results alone do not provide a good representation of the Southeast. There are no SRWC experimental data from the delta region of the South. However, pulpwood yields (bole only to a 10-cm top) of 10-year-old *P. deltoides* grown along the Mississippi River have been reported to equal 15 to 17 green  $\text{Mg}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$  (about 7.5 to 8.5 dry  $\text{Mg}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$ ) (DeBell 1988). Whole-tree (biomass) yields of cottonwoods grown with SRWC techniques in the South are likely to be much higher. Collection of data from several additional regions and site types is needed to provide a truly representative information base on the potential of SRWC in the United States.

### 3. GENETIC COMPONENTS OF PRODUCTIVITY

#### 3.1 BREEDING AND GENETIC IMPROVEMENT

Research on *Populus* for SRWC applications has been conducted in the North Central region and Pacific Northwest since the early 1970s; however, only the Pacific Northwest began genetic improvement of *Populus* for SRWC at that time. Currently, the North Central region is utilizing the experience gained in the Pacific Northwest in their efforts to develop new *Populus* clones for SRWC plantations in the region. During FY 1988, Dr. R. Hall of Iowa State University assembled a research team and initiated a major program to improve *Populus* for the North Central region. Hall and coworkers began the *Populus* genetic improvement program by evaluating the current situation. Most improvement efforts over the past two decades have focused on screening clones from other regions and selecting those showing the most promise in the North Central region. The most important criteria for using a clone in the region was found to be disease resistance. Only five clones are currently recommended for use in the region (*P. x euramericana* cv. 'Eugenei,' *P. x euramericana* cv. 'Raverdeau,' *P. x euramericana* I-45/51, *P. alba* x *P. grandidentata* 'Crandon,' and *P. tristis* x *P. balsamifera* 'Tristis #1') (Ostry 1988).

Hall and his coworkers have concentrated on the establishment of a network of cooperators from industry, government, and universities to assist with *Populus* improvement for the North Central region. The major effort during FY 1988 has been the development of a draft improvement plan for review by all cooperators. There are both short- and long-term aspects of the plan. The short-term objectives of the plan are to screen newly available trees quickly for pest tolerance and biomass potential and to release acceptable materials to growers. The long-term objective is to establish base populations, especially of *P. deltoides*, and to breed these to provide a continuous source of genetically improved material for users.

A final improvement plan will be developed by 1989, but implementation of some aspects began in 1988. During the summer of 1988, 127 *Populus* clones and families (provenances) were acquired from

Belgium (after quarantine), the Pacific Northwest, and other regional sources to further testing. Most of these were established in nursery beds at the Iowa Department of Natural Resources Nursery, Ames, Iowa. Although severe drought impacted tree growth and disease effects, progress was made in disease screening (summarized results not currently available). Cuttings from this material will provide planting material for more intensive and better-replicated testing during the summer of 1989 (R. Hall, personal communication).

In the Pacific Northwest, the significance of genetic improvement of *Populus* was highlighted by outstanding yields of 4-year-old coppice hybrids ranging from 21.5 to 43.5 dry Mg·ha<sup>-1</sup>·year<sup>-1</sup>. The yield from native *P. trichocarpa* clones in the same test ranged from 7.7 to 15.7 dry Mg·ha<sup>-1</sup>·year<sup>-1</sup>. There was a competitive advantage for the hybrids because of mortality among their neighboring native clones and, therefore, the yields reported are somewhat higher than what might be expected in a large monoclonal trial (Stettler et al. 1988b).

The breeding program at the University of Washington continues to expand and to improve on the genetic quality of the trees it produces. During the last 10 years, 25,000 seedlings have been produced by the breeding program from which a selection of 1900 clones are currently under testing in 12 field trials from central Oregon to northern Washington and on both sides of the Cascade Mountains (Stettler et al. 1988b). Hybrid clones produced in this effort were sired by selected male *P. deltoides* clones selected for their growth and form. The breeding has expanded from F<sub>1</sub> crosses of *P. trichocarpa* and *P. deltoides* to F<sub>2</sub> crosses, backcrosses, and trihybrids. Pollen from superior trees in Japan and Belgium has been used in recent breeding work expanding the number of parental species used in the program. These species should contribute pest tolerance and site adaptability to the program's clones.

Stettler et al. (1988a) reported on studies on the comparative growth and morphology of *P. trichocarpa* (T) and *P. deltoides* (D) with their hybrids from a F<sub>1</sub> (T × D) or F<sub>2</sub> (TD × TD) generation and backcrosses (B<sub>1</sub>) (TD × T and T × TD). The results of the studies identified that F<sub>1</sub> hybrids had the best growth, followed in order by B<sub>1</sub>, T, F<sub>2</sub>, and D. The growth of the D clones was limited more by their

growing so far from their natural range than by their genetic potential to grow. Several of the F<sub>1</sub> clones were similarly ranked across two widely diverse sites. These results imply that there is stability of performance of clones over sites and that emphasis should be placed on selection and breeding within the parental species and crossing between these to produce F<sub>1</sub> hybrids for use in the production population.

An important aspect of the work in the Pacific Northwest is the study of the genetic variation in native *P. trichocarpa*. Previous studies evaluated differences among clones obtained from 10 river drainages in a north-to-south direction (Heilman and Stettler 1985; Weber et al. 1985). In 1985 a new study was initiated to study the variation that might occur in an east-west direction. Collections were made from four river valleys--the Hoh, Dungeness, Nisqually, and Yakima. The clones were grown in a stoolbed for 1 year at Puyallup and then outplanted at Puyallup and Wenatchee, Washington (Fig. 2), where they were grown under similar SRWC conditions. After 2 years in the field, the Hoh and Nisqually sources have superior height growth at both sites, while the Yakima sources have the least height growth at both sites. For all sources, height growth is better at Puyallup (Stettler et al. 1988c). In a preliminary analysis, there is an apparent ecotypic change in the population about halfway down the Yakima River valley (eastern half of the population). These lower-elevation populations generally grow less, are more susceptible to *Melampsora* rust, and lose their leaves earlier than populations from the western half (higher in elevation) (Stettler et al. 1988c). Of general interest, however, is the relative stability of the clones at both sites.

Genetic improvement of *Populus* is continuing to move forward for at least two regions of the United States as evidenced by the work presented here. Further development of genetically improved clones in other regions of the country is needed but is limited by funding and research priorities. *Populus* species and hybrids can be grown on a number of sites across the United States, but there are many sites where they either cannot be grown or will not grow as well as other species. Genetic improvement of the other model species in the SRWCP, therefore,

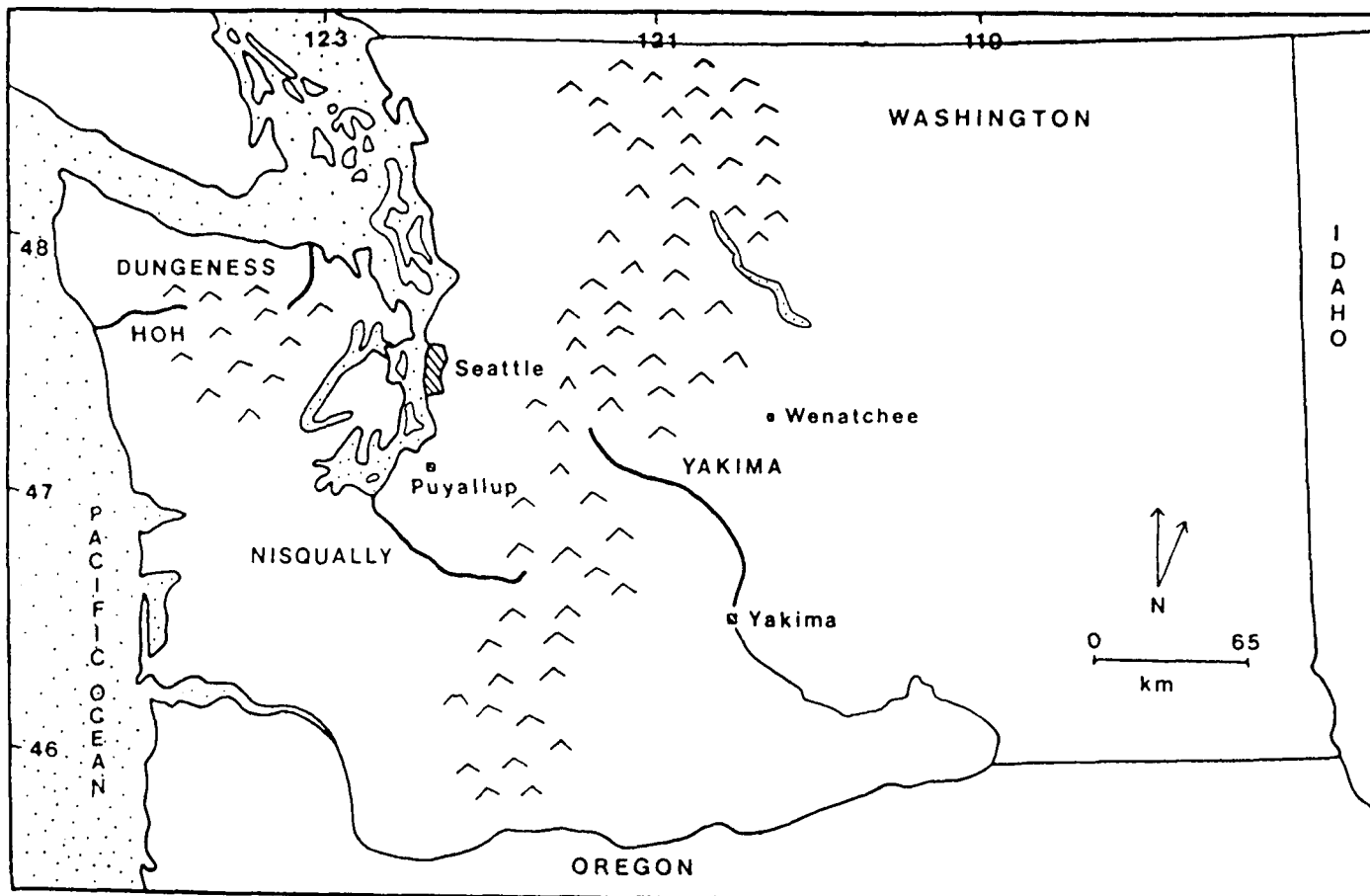


Fig. 2. Locations of river drainages from which collections were made for *Populus trichocarpa* and the test plantations (from Stettler et al. 1988c).

is being done to fill the need for highly productive planting materials for many of those sites.

Genetic improvement projects for three of the model species are currently ongoing. *Robinia pseudoacacia* improvement is being performed by researchers at the University of Georgia. The major goal of their project is to use SRWC methods and genetic selection to increase the proportion of aboveground biomass of the species. Their results on isozyme analysis of mating systems and geographic variation have shown that to date *R. pseudoacacia* is primarily an outcrossing species, and there is no geographic pattern in isozyme variation. Gene flow estimates were found to be rather high for an insect-pollinated species, suggesting that widespread artificial regeneration has affected the results (Huber et al. 1988). The researchers have obtained seeds and clonal materials from a variety of sources and will be evaluating their growth under various silvicultural conditions including drought to select superior clones for use in biomass energy programs. They will also be studying their physiology and nitrogen-fixation relationships. First-year field trials at the University of Georgia resulted in approximate heights of 3 and 2 meters for irrigated and nonirrigated seedlings, respectively (Bruce Bongarten, University of Georgia, personal communication). The field trial was located in an area where drought was severe the first growing season. Clonal propagation of materials has proved somewhat difficult for some clones, but progress is being made in developing these methodologies for *Robinia pseudoacacia*.

Clonal propagation is also one aspect of the genetic improvement of *Platanus occidentalis* at Mississippi State University. Researchers there hedged clones and treated some with plant growth regulators in an attempt to enhance the number and quality of cuttings that could be obtained (Land et al. 1988). The researchers have also investigated the relationship between seed and seedling traits and the productivity of harvestable trees. Germination value (an indication of the rapidity and success of germination) was found to be significantly correlated with field performance at ages beyond the nursery (Land et al. 1988). The researchers also have described the stages of floral development for sycamore, which will make control-pollination efforts more efficient in

the future (Land et al. 1988). These research efforts should lead to shorter generation times, easier clonal propagation techniques, and identification of important physiological traits that can enhance biomass production of *Platanus occidentalis*.

The genetic improvement of *Acer saccharinum* is at the earliest developmental phase of all the species being studied by the SRWCP. Seed collections were made across the natural range for this species. These were then planted in a nursery to provide a stock of juvenile specimens for clonal propagation and field testing on other sites within its native range (Preece et al. 1988a). Field planting was scheduled to be done in the spring of 1988. This was a very fortunate decision, since most of the planting sites suffered a severe drought during 1988. Nursery growth has been monitored for the second year, and some trees reached 3 m in height.

Variation in growth, phenology, and morphology of the seedlings as related to their geographic origin is being observed in the nursery (Preece et al. 1988a). In a related study at Kansas State University, geographic variation in western seed sources grown in Nebraska for 7 years was reported by Kopp et al. (1988). They reported that selection of the appropriate seed source and selection within that source could enhance biomass productivity. These researchers will be participating in the SRWCP study by providing an additional test site.

From research on poplars at the University of Washington, The SRWCP genetic improvement of a biomass species has significantly increased yields. In the Pacific Northwest, hybrid biomass yields have more than doubled those of unselected parental clones. Recently developed disease screening techniques will be used in the North Central region to eliminate susceptible trees quickly, thereby allowing more efficient selection of good biomass producers from the remaining resistant population (Hall et al. 1988). Disease screening for known disease-causing organisms is already incorporated in selection of superior clones in the Pacific Northwest. However, as more plantations are established, new pathogen problems may emerge and require the development of additional screening techniques. Breeding and selection of the other model species is anticipated to increase yields in a manner

similar to that of *Populus*. Although projects of this type require significant time and dollar resources, they provide the only method available for continuous enhancement of multigenic traits such as survival, growth, and resistance to pathogens.

### 3.2 PHYSIOLOGICAL RESEARCH

An integrated research program to develop woody biomass energy crops is approached in logical fashion by examining components of productivity and then manipulating the components to optimize productivity for a specific conversion technology (Stettler et al. 1988c). The SRWCP has ongoing research in many of the categories identified as components of growth in Fig. 3. Other components are being researched by investigators affiliated with SRWCP projects but funded from other sources. The most complete set of research on these components is occurring on the model genus, *Populus*. Other model species have some ongoing aspects of research from among these various components. This report cannot describe the entire research program on these components but will attempt to highlight some of the more recent research developments from among the various projects.

#### 3.2.1 Nutrition Research

At ORNL, researchers are investigating the effects of urea-nitrogen fertilization applied to sycamore plantations under various application and timing strategies. Their hypothesis is that maximum efficiency in biomass production requires optimum nitrogen fertilization, defined as that which maximizes growth while minimizing nitrate leaching to groundwater. This should be done with minimal effect on the physiological processes that alter a tree's resistance to environmental stress. In their first year, tree growth and physiological parameters were monitored throughout the growing season to identify the best indicators of the onset of nitrogen deficiency and thereby predict the need for fertilization. Physiological parameters included net photosynthetic rate, pigment concentrations, plant-water relations, osmotic potentials at full turgor and at turgor loss, and leaf and stem constituent soluble sugar concentrations. Plant nitrogen

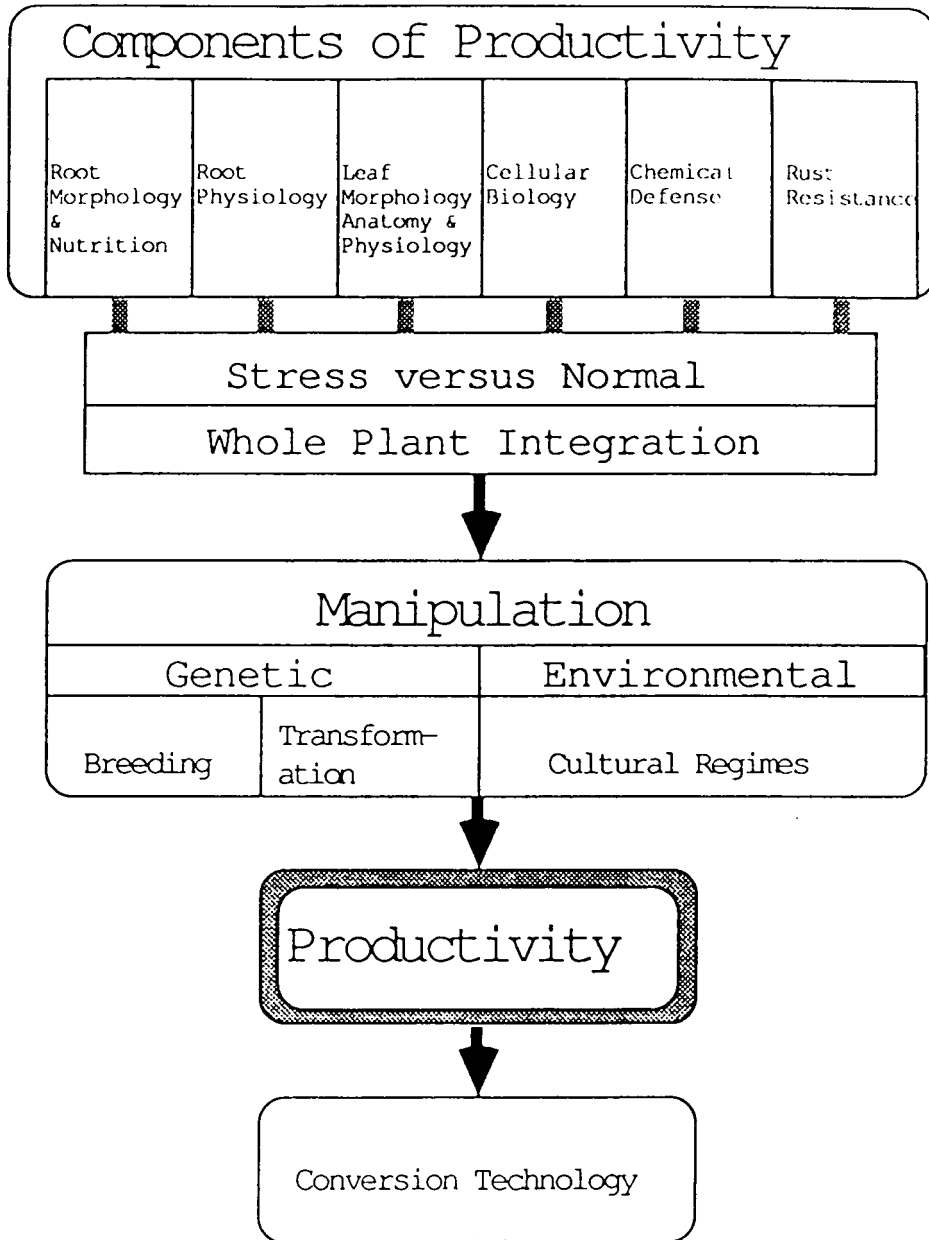


Fig. 3. Biomass productivity; its components and their manipulation (adapted from Stettler et al. 1988c).

status was assessed by leaf nitrate reductase activity and by concentrations of nitrate, soluble protein, total nitrogen, and constituent amino acids.

In the first year the greatest aboveground biomass accumulation (3 times greater than that of unfertilized controls) was obtained with a heavy single addition of nitrogen (450 kg/ha), but nearly as much was obtained when much less nitrogen was added either as a single application early in the season (150 kg/ha) or in periodic applications (37.5 kg/ha 3 times). Tschaplinski et al. (1989) stated that the increased growth resulted from an early-season stimulation of leaf area production (Table 5) and a stimulation of photosynthetic capacity later in the growing season. There was no evidence that fertilization extended the physiologically active season or increased susceptibility to drought (which did occur) or frost. Photosynthetic pigment concentrations, net photosynthetic rate, and leaf nitrate reductase activity (Figs. 4, 5, and 6) were found to be the most sensitive indicators of plant response to nitrogen fertilization. Foliar concentrations of nitrate, total nitrogen, soluble carbohydrate, and soluble protein were poor indicators. Amino acid concentrations were indicative of nitrogen deficiency, but the response was somewhat delayed, limiting their use as sensitive indicators (Tschaplinski et al. 1989).

### 3.2.2 Crown Architecture and Carbon Allocation

Two of the major influences on forest productivity and yield are crown architecture and canopy density (Stettler et al. 1988c). For the last 4 years an intensive study of *Populus trichocarpa*, *P. deltoides*, and their hybrids has been used to analyze the carbon allocation between leaves, branches, roots, and stems of hybrids compared to those in their parental types. This work has been a cooperative effort among scientists and students at the University of Washington, Washington State University, and the U.S. Forest Service, Rhinelander, Wisconsin. The methods and materials used in this study were described by Isebrands et al. (1988). During the last year, a large amount of the data from the first 3 years of the study has been analyzed. These results have

Table 5. Early-, mid-, and late-season leaf area and stem dry weight (dw) of nitrogen-treated *Platanus occidentalis* trees<sup>a</sup>

Treatment	Date	Leaf area (cm <sup>2</sup> )	Stem dry wt. (g)
C	June 25	855 ± 124	
P	June 25	1182 ± 153	
01	June 25	1914 ± 323	
C	August 21	2405 ± 420	16.1 ± 3.1
P	August 21	3612 ± 412	27.7 ± 3.1
01	August 21	4785 ± 564	34.5 ± 4.2
C	November 16	256 ± 793	3.0 ± 4.8
P	November 16	626 ± 196	74.8 ± 10.7
01	November 16	876 ± 176	99.1 ± 7.3

<sup>a</sup>Treatments include unfertilized controls (C), low-level periodic doses (P, 37.5 kg/ha x 3), and heavy single dose (01, 450 kg/ha).

ORNL DWG 88M-9692

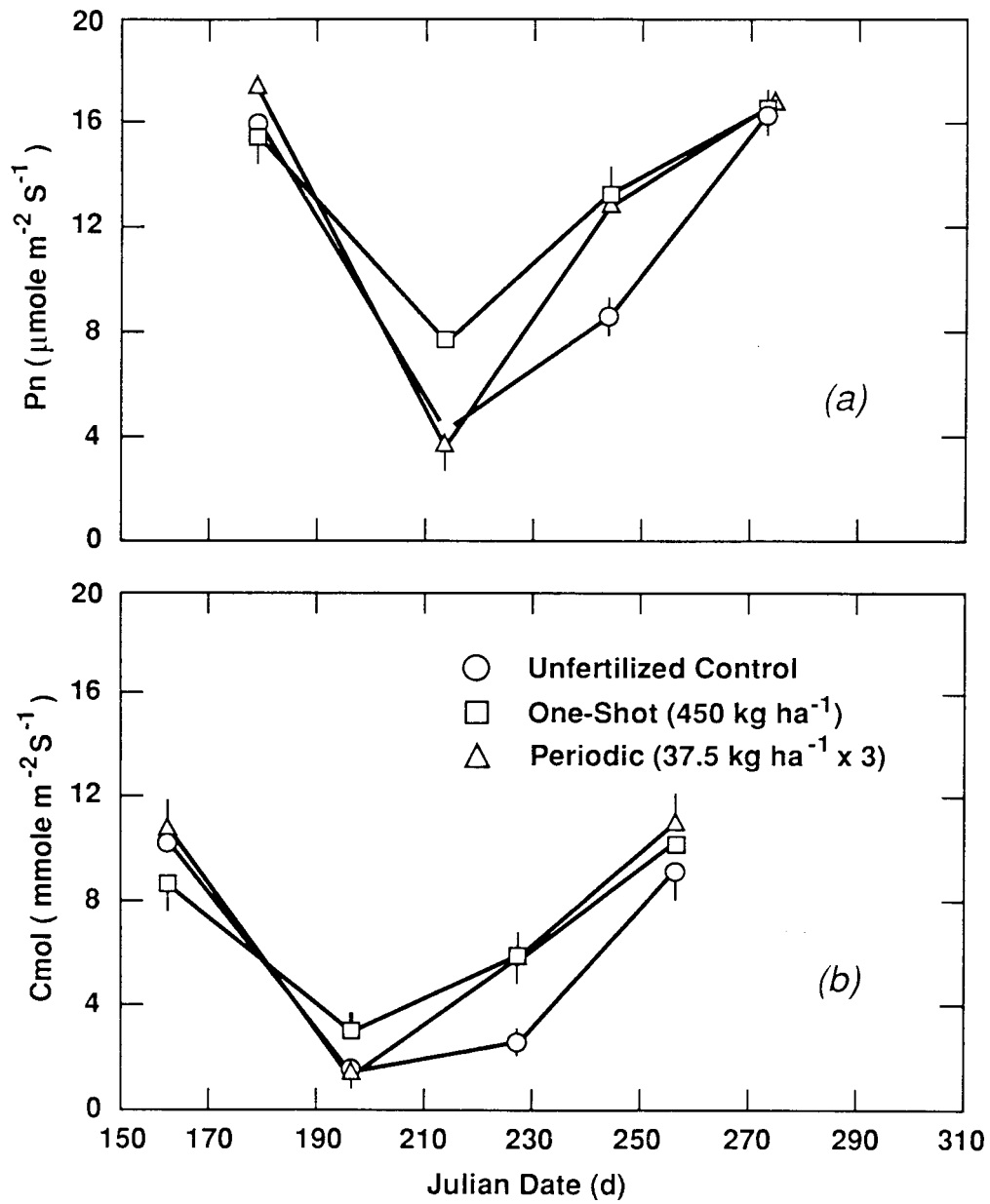


Fig. 4. Net photosynthetic rate (Pn) and stomatal conductance (Cmol) of nitrogen-treated *Platanus occidentalis* trees over the growing season.

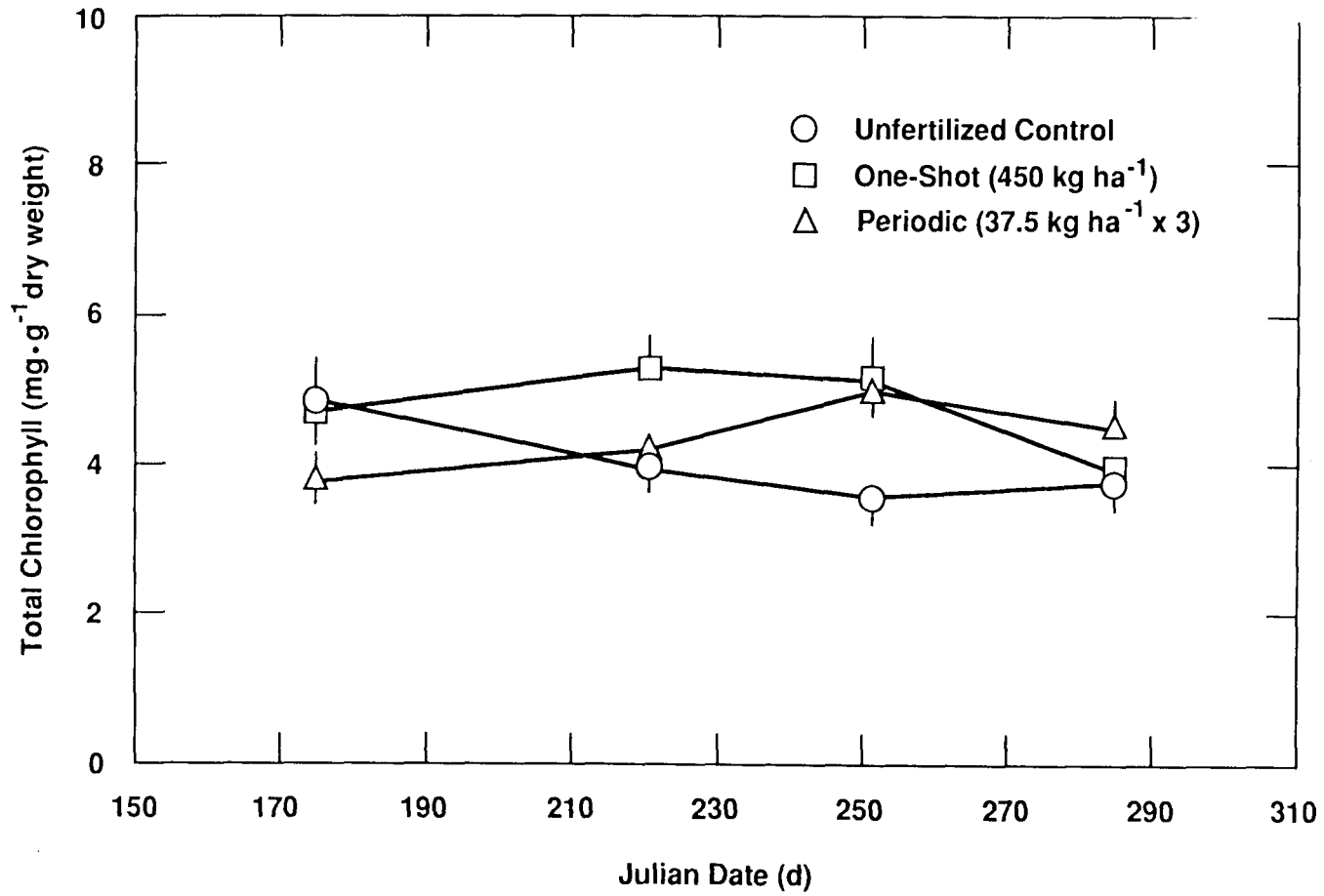


Fig. 5. Total chlorophyll concentration of nitrogen-treated *Platanus occidentalis* trees over the growing season.

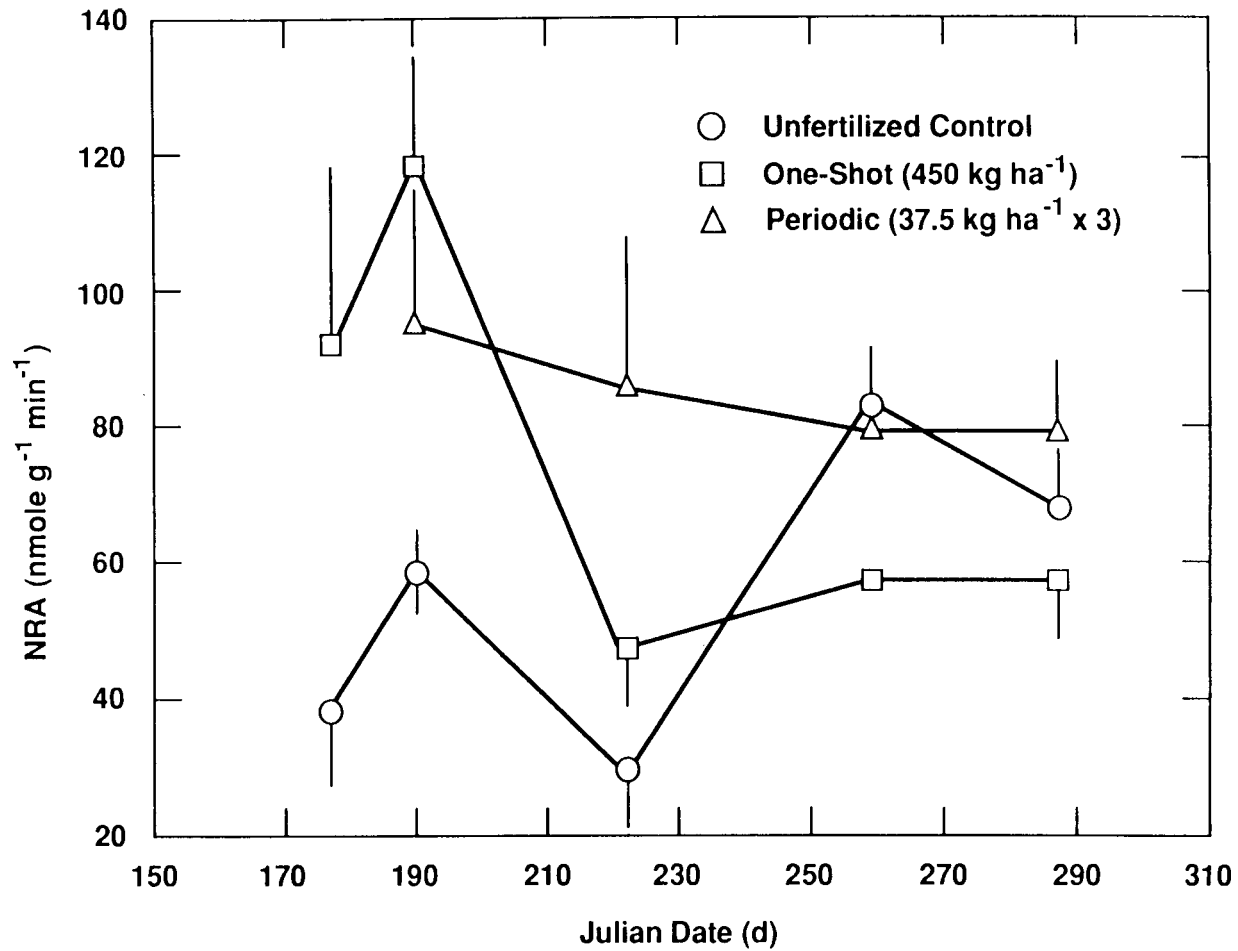


Fig. 6. In vivo leaf nitrate reductase activity (NRS) of nitrogen-treated *Platanus occidentalis* over the growing season.

provided new insights into the high productivity of hybrids and identification of ideal canopies.

Stem volumes of the hybrid clones averaged 1.5 times better growth than their *P. trichocarpa* parental types and 3 times better than the *P. deltoides* clones (Fig. 7) (Stettler et al. 1988b). Leaf area index (LAI) continued to increase over the 3 years and by mid-August 1987 the two parental type clones had LAIs of 6.3 and 6.2, while the two hybrid clones had LAIs of 11.6 and 11.2; leaf dry weight ranged from 10 to 16% of total aboveground biomass (Stettler et al. 1988b). These LAIs of the hybrids are extraordinarily high values when compared to those of other hardwoods but are very similar to values reported for several conifer species (*Pseudotsuga menziesii* and *Picea sitchensis*) and for agricultural crops such as corn and sunflower. The early, rapid production of many leaves by the hybrids and the distribution of leaf area result in their impressive growth performance (Stettler et al. 1988b).

Data from two clones in these studies were used to provide an independent validation of the ecophysiological growth model developed by J. Isebrands and his associates (Rauscher et al. 1988). Transport coefficients used in the model were obtained from *P. x euramericana* cv. 'Eugenei' and, therefore, were not entirely appropriate for the validation. A graphical output of the *P. deltoides* clone Ill-5 and its observed range of values compared with the model prediction can be seen in Fig. 8. The match between model prediction and observed growth is relatively good now, but it is anticipated that it will be much improved once the appropriate transport coefficients are incorporated in the model. In order to make comparisons across sites, Dr. Isebrands and two other members of the Populus Energy Consortium planted replicated plots of the same four clones in April 1988. Phenological, morphological, physiological, and environmental data have been collected during the growing season and will be used to study why Populus growth differs among regions.

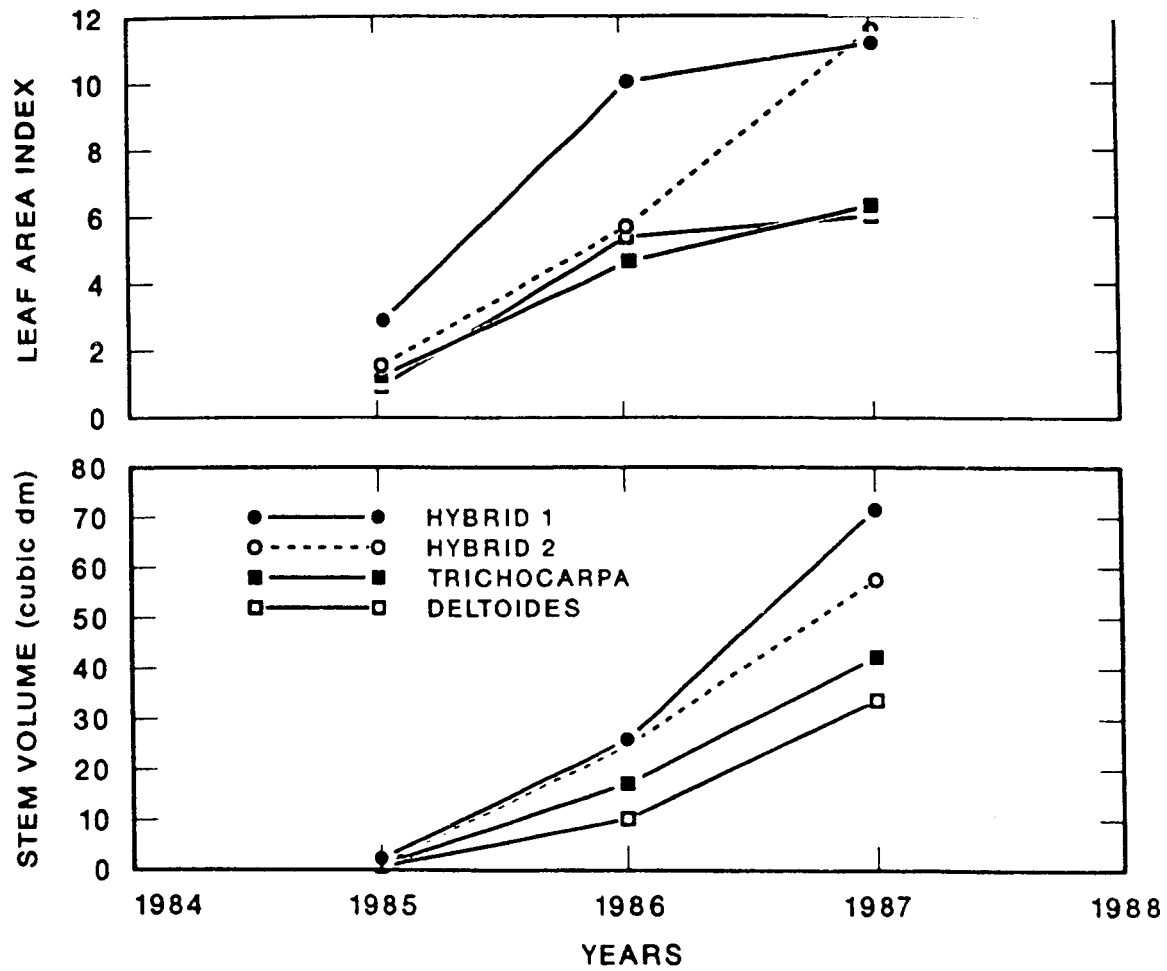


Fig. 7. Comparison of stem volume (basal diameter x height) of two hybrid *Populus* clones and one clone of each parental species with the development of their leaf area index during their first three growing seasons (adapted from Stettler et al. 1988b).

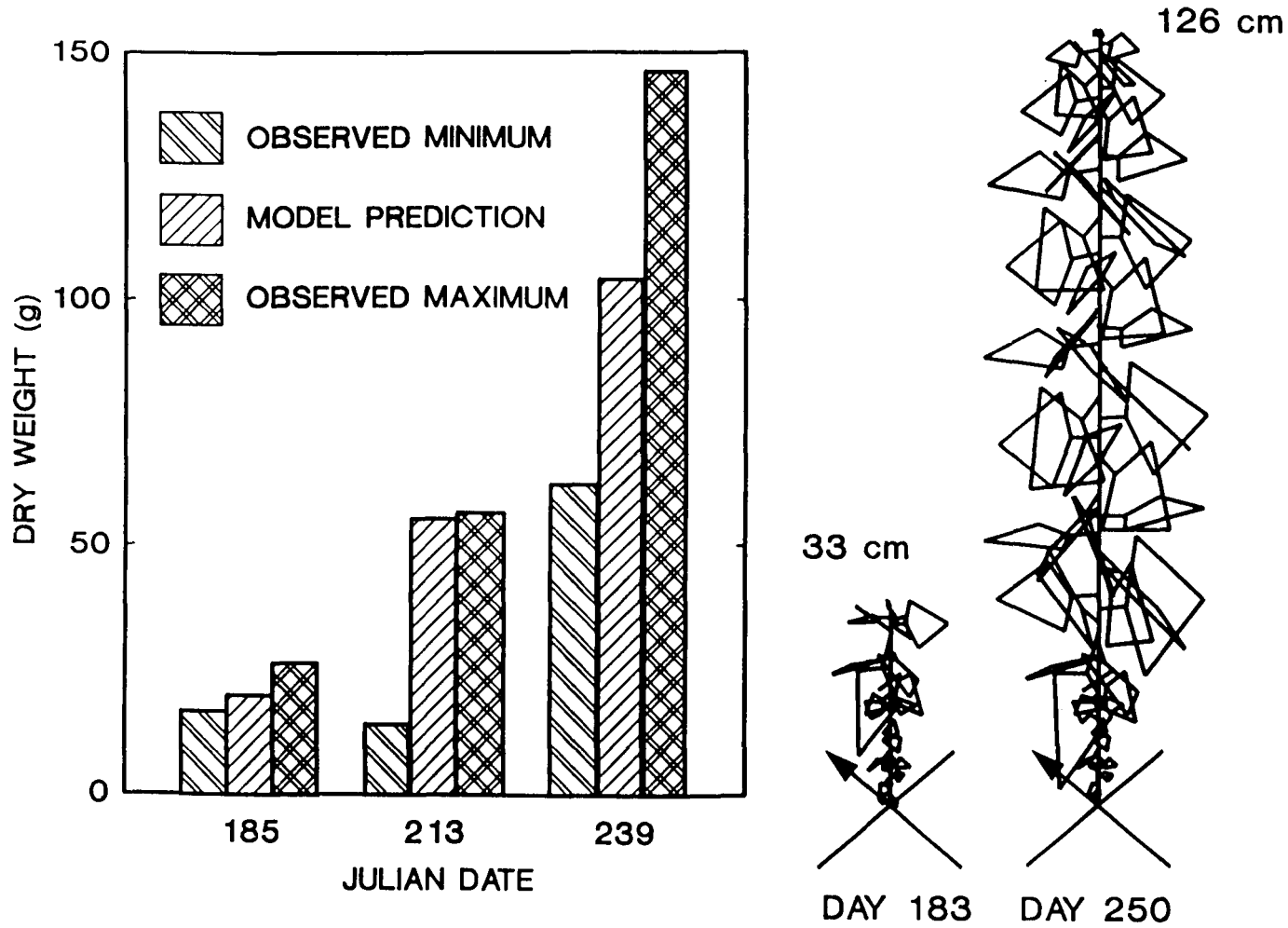


Fig. 8. ECOPHYS model validation of *Populus deltoides* clone Ill-005 total aboveground biomass grown in Puyallup, Washington, and a graphical display of the predicted tree twice during the growing season (adapted from Hansen et al. 1988).

### 3.2.3 Root Morphology and Physiology

Two of the six components of productivity identified by Stettler and his coauthors (1988c) concern roots (Fig. 3). Since 1986 several projects within the SRWCP have researched roots, investigating physiological processes, morphology, and genetic variation.

In the Pacific Northwest, investigators evaluated the position and size of roots on 19 3-year-old hybrid *Populus* clones (Stettler et al. 1988b, 1988c). The roots were at depths greater than 3 m, and soil layering (fine silty loam to coarse sand) was influencing root distribution. Larger but fewer roots were found in coarser textured layers, while finer textured layers contained large numbers of fine roots. The researchers found that, in general, the roots on the upper part of the cutting were horizontal, and those coming from the lower part of the cutting were vertical or oblique in orientation. Root size increased as the point of attachment on the cutting got lower. Most of the root biomass was vertically oriented, but there were differences among clones. Based on this limited data set, family and male and female parentage effects were found in the amount of vertical rooting (Stettler et al. 1988c).

In two studies at Michigan State University, researchers also found differences in root production between clones. They have evaluated two clones of hybrid *Populus*, *Tristis* and *Eugenei*, under different water and nutrient regimes. *Tristis* has a fairly determinant pattern of growth, while *Eugenei* is indeterminate. In a 3-year-old study they found that fine-root numbers were higher in irrigated plots of *Eugenei* and that the numbers peaked in October (Dickmann et al. 1988). In *Tristis* the opposite was true; there were more fine roots in the nonirrigated plots, and the number of fine roots declined after September. The *Tristis* trees were much smaller than the *Eugenei* trees, and when evaluated on the basis of stem size, *Tristis* had invested more of its productivity into fine roots and had greater fine-root turnover. Based on this and other data, Dickmann et al. (1988) suggest that there is strong genetic control of phenology and carbon allocation. They found that *Eugenei* was very plastic in its aboveground response to environmental differences, while nonplastic belowground. *Tristis* was

just the opposite, nonplastic aboveground and very responsive belowground. Further information on root growth will be forthcoming as the development of techniques to analyze mini-rhyzotron images of tree roots progresses.

At Mississippi State University, researchers exhumed *Platanus occidentalis* seedlings throughout the growing season from a nursery study. They found that although shoot growth was complete in September, the roots were still growing when a final harvest of all seedlings was made the following January (Land et al. 1988). In some of the traits there was evidence of genetic variation, but further work is needed to relate this to biomass productivity at harvest. The exploitation of new soil area during this time period may provide more or better nutrition for the tree.

The relationship between nutrition and root growth is not well understood and will be a continuing area of research within the SRWCP. Only by understanding all the components of growth and their relationships to each other can we truly begin to manipulate, both genetically and silviculturally, energy crops to maximize their productivity while minimizing their cost.

### 3.3 BIOTECHNOLOGY

An evaluation was performed during FY 1988 to determine what needs within the SRWCP could be met with the use of biotechnology. The state of knowledge on each of the SRWCP model species and on biotechnological approaches was reviewed to establish a basis for determining how biotechnology could meet research needs. The evaluation has led to an informal plan of action that might be taken under various funding scenarios (Ellis and McCown 1988). Although many possibilities exist for using biotechnology in the SRWCP, the scope is limited and is only appropriate where a viable genetics and physiology research program is ongoing. One of the major points brought out during the evaluation was the success of current projects on biotechnology within the program. Accomplishments in three areas--cell and tissue culture, somaclonal variation, and gene insertion-- can be pointed to and identified as major successes.

### 3.3.1 Cell and Tissue Culture

In the area of cell and tissue culture, two SRWCP projects have achieved success. Results will be only briefly summarized here, but more details have been provided by Layton and Ostry (1989). A study conducted by Charles Michler at the U.S. Department of Agriculture (USDA) Forest Service Laboratory at Rhinelander, Wisconsin, has developed regeneration protocols to produce plants by somatic embryogenesis (Fig. 9) and/or shoot organogenesis from cell suspension cultures. Protocols were developed for hybrid poplar clones NC-5339, NC-5326, NC-5331, NC-5272, and NC-11390, and *P. trichocarpa* clones NC-12624 and NC-12519 (Hansen et al. 1988). In addition, Michler has produced somatic embryos and continuous shoot cultures for several *P. deltoides* clones. A manuscript detailing this work is in preparation. Of the seven clones listed above, Michler had successful somatic embryogenesis with three clones and was able to get shoot organogenesis with all seven. In addition to this work, Michler has refined his methods for continuous shoot culture of *P. x euramericana* cv. 'Eugenei' (NC-5326).

In a tissue culture-related study, D. Riemenschneider, also at the Rhinelander laboratory, has evaluated the genetic variation in adventitious rooting of *P. deltoides*. Clones differed in rooting percentage (8 to 90%) and mean number of roots per explant (0.2 to 5.3,  $p < 0.001$ ) (Riemenschneider et al. 1988). The authors concluded that clonal selection could markedly improve in vitro adventitious rooting ability in *P. deltoides*.

At Southern Illinois University, J. Preece and his associates have developed regeneration protocols for *Acer saccharinum*. Using a medium with added thidiazuron (10 nM), they were able to get shoots to produce at least 60 axillary shoots. More than 90% of these shoots could then be rooted under mist (Preece et al. 1988b). These resulting plantlets will be used in the University's clonal provenance study.

## Direct Somatic Embryogenesis

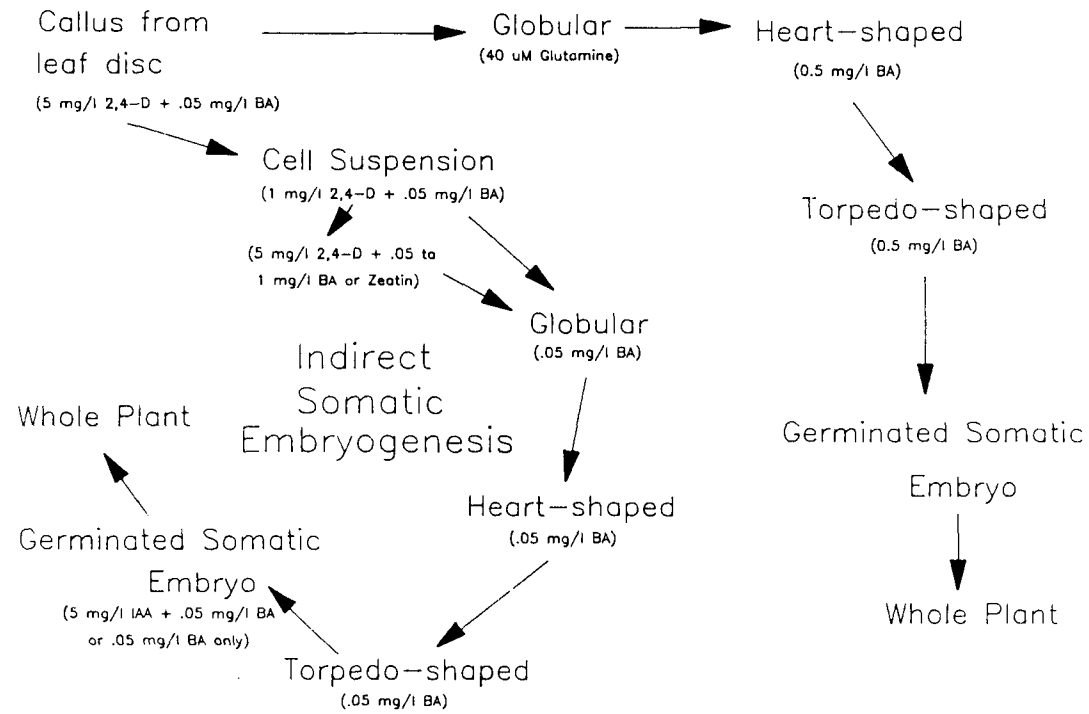


Fig. 9. Diagram of *Populus* somatic embryo development from callus to germinated microplantlet (from Hansen et al. 1988).

### 3.3.2 Somaclonal Variation

During the past year Dr. Michler has selected somaclonal variants of hybrid poplars with increased tolerance to the herbicide sulfometuron methyl. In vitro plants have survived applications of the herbicide at a level 10 times greater than that needed to kill the parent clones. Michler, quoted in Agricell Report, stated that "this is the first example of useful chemical tolerance produced in a forest tree species by tissue culture" (Michler 1988). Michler has used similar methods to find somaclonal variants tolerant to glyphosate. Preliminary greenhouse spray testing of putative tolerant variants confirmed increased tolerance to the two herbicides (Hansen et al. 1988, Michler and Bauer 1988).

Michler (1988) reported that there appeared to be at least two different kinds of mutations responsible for tolerance to sulfometuron methyl. Enzyme analyses indicated that the target enzyme of sulfometuron methyl (acetohydroxyacid synthase) had greater activity and less sensitivity to sulfometuron methyl, when compared to control plants (Michler and Bauer 1988). Michler (1988) suggested that the less sensitive enzymes may reflect a change in the site of attachment or action of the enzymes, whereas overproduction of the enzyme may be caused from the presence of multiple copies of the genes that direct the synthesis of the enzyme.

### 3.3.3 Gene Transfer

Successful transformation of poplars using this species continued at the U. S. Forest Service Laboratory at Rhinelander. Riemenschneider (personal communication) has been performing factorial experiments to test bacterial concentrations and cocultivation times for optimum transformation. He recommends, as an optimum, 48 hours of cocultivation with  $10^8$  colony-forming units of *Agrobacterium*. He has also determined that 50 mg/L of kanamycin will inhibit regeneration of plants from controls (or nontransformed cells) but will not inhibit regeneration from transformed material.

Building on the initial success of inserting a gene for glyphosate tolerance into hybrid poplar (Fillatti et al. 1988), Riemenschneider is

inserting a new construct of the gene obtained from Calgene, Inc. into clone NC-5339. Shoots regenerated after transformation have been tested on a medium containing 100  $\mu\text{m}$  glyphosate (this concentration exceeds the  $\text{LD}_{100}$  for untransformed NC-5339 shoots in vitro). Future plans for this material include analysis for Southern Blot and eventual greenhouse spray test of regenerated plants (D. Riemenschneider, personal communication).

#### 4. ENVIRONMENT-RELATED FACTORS OF PRODUCTIVITY

Research initiatives of the SRWCP have focused on maximizing the energy return from biomass production while minimizing the cost and biological risks to achieve high yields. In only a few years, the SRWCP has realized productivity gains in experimental and production-level field trials far beyond what was once deemed possible. These productivity achievements have resulted primarily from genetic improvements and advances in cultural practices. As efforts to extend the genetic potential for productivity continue, the importance of demonstrating sustained yields over a wide range of site and environmental conditions becomes more crucial. In this section, we consider the research advances that have been made over the last year to broaden the bounds of productivity gains with respect to cultural interventions and environmental stress.

##### 4.1 COMPETITION AND SPACING RELATIONSHIPS

Competition is a major stress factor that results in reduced growth and survival. In the early stages, competition from native trees and grasses may limit the availability of essential resources to the extent that planted seedlings succumb to mortality. The need for "weed" control in these cases raises the cost and risk involved with intensive cultural practices. Because some species and clones may not be herbicide resistant, weed control practices utilizing herbicidal treatments may further complicate the success of any planting. Studies of clonal resistance to effective herbicides are ongoing (see Section 3.3).

Inter-tree competition among planted seedlings presents yet another stress that involves biotic and abiotic, as well as aboveground and belowground, processes. Competition is difficult to observe directly since it does not exist as a physical element of growth or survival but rather as a process controlling the condition of the surrounding environment in such a way that it is less favorable for mutual coexistence. In the abiotic sense, it comprises the manner in which trees alter their environment (microclimate) and resource

allocation of essential elements for growth (e.g., light, water, nutrients, and CO<sub>2</sub>). Some species and clonal types are known to be less tolerant of environmental changes that result with sharing proximal space. Testing the effects of various spacing schemes for given species has aided efforts to maximize stand productivity.

SRWC research has already instituted spacing standards much less than conventional plantation measures as a means to significantly increase productivity. Square spacing of about 1.6 to 2.0 m with harvest rotations of less than 5 to 8 years are thought to be optimum for energy plantations (Ranney et al. 1987b). Recent efforts have included evaluations of even tighter spacings based on the "woodgrass concept." Woodgrass spacings (0.18 and 0.30 m between plants) were implemented by D. S. DeBell of the USDA Forest Service Pacific Northwest Forest Experiment Station to consider the potential of achieving maximum productivity with a high density of trees (DeBell et al. 1988a) and an annual harvest. These studies have demonstrated with *Populus* hybrids (clones D-01 and H-11) that within 2 years the cumulative yield from woodgrass spacings (13.1 and 11.2 dry Mg·ha<sup>-1</sup>·year<sup>-1</sup> at 0.18 m and 0.3 m, respectively) is already exceeded by the cumulative yield at wider spacings (17.0 dry Mg·ha<sup>-1</sup>·year<sup>-1</sup> at 0.5 m and 11.5 dry Mg·ha<sup>-1</sup>·year<sup>-1</sup> at 1.0 m). The yield differences between woodgrass spacings and those greater than 0.5 m<sup>-2</sup> were mainly attributed to interactions between spacing and the patterns of bud and branch production. It was hypothesized that selecting for certain traits of clonal budding and branching could optimize productivity and utility of woodgrass plantings.

Understanding competitive processes and factors that limit species performance will only foster our ability to evaluate and propagate traits and characteristics that allow greater productivity in a closely spaced environment. An ORNL study has been initiated to construct a forest stand model for SRWC applications and to utilize data compiled within the SRWCP data base. This builds on a plantation growth-and-yield model (SELVA, Doyle 1988) that was developed to test hypotheses of competition effects at different spacings, given species growth and structural characteristics. SELVA is a spatially explicit stand model

that simulates square, rectangular, and triangular planting patterns for any given spacing distances. The model has been primarily used to evaluate the temporal and spatial behavior of mathematical models of competition in assessing the onset and degree of competition (Doyle 1988). In a forecast mode, SELVA predicts individual tree interaction and stand productivity for a given spacing regime. In a backcast mode, the model inputs plantation data and evaluates the growth response and mortality of individual trees in order to identify the timing and process of competitive interactions. Other potential uses include (1) productivity and risk assessment of continental plantings as affected by possible direct climate change and CO<sub>2</sub> effects, and (2) pathogen transferral scenarios.

#### 4.2 EFFECTS OF COPPICE MANAGEMENT

Coppice management provides a strategy for maintaining a stand in a phase of rapid juvenile growth, but optimal management requires a good understanding of competition dynamics. An understanding of these dynamics is being gained through coppice studies being conducted by several SRWCP contractors.

Growth and yield studies of coppice *Populus* plantations conducted by SRWCP contractors at Pennsylvania State University have provided some interesting results this year. Based on the planting established in 1980, which had a severe growth lag in the first year due to weed competition, total second-rotation production increased by 15 to 33% depending on treatment (Table 6). The 1981 planting, which has much better weed control during the first rotation, is considered to be more representative of first-rotation yields. If the 1980 planting fourth-year coppice yields are compared against the 1981 planting first-rotation yields, the results suggest that coppice yield gain may be modest (8 to 16%). This hypothesis will be more adequately tested when the fourth-year yields of the 1981 planting become available. The most interesting aspect of the second-rotation growth pattern is that incremental growth of the fertilizer treatments peaked by year 3 and fell sharply during the fourth year. An analysis of costs by Strauss et al. (in press) showed that the coppice stands should be harvested by

Table 6. Hybrid *Populus* biomass yields from first and second rotations by management strategy (Blankenhorn et al. 1989)

Management strategy	Four-year-old oven-dry biomass (Mg/ha)					
	1980 planting		1981 planting		Net gain (%)	
	Rotation		Rotation		$\frac{b-a^a}{a}$	$\frac{b-c^b}{c}$
	1	2	2	1		
Control	(a) 27	(b) 36.4	(c) 33.5	NA	33	8.65
Irrigation	30	38.7	33.3	NA	30	16.21
Fertilization	35	45.4	40.4	NA	29	12.32
Fertilization/irrigation	40	45.7	42.1	NA	15	8.55

<sup>a</sup>Second-rotation yields of 1980 planting compared against 1980 planting first-rotation yields, which were limited by severe weed competition in the first year.

<sup>b</sup>Second-rotation yields of 1980 planting compared against 1981 planting first-rotation yields as recently done by Strauss et al. 1989 to evaluate optimum economic strategy.

age 3 to obtain the lowest production costs. An earlier analysis had shown that the control treatment was the most economical, although the fertilization strategy was only 6% higher in cost (Strauss 1989). Of particular interest was the decline in root-stock survival that occurred throughout the second rotation, particularly among fertilized treatments (See Table 7). The loss of root-stump viability did not appear to affect total biomass production, but could limit long-term productivity in future coppice rotations should survival rates continue to decline. It is not known to what degree inter-tree competitive interactions in concert with cultural treatments may have accounted for these differences. Survival dropped most noticeably between the third and fourth year of the coppice rotation in all but the control treatment. The fertilization treatment was not only more expensive but apparently more stressful to the trees. While fertilization is recommended to maintain long-term productivity of the site, lower cost and more effective fertilization strategies are obviously required.

#### 4.3 MIXED-SPECIES CULTURES

Species mixing in SRWC applications has been proposed as a measure to lessen environmental stress and competitive interactions. Mixed-species plantations have long been theorized as a cultural intervention to increase site and stand productivity where mutually compatible species are involved. Studies by DeBell et al. (1988b) and Stettler et al. (1988) have demonstrated limited productivity gains based on different site and species complement trials. In Hawaii, mixed plantings of *Eucalyptus* spp. with leguminous genera, *Albizzia*, and *Acacia* have shown enhanced biomass production, particularly on nitrogen-poor soils (DeBell et al. 1985, DeBell et al. 1988b). In some cases, diminished productivity resulted, presumably due to interactions with site characteristics and species adaptability. The proportion of species mixtures and spacing may yet elevate existing productivity potential for mixed plantings on compatible sites with nutrient-deficient soils.

Pure and mixed cultural studies in the Pacific Northwest of *Populus* spp. and its leguminous complement, *Alnus rubra*,

Table 7. Survival of planted hybrid *Populus* trees by site and cultural treatment for the 1980 planting in Pennsylvania (taken from Bowersox et al. 1988)

Site	Cultural treatment	Survival <sup>a</sup> (%)				Net root-stock loss by end of each rotation
		<u>Seedling rotation</u> root age		<u>Coppice rotation</u> root age		
		1	4	5	8	
Basher	Control	84	82	76	71	11
	Irrigation	86	84	79	67	17
	Fertilization	81	71	57	40	31
	Fertilization/ irrigation	82	72	60	41	31
Morrison	Control	88	89	88	85	4
	Irrigation	82	79	78	71	8
	Fertilization	80	76	73	45	31
	Fertilization/ irrigation	80	78	75	46	32

<sup>a</sup>Based on a subsample of randomly selected planting positions.

demonstrated slight but insignificant increases in yield with mixed-species planting (Table 8) (Stettler et al. 1988b). Clonal sources of *Populus* spp., their source, and testing plot differences accounted for much of the variation between planting mixtures (Table 9). *Populus* consistently outperformed *Alnus* in mixed stands, perhaps lending to the minimal productivity gains over pure poplar plantings. It was concluded that the nitrogen-fixing qualities of red alder were severely limited by the strong competitive influence imposed by the overshadowing from the taller poplars. The study recognized the potential for improved performance with mixed cultures under certain site conditions and modified spacing schemes.

#### 4.4 SITE AND SPECIES ADAPTABILITY

Realizing the productivity potential of genetically improved species on a large land base will come only if superior genotypes are also able to sustain their yields in adverse environments. Two studies reported this year provide some information on what can be expected from superior pure clones and hybrids.

One study mentioned earlier (Section 3.1) involved tests of clonal *P. trichocarpa* collected along an east-west transect from four separate river drainages in Washington. Replicate plantations of these clonal types were established at Puyallup and Wenatchee, Washington, representative of wet and dry sites, west and east of the Cascade Range, respectively (Fig. 2). Results after 2 years showed greater growth gains in average height and diameter at the milder Puyallup site as compared with the more harshly dry Wenatchee site. Of significance, however, is the fact that ranking of clonal performance by drainage source remained consistent across these two widely different sites.

In a related study, hybrid *Populus* performance relative to parental species, *P. trichocarpa* and *P. deltoides*, from different source populations were evaluated in field trials on high- and low-quality sites near Westport, Oregon, and Pack Forest, Washington, respectively (Stettler et al. 1988b). As expected, productivity on the high-quality site was two or more times greater than on the poorer site. Hybrid crosses clearly outperformed their parental types on both sites.

Table 8. Effect of mix (pure vs mixed cottonwood/alder) on yield and basal area of Field Trial 1-b

	Pure cottonwood	Mixed cottonwood/alder	Significance
Mean yield dry Mg·ha <sup>-1</sup> ·year <sup>-1</sup> )	11.1	11.4	N.S. <sup>a</sup>
Basal area (m <sup>2</sup> /ha)	18.5	18.9	N.S.

<sup>a</sup>No significance.

Source: Stettler et al. 1988b.

Table 9. Yield of pure cottonwood vs mixed cottonwood/alder in the second rotation of Field Trial 1-b

Source code	Pure cottonwood	Mixed cottonwood/alder
	-----Dry Mg·ha <sup>-1</sup> ·year <sup>-1</sup> -----	
11	20.2	29.7
9	11.5	10.2
10	10.4	10.7
1	11.6	7.9
3	8.9	10.2
8	7.7	10.6
4	7.4	7.2

Source: Stettler et al. 1988b.

Relative growth response of hybrid *Populus* was significantly greater on the poor site, indicating a gained tolerance and adaptability to intense environmental stress brought about by hybridization. The two studies suggest that selection of clones for specific site conditions may not be necessary, but selection for superior growth will enhance growth on both good and poor sites.

#### 4.5 CLIMATE CHANGE AND GLOBAL ISSUES

Many environmental issues of global proportion have recently drawn considerable attention from scientists. Matters of energy and environment that once were only of national concern have now become urgent and international in scope. Of particular concern are the accumulation of greenhouse gases and their contribution to global warming and climate change. Leading climatologists agree on the certainty of an increase in global surface-air temperature that is likely to be felt more substantially in the midlatitudes than near the equator. Other potential climate-change effects include changes in regional precipitation patterns, seasonality, and increased natural disturbances. Efforts to characterize the response of natural ecosystems to projected global warming and climate-change trends are in their infancy, but already suggest profound ecological consequences. The most pressing issue revolves around a warming trend over the next 50 years unequalled in past millennia that may threaten the biodiversity of our planet through vegetation shifts and species extinction. Several plausible abatement strategies have been proposed, most notably the use of biomass production from woody and herbaceous crops to assimilate atmospheric CO<sub>2</sub> into carbon stored as standing biomass. This section focuses on a few of the areas of environmental concern where SRWC research and applications might play an important role in stabilizing the greenhouse effect and its associated impacts.

Energy analysts have estimated a current annual release of 5 billion tons of carbon into the atmosphere from the burning of fossil fuels. This figure does not include the amount of additional carbon input from clearing and burning existing forests that contributes another 2 to 3 billion tons annually. Using a dry-weight production

rate of about 15 Mg ha<sup>-1</sup> year<sup>-1</sup> based on *Platanus occidentalis* (Steinbeck and Brown 1976), Dyson and Marland (1979) calculated 7 million km<sup>2</sup> of plantation-grown *P. occidentalis* would be required to assimilate the yearly atmospheric input of CO<sub>2</sub> from industrial sources into woody biomass. Based on the net atmospheric CO<sub>2</sub> accumulated on an annual basis, an estimated 3 billion tons of carbon, Myers figured that only half the amount of planted land area would be required to balance the carbon budget in the atmosphere under present-day conditions (Booth 1988). In either case, the magnitude of planting area affirms the need for SRWC efficiency and technology to provide a viable abatement alternative (Marland 1988). The ongoing SRWCP monoculture trials described in Section 5 will provide important information on the feasibility of using large biomass plantations to offset CO<sub>2</sub> emissions in the United States.

Deforestation of tropical moist forests presents a threefold problem of contributing to the rise of atmospheric CO<sub>2</sub>, threatening plant diversity, and causing land degradation. The major focus of attack on the biodiversity issue remains with halting deforestation practices of tropical forests where more than half the known species are presently concentrated. Reducing the slash-and-burn practices in the tropics would preserve the existing species pool and site productivity, as well as curb the additional nonindustrial input of carbon into the atmosphere of 2 to 3 billion tons yearly. While these measures may improve matters, other solutions like massive tree-planting programs are still necessary to ameliorate the effects of site deterioration and global climate change. Information developed in the SRWCP, particularly on methods and species suitable for subtropical and semiarid conditions, could be very relevant to establishing successful tree plantations in tropical regions.

The effects of climate change on natural vegetation may involve major shifts in the geographical distribution of species ranges. As a result, many species are expected to undergo local extinction along present boundaries where physiological tolerance and competitive capacities might be exceeded under climate-change conditions. Also, findings indicate that the rate and extent of climate change may be more

rapid than the natural migration capabilities of most species will allow. Therefore, artificial regeneration may become an important method to supplement forest succession and/or to recreate natural forest communities on a megascale. Advances in plant propagation and genetic improvement techniques from SRWC applications may augment the development of climatically adaptive progeny with high yield potential (see Section 3.1). The success and experience of the SRWCP with this sort of research and technology warrant the SRWCP's involvement in research initiatives to combat global warming and climate-change impacts on our natural vegetation.

There is insufficient evidence of how global warming might exacerbate soil erosion problems, except as related to deforestation practices of fragile ecosystems in the tropics and denuded sites from catastrophic disturbances and/or regressive succession resulting from species extirpation. SRWC applications allow rapid occupation of a site such that vegetative cover and root establishment stabilize the soil base and control erosional agents.

## 5. MONOCULTURE VIABILITY TRIALS

Monoculture viability trials are operational-scale plantations of 20 ha or larger established to obtain valid data on the costs and risks of growing wood-energy feedstocks with SRWC technology. Three large-scale operations of this kind were initiated in 1986 to determine the economic viability of SRWC techniques and to identify disease and pest risks associated with large single species or monoclonal plantings. These projects also served to demonstrate SRWC feasibility and to facilitate technology transfer.

The first project links a potential wood-energy user with a highly experienced group of SRWC researchers. The project outlined is a cost-shared venture with Northern States Power Company located primarily in Minnesota, and will hereafter be referred to as the Northern States project. The project consists of one monoculture (70-ha) site plus small (4-ha) clone-site trials at 11 locations. In addition, this project utilizes *Populus* hybrids, the most studied model species in the program, and is regional in scope with 12 plantings scattered over 4 of the northern lake states. All of the plantings are in areas that are considered to have high potential for the viable production and use of wood-energy feedstocks.

The second project is with the North Carolina State University (NCSU)-Industry Hardwood Cooperative. This project is cost-shared with the Federal Paper Board of North Carolina. However, as a result of contracting with the Industry Hardwood Cooperative research staff, the SRWCP is also gaining access to information on other SRWC plantations established independently of the SRWCP. The primary site established with SRWCP funding is located on Coastal Plain "Blackland" soils owned by Federal Paper Board in eastern North Carolina, and *Liquidambar styraciflua* is the species under investigation. The second site (a 120-ha *Platanus occidentalis* SRWC plantation) was established by Scott Paper Company on upland soils in southern Alabama specifically for the purpose of providing a guaranteed supply of hardwood for their 80-MW wood-fired boiler. Access to this information results from Scott Paper Company's membership in the NCSU-Industry Hardwood Cooperative. The

third NCSU project that may provide some information on the success of large-scale SRWC plantations is a 120-ha site established by the city of Edenton, North Carolina, as part of a large Environmental Protection Agency (EPA)-funded wastewater-disposal project. The only connection to the SRWCP is that NCSU-Industry Hardwood Cooperative staff served as consultants in designing and establishing the plantation. Although they have no control over maintenance decisions, the NCSU staff have continued to monitor the site for growth and yield.

The third project is located in Iowa on Amana Society land. The Amana Society is a corporation that not only owns land but also owns several small businesses, some of which can or do use wood energy. The project is being done cooperatively with experienced SRWC researchers from Iowa State University and with staff from the Iowa State Department of Natural Resources Forestry Division and Energy Office. The Amana Society project, which is just now getting underway, will be evaluating *Acer saccharinum* on a bottomland that experiences occasional flooding. The site is typical of Iowa bottomland that was cleared at one time for farming and later used for pasture or abandoned. Details on site type preparation and maintenance procedures have been more fully described in Wright (in press).

Comparison of the data produced by these projects is being facilitated by requiring a standardized report format, which includes site descriptions, climate conditions, site preparation techniques, planting material, plantation design, maintenance procedures, and harvesting information, as well as growth and yield results. This information is input to a computerized data base on SRWC. Although the SRWC data base contains information relevant to cost, a separate data base and reporting format for cost accounting was developed cooperatively with principal investigators and economists from each of the SRWCP scale-up projects. During a workshop held at ORNL, a set of cost parameters was agreed upon and later formalized in a LOTUS® spreadsheet. In addition to the spreadsheet, detailed explanations of cost parameters are expected.

As of this writing, data on growth are only available from the two scale-up projects that established their initial plantings in spring of

1987--the Northern States project and the NCSU/Federal Paper Board project. Observational data only are available from all spring 1988 plantings. In both years, plantings were affected by drought problems. The Minnesota project was particularly affected with all plantings in regions where drought conditions were considered severe or extreme. Nevertheless some very positive results can be reported from all scale-up SRWC plantings. In eastern North Carolina first-year survival of the 1987 SRWC plantations was 89%, and first-year survival of the 1988 plantings is anticipated to be about 76%. Average first-year height growth of the 1987 *Liquidambar styraciflua* was 0.89 m. Survival and height growth of hybrid *Populus* in the Northern States project varied with severity of drought conditions, effectiveness of site preparation, clone, and soil type. The clone showing best survival and height growth at most sites in 1987 was NE308. In 8 of 11 sites, first-year survival of NE308 ranged between 80 and 98%. Height growth of NE308 was 1.34 m averaged over all sites, while best height growth was 2.3 m (Fig. 10). Those clones that performed well in 1987 continued to perform exceptionally well in 1988. Some 2-year-old trees were observed to be 5 to 7 m (Fig. 11) in height by the end of the growing season. More than one clone showed outstanding performance, but several clones performed very poorly with respect to both survival and height growth. Two sites that supported good growth of all clones in both 1987 and 1988 were located in or near the southeast corner of Minnesota where the drought was slightly less severe in both years. At the best of these sites, the landowner participated in the maintenance of the plantings, and average first-year height growth of all 10 clones was 1.7 m in 1987.

Although the scale-up research has just been initiated, some important information on technological risk is already emerging. Probably the most valuable information was that obtained on the relative performance of ten different *Populus* poplar clones under two successive years of drought. The best clones not only survived well but also demonstrated exceptional growth rates (Fig. 11). The risk of inadequate site preparation on survival and early growth was reflected in the variation of survival and growth from site to site. Tight spacing (1.2 m x 2.4 m) proved to be very high risk since extreme drought



Fig. 10. Example of height at the end of the first growing season of a hybrid *Populus* tree grown in southern Minnesota.



Fig. 11. Height growth of clone NE308 grown in South Dakota at the end of the second growing season.

conditions reduced herbicide effectiveness, and mechanical cultivation between the trees within the rows was not possible. Total mortality of most clones due to weed competition within the rows was the result. On the positive side, survival and growth of the *Populus* hybrids in the Minnesota project was quite good, while corn yields recorded 50-year lows. The Minnesota State Department of Natural Resources reported almost total establishment failure of all operational non-SRWC trees planted during 1987 and 1988. The *Platanus occidentalis* in southern Alabama showed excellent survival and growth (Fig. 12), while nearby corn fields and soybean fields were observed to be totally dried up. The results suggest that in a drought year, SRWC plantations are less risky than many farm crops.

A major reason for initiating the scale-up trials was to learn whether experimental results gained in small trials would be sustained in scale-up operations. Initial results are somewhat promising. The first-year average *L. styraciflua* height growth (0.88 m) and survival (88%) in the North Carolina monoculture were only slightly less-than-average experimental results from southern Alabama (1.0 m and 91.5%). The 1988 *P. occidentalis* survival and growth appeared similar to or better than results from experimental trials established by Scott Paper Company in 1980. In the Minnesota hybrid *Populus*, average survival (43%) of all 10 clones was much poorer than that found in previous experimental trials, while height growth was similar to experimental growth observed in Rhinelander, Wisconsin. However, the clone NE308 discussed previously had first- and second-year height growth, which greatly exceeds experimental height growth previously recorded at Rhinelander, Wisconsin, and equals the best experimental height growth found in the Pacific Northwest.

Analysis of cost information is not yet possible since, for the SRWCP projects, only first-planting-year data are currently available. It is interesting, however, to note the actual cost differences that are being reported from various sources (Table 10). Examples 1 and 3 are from the first establishment year of two of the SRWCP cost-shared projects, while example 2 is information from a corporation that has been commercially planting SRWC crops for several years. The cases are



Fig. 12. *Platanus occidentalis* at the end of the first growing season in a 120-ha SRWC plantation established in 1988 in southern Alabama by Scott Paper Company for energy purposes.

Table 10. Costs of short rotation woody crops  
plantation establishment

Category	Cost per hectare (\$) <sup>a</sup>		
	Case 1	Case 2	Case 3
Site preparation	289	266	232
Planting material	109	68	151
Planting	77	136	160
Weed control	0	53	261
Infrastructure	145	0	0
Overhead	179	11	111
Total	799	534	915

<sup>a</sup>Does not include land rent and taxes.

not being specifically identified due to the preliminary status of these data. It can be seen that there is a considerable range in the major cost categories. Cases 1 and 2 represent situations where the crews had previous experience with weed control techniques on the specific site types planted. In case 3, a considerable amount of labor was required to maintain weed control by cultivation during the first year of growth, since the best herbicide prescriptions were not yet defined, and herbicide applications were of reduced effectiveness under the drought conditions. In all cases, however, establishment costs are much lower than the cost of \$1251/ha projected for a plantation established at 20,833 cuttings/ha (Strauss et al. in press). One reason for the difference is the cost of planting material at \$548.60/ha (Blankenhorn et al. 1985). In all 3 operational cases given in Table 10, the number of cuttings established per hectare is less than 2200.

Major research challenges will be addressed over the next several years with these monoculture viability plantations. The impact of drought stress on SRWC plantations as they approach crown closure and competition stress will offer additional insight. A major question of interest will be whether the large monoculture plantings exacerbate pest and disease outbreaks and whether such infestations can be successfully controlled. Our fastest-growing SRWC trees (the hybrid *Populus*) are anticipated to be more susceptible to these problems than the other species currently being tested in scale trials. For example, the clone that is showing optimum growth in Minnesota under drought conditions (NE308) is known to be quite susceptible to septoria canker disease. The results from these trials may determine whether the growth advantages provided by the hybrid poplars are sufficient to make up for costs associated with protection of the plantations. If funding permits, these plantations will be carried through at least one full rotation; thus they will provide a good situation for testing the cost efficiency of the best harvesting equipment available by that time. Although it will take several years to collect all of this information, it should prove invaluable for determining under what conditions SRWC of hardwoods can be cost effective for supplying energy feedstocks for biofuel production.

## REFERENCES

- Blankenhorn, P. R., T. W. Bowersox, C. H. Strauss, L. R. Stover, S. C. Grado, K. R. Kessler, W. R. Kilmer, M. L. DiCola, and B. E. Lord. 1988. Economic analysis for producing *Populus* hybrids under four management strategies. Unpublished annual report submitted to DOE's Short Rotation Woody Crops Program. Pennsylvania State University, University Park.
- Blankenhorn, P. R., T. W. Bowersox, C. H. Strauss, L. R. Stover, S. C. Grado, G. L. Stimely, M. L. DiCola, and C. Hornicsar, and B. E. Lord. 1985. Net financial and energy analyses for producing *Populus* hybrid under four management strategies: First rotation. Final report for the period July 2, 1980-June 1, 1985. ORNL/Sub/79/019281/1. Oak Ridge National Laboratory, Oak Ridge, Tennessee.
- Booth, W. 1988. Johnny Appleseed and the Greenhouse. *Science* 242:19-20.
- Bowersox, T. W., P. R. Blankenhorn, and C. H. Strauss. 1988. Second rotation growth and yield of a *Populus* hybrid. IN Proc. of the IEA Task II Meeting and Workshop on Cell Culture and Coppicing, August 24-29, 1987, Oulu, Finland.
- DeBell, D. S. 1988. Activities related to poplar and willow cultivation, exploitation, and utilization: 1984-1987. Report to the 18th session of the International Poplar Commission, Beijing, China. USDA Forest Service Pacific Northwest Station, Olympia, Washington.
- DeBell, D. S., C. D. Whitesell, and T. H. Schubert. 1985. Mixed plantations of Eucalyptus and leguminous trees enhance biomass production. Res. Paper PSW-175. Pacific Southwest Forest and Range Experiment Station, USDA Forest Service, Berkeley, California.

- DeBell, D. S., M. A. Radwan, D. L. Reukema, J. C. Zasada, W. R. Harms, and R. A. Cellarius. 1988a. Increasing the productivity of biomass plantations of alder and cottonwood in the Pacific Northwest. Unpublished annual report submitted to DOE's Short Rotation Woody Crops Program. USDA Forest Service, Forestry Sciences Laboratory, Olympia, Washington.
- DeBell, D. S., C. D. Whitesell, and T. B. Crabb. 1988b. Benefits of Eucalyptus-Albizia mixtures vary by site on Hawaii Island. Res. Paper PSW-187. Pacific Southwest Forest and Range Experiment Station, USDA Forest Service, Berkeley, California.
- Dickmann, D. I., K. S. Pregitzer, and P. V. Nguyen. 1988. Net assimilation photosynthate allocation of *Populus* clones grown under short-rotation intensive culture: Physiological and genetic responses regulating yield. Unpublished annual report submitted to DOE's Short Rotation Woody Crops Program. Michigan State University, East Lansing, Michigan.
- Doyle, T. W. 1988. An evaluation of competition models for investigating tree and stand growth processes. IN Forest Growth: Process Modeling of Responses to Environmental Stress by Timber Press (in press).
- Dyson, F. J., and G. Marland. 1979. Technical fixes for the climatic effects of CO<sub>2</sub>. pp. 111-118. IN W. P. Elliott and L. Machta (eds.), Workshop on the Global Effects of Carbon Dioxide from Fossil Fuels, Miami Beach, Florida, March 7-11, 1977. U.S. Department of Energy, CONF-770385.
- Ellis, D. D., and B. H. McCown. 1988. The potential of biotechnology in the Biomass Production Program. ORNL-M-606.
- Fillatti, J. J., B. Haissig, B. H. McCown, L. Comai, and D. Riemenschneider. 1988. Development of glyphosate-tolerant *Populus* plants through expression of a mutant *aroA* gene from *Salmonella typhimurium*. pp. 243-250. IN J. W. Hanover, D. E. Keathly, C. M. Wilson, and G. Kuny (eds.), Genetic Manipulation of Woody Plants. Plenum Press, New York.

- Hall, R. B., R. D. Hanna, and E. R. Hart. 1988. Breeding *Alnus* for intensive culture of biomass for energy. Unpublished annual report submitted to DOE's Short Rotation Woody Crops Program. Iowa State University, Ames.
- Hansen, E., B. Haissig, J. G. Isebrands, C. Michler, D. Riemenschneider, and T. Strong. 1988. Increasing yields of poplar energy plantations. Unpublished annual report submitted to DOE's Short Rotation Woody Crops Program. USDA/FS North Central Forest Experiment Station, Rhinelander, Wisconsin.
- Harry & Sederoff. 1988.
- Heilman, P. E., and R. F. Stettler. 1985. Genetic variation and productivity of *Populus trichocarpa* T. and G. and its hybrids. II. Biomass production in a 4-year plantation. *Can. J. For. Res.* 15:348-388.
- Huber, D. A., B. C. Bongarten, L. R. Boring, and R. O. Teskey. 1988. Optimizing energy yields in black locust through genetic selection. Unpublished annual report submitted to DOE's Short Rotation Woody Crops Program. University of Georgia, Athens.
- Isebrands, J. G., R. Ceulemans, and B. M. Wiard. 1988. Genetic variation in photosynthetic traits among *Populus* clones in relation to yield. *Plant Physiol. Biochem* 26:427-437.
- Jarvis, P. G., and Leverenz, J. W. 1983. Productivity of temperate, deciduous, and evergreen forests. pp.234-280. IN O. L. Lange, P. S. Nobel, C. B. Osmond, and J. Ziegler (eds.), *Encyclopedia of Plant Physiology, Vol. 12 D, Physiological Plant Ecology IV*. Springer Verlag, Berlin.
- Kopp, R. E., W. A. Geyer, and W. R. Lovett. 1988. Silver maple seed sources for increased biomass production. *North. J. Appl. For.* 5:180-184.
- Land, S. B., Jr., W. W. Elam, E. B. Schultz, F. T. Bonner, and J. A. Vozzo. 1988. Early selection criteria and clonal propagation methods for increased productivity of sycamore in short-rotation energy systems. Unpublished annual report to DOE's Short Rotation Woody Crops Program. Mississippi State University, Starkville.

- Layton, P. A., and M. E. Ostry. 1989. Biotechnology and poplars: A U.S. perspective. IN Proc. of a Joint Workshop on Willow Breeding and Biotechnology Development, IEA\*Task II Meeting, September 28-October 1, 1988, Long Ashton, United Kingdom.
- Linder, S. 1985. Potential and actual production in Australian forest stands. pp. 11-34. IN J. Landsberg and W. Parsons (eds.), Research for Forest Management. Commonwealth Scientific and Industrial Research Organization, Australia.
- Marland, G. 1988. The prospect of solving the CO<sub>2</sub> problem through global reforestation. Internal report TR039 prepared for the Carbon Dioxide Research Division of the U.S. Department of Energy, DOE/NBB-0082.
- Michler, C. H. 1988. Herbicide-tolerant forest trees via in vitro selection. Agricell Rep. 10:27(4).
- Michler, C. H., and E. O. Bauer. 1988. Somaclonal variants of poplar that tolerate sulfometuron methyl. In Vitro Cell. Dev. Biol. 24(3): Part II: 52A.
- Ostry, M. E. 1988. Hybrid poplar diseases. IN Forest Insect and Disease Newsletter, June 15, 1988. Minnesota Department of Natural Resources, Division of Forestry, St. Paul.
- Preece, J. E., W. C. Ashby, P. L. Roth, C. A. Huetteman, and D. F. Bresnan. 1988a. Genetic biomass and growth analysis of clonal silver maple (*Acer saccharinum* L.) in several locations. Unpublished annual report submitted to DOE's Short Rotation Woody Crops Program. Southern Illinois University, Carbondale.
- Preece, J. E., C. A. Huetteman, W. C. Ashby, D. F. Bresnan, and P. L. Roth. 1988b. Provenance tests for biomass production using micropropagated clonal silver maple (abstract). Hort. Sci. 23:603.
- Ranney, J. W., L. L. Wright, and P. A. Layton. 1987a. Hardwood energy crops: The technology of intensive culture. J. For. 85(9): 17-28.
- Ranney, J. W., L. L. Wright, P. A. Layton, W. A. McNabb, C. R. Wenzel, and D. T. Curtin. 1987b. Short Rotation Woody Crops Program: Annual progress report for 1986. ORNL-6348.

- Rauscher, H. M., J. G. Isebrands, T. R. Cros, R. E. Dickson, D. I. Dickmann, and D. A. Michael. 1988. Simulating the influence of temperature and light on the growth of juvenile poplars in their establishment year. pp. 331-399. IN Proc. IJFRO Forest Growth Modeling and Prediction Conference, August 24-28, 1987, Minneapolis, Minnesota.
- Riemenschneider, D., B. Hassig, and C. Michler. 1988. Genetic effects on adventitious rooting in vitro in *Populus deltoides*. In Vitro Cell. Dev. Biol. 24(3): Part II: 52A.
- Sederoff, R., and D. Harry. 1988. Biomass biotechnology - A brief analysis of the relationship of biomass production and the new technology of plant genetic engineering. Unpublished final report submitted to DOE's Biomass Production Program. Oak Ridge National Laboratory, Oak Ridge, Tennessee.
- Steinbeck, K., and C. L. Brown. 1976. Yield and utilization of hardwood fiber grown on short rotations. pp. 393-401. IN Applied Polymer Symposium, No. 28. J. Wiley and Sons, New York.
- Stettler, R. F., R. C. Fenn, P. E. Heilman, and B. J. Stanton. 1988a. *Populus trichocarpa* x *Populus deltoides* hybrids for short-rotation culture: Variation patterns and 4-year field performance. Can. J. For. Res. 18:745-753.
- Stettler, R. F., T. M. Hinckley, and P. E. Heilman. 1988b. Genetic improvement and evaluation of black cottonwood for short-rotation biomass production. Unpublished annual report submitted to DOE's Short Rotation Woody Crops Program. University of Washington, Seattle.
- Stettler, R. F., T. M. Hinckley, and P. E. Heilman. 1988c. Short-rotation intensive culture of northwest hardwoods: Highlights of an integrated research program. Report prepared for the DOE Subcontractors' Workshop, August 1-5, 1988, Short Rotation Woody Crops Program, Tacoma, Washington,
- Strauss, C. H., S. C. Grado, P. R. Blankenhorn and T. W. Bowersox. Economic evaluations of multiple-rotation SRIC biomass plantations. IN Energy from Biomass and Wastes XII. Institute of Gas Technology, Chicago, Illinois (in press).

- Strauss, C. H., S. C. Grado, P. R. Blankenhorn, and T. W. Bowersox.  
Economic evaluations of optimum rotation age for SRIC plantations.  
IN Energy from Biomass and Wastes XIII. Institute of Gar  
Technology, Chicago, Illinois (in press).
- Tschaplinski, T. J., R. J. Norby, D. W. Johnson, and D. E. Todd. 1989.  
Photosynthetic rates, pigment concentrations, and nitrate  
reductase activity are sensitive bioindicators of sycamore  
response to nitrogen fertilization. IN Environmental Sciences  
Division Annual Progress Report for the Period Ending September  
30, 1988 (in press).
- Weber, J. C., R. F. Stettler, and P. E. Heilman. 1985. Genetic  
variation and productivity of *Populus trichocarpa* and its hybrids:  
I. Morphology and phenology of 50 native clones. Can. J. For.  
Res. 15:384-388.

## APPENDIX I - CONVERSION FACTORS

## ABBREVIATIONS AND EQUIVALENTS

Common Metric Units		<u>Power or heat flow rate</u>	
Length		kilowatt	kW
kilometer	km	watt	W
meter	m	Metric Unit Prefixes	
centimeter	cm	<u>Prefix Symbol Factor</u>	
millimeter	mm	exa	E 10 <sup>18</sup>
Area		peta	P 10 <sup>15</sup>
square kilometer	km <sup>2</sup>	tera	T 10 <sup>12</sup>
hectare	ha	giga	G 10 <sup>9</sup>
square meter	m <sup>2</sup>	mega	M 10 <sup>6</sup>
square centimeter	cm <sup>2</sup>	kilo	k 10 <sup>3</sup>
square millimeter	mm <sup>2</sup>	hecto	h 10 <sup>2</sup>
Volume		deka	da 10 <sup>1</sup>
cubic meter	m <sup>3</sup>	deci	d 10 <sup>-1</sup>
cubic centimeter	cm <sup>3</sup>	centi	c 10 <sup>-2</sup>
liter	L	milli	m 10 <sup>-3</sup>
milliliter	mL	micro	μ 10 <sup>-6</sup>
Mass		Metric Equivalents	
megagram	Mg	1 km	1000 m
kilogram	kg	1 m	100 cm
gram	g	1 cm	10 mm
milligram	mg	1 km <sup>2</sup>	100 ha
Density		1 Ha	10,000 m <sup>3</sup>
kilogram per cubic meter	kg/m <sup>3</sup>	1 m <sup>2</sup>	10,000 cm <sup>2</sup>
Energy, work, or quantity of heat		1 cm <sup>2</sup>	100 mm <sup>2</sup>
gigajoule	GJ	1 m <sup>3</sup>	1000 liters
megajoule	MJ	1 liter	1000 cm <sup>3</sup>
kilojoule	kJ	1 metric ton	1000 kg
joule	J	1 metric ton	1 Mg
kilowatt-hour	kWh	1 quintal	100 kg
		1 kg	1000 g
		1 g	1000 mg
		1 cal	4.1840 J
		1 cal	1.5586x10 <sup>-6</sup> hp-h
		1 cal	1.1622x10 <sup>-6</sup> kWh

## English-Metric Conversions

Length

<u>Multiply</u>	<u>by</u>	<u>To obtain</u>
miles	1.6093	kilometers
kilometers	0.6214	miles
feet	0.3048	meters
meters	3.2808	feet
inches	2.5400	centimeters
centimeters	0.3937	inches

Area

<u>Multiply</u>	<u>by</u>	<u>To obtain</u>
square miles	2.5901	square kilometers
square kilometers	0.3861	square miles
square miles	259.0000	hectares
hectares	0.0039	square miles
square feet	0.0929	square meters
square meters	10.7639	square feet
square inches	6.4516	square centimeters
square centimeters	0.1550	square inches
square yards	0.8361	square meters
square meters	1.1960	square yards
hectare	2.4710	acres
acres	0.4047	hectares

Volume

<u>Multiply</u>	<u>by</u>	<u>To obtain</u>
cords	3.6246	cubic meters
cubic meters	0.2759	cords
thousand board feet	2.3598	cubic meters
cubic meters	0.4238	thousand board ft
cubic feet	0.0283	cubic meters
cubic meters	35.3145	cubic feet
cubic inches	16.3872	cubic centimeters
cubic centimeters	0.0610	cubic inches
gallons	3.7853	liters
liters	0.2642	gallons

Mass

<u>Multiply</u>	<u>by</u>	<u>To obtain</u>
ounces	28.3495	grams
grams	0.0353	ounces
pounds	0.4536	kilograms
kilograms	2.2046	pounds
tons (2000 lb)	907.1940	kilograms
kilograms	0.0011	ton (2000 lb)
tons (2000 lb)	0.9072	tonne (Mg)
tonne (Mg)	1.1023	tons (2000 lb)

Density

<u>Multiply</u>	<u>by</u>	<u>To obtain</u>
pounds per cubic foot	16.0184	kilograms per cubic meter
kilograms per cubic meter	0.0624	pounds per cubic foot
pounds per cord	0.1251	kilograms per cubic meter
kilograms per cubic meter	7.9910	pounds per cord
tons per cord	0.2503	tonne per cubic meter
tonne per cubic meter	3.9954	tons per cord

Energy

<u>Multiply</u>	<u>by</u>	<u>To obtain</u>
calories	4.1900	joules
joules	0.2387	calories
British thermal units (Btu or MBtu)	1.0559	kilojoules (or GJ)
kilojoules (or GJ) (Btu or MBtu)	0.9470	British thermal units
horsepower-hours	0.7457	kilowatt-hours
kilowatt-hours	1.3410	horsepower-hours
Btu	0.2520	kilogram calories
kilogram calories	3.9680	Btu
kWh	3412	Btu

Power

<u>Multiply</u>	<u>by</u>	<u>To obtain</u>
Btu per hour	0.2928	watts
watts	3.4153	Btu per hour
horsepower	0.7457	kilowatts
kilowatts	1.3410	horsepower

Temperature

Fahrenheit = 1.8 [(Celsius) + 32]

Celsius = .556 [(Fahrenheit) - 32]

Kelvin = .556 [(Fahrenheit) + 459.67]

Fahrenheit = [1.8 (Kelvin) - 273.15] + 3

Cubic Volume per Area

<u>Multiply</u>	<u>by</u>	<u>To obtain</u>
cubic feet per acre	0.0700	cubic meters per hectare
cubic meters per hectare	14.2913	cubic feet per acre
cords per acre	8.9565	cubic meters per hectare
cubic meters per hectare	0.1117	cords per acre

Weight per Area

<u>Multiply</u>	<u>by</u>	<u>To obtain</u>
pounds per square foot	4.8824	kilograms per square meter
kilograms per square meter	0.2048	pounds per square foot
tons per acre	2.2417	tonne per hectare
tonne per hectare	0.4461	tons per acre
pounds per acre	0.91	kilograms per hectare
kilograms per hectare	1.1	pounds per acre

<u>Multiply</u>	<u>Costs</u>	<u>by</u>	<u>To obtain</u>
\$/ton	1.1023		\$/Mg
\$/Mg	0.9072		\$/ton
\$/MBtu	0.9470		\$/GJ
\$/GJ	1.0559		\$/MBtu

Energy per Weight or Area

<u>Multiply</u>	<u>by</u>	<u>To obtain</u>
Btu per pound	2.3244	kilojoules per kilogram
kilojoules per kilogram	0.4302	Btu per pound
Btu per pound	$5.556 \times 10^{-4}$	kilocalories per gram
kilocalories per gram	1800	Btu per pound
MBtu per acre	2.6054	GJ per hectare
GJ per hectare	0.4231	MBtu per acre

Areas and Radii of Circular Plots

Plot size in acres	Area in ha	Radius ft	Radius m	Area in F2	Area in m <sup>2</sup>
1/10	.0405	37.2365	11.3497	4356	404.67
1/5	.0809	52.6604	16.0509	8712	809.34
1/4	.1012	58.8761	17.9454	10890	1011.68
1/2	.2024	83.2634	25.3787	21780	2023.36
1	.4047	117.752	35.8909	43560	046.72

Diameter at breast height (d<sub>hb</sub>) = 4.5 feet above ground = 1.372 meters above ground

Standard U.S. Fuel Energy Values

Coal: Anthracite: High heat value (HHV) = 12,700 Btu/lb or 29,540 kJ/kg  
= 25.4 MBtu/ton (2000 lb) or 29.54 GJ/Mg

Coal: Bituminous: HHV = 11,750 Btu/lb or 27,330 kJ/kg  
= 23.5 MBtu/ton or 27.33 GJ/Mg

Coal: Lignite: HHV = 11,400 Btu/lb or 26,515 kJ/kg  
= 22.8 MBtu/ton or 26.515 GJ/Mg

Crude oil: HHV = 18,100 Btu/lb or 42,100 kJ/kg = 138,100 Btu/gallon  
= 36.2 MBtu/ton or 42.1 GJ/Mg also 5.8 MBtu/barrel (42 gallons)

Natural gas (dry): HHV at 24,700 Btu/lb or 57,450 kJ/kg = 1021 Btu/ft<sup>3</sup>  
= 49.4 MBtu/ton or 57.45 GJ/Mg

Wood (dry) at 8,500 Btu/lb\* or 19,805 kJ/kg  
= 17.0 MBtu/ton or 19.805 GJ/Mg

\*Short-rotation woody crops may vary from 6000 to 8600 Btu/lb

Useful Equivalents for Energy Comparisons

1 dry ton of wood at 8,500 Btu/lb has the approximate energy value of the following:

0.72 tons of bituminous coal,  
2.93 barrels of average-weight crude oil,  
16,642 ft<sup>3</sup> of natural gas, and  
4,981 kWh of electricity.

1 Quad = 1 quadrillion Btu or  $1 \times 10^{15}$  Btu  
=  $1.0559 \times 10^{18}$  joules or 1 exajoule

## APPENDIX II - LATIN AND COMMON NAMES OF WOODY SPECIES

Latin name	Common name
<i>Acer saccharinum</i>	Silver maple
<i>Alnus glutinosa</i>	European alder
<i>Alnus rubra</i>	Red alder
<i>Atriplex canescens</i>	Fourwing saltbush
<i>Betula pendula</i>	European white birch
<i>Elaeagnus umbellata</i>	Autumn olive
<i>Eucalyptus saligna</i>	Eucalyptus
<i>Fraxinus americana</i>	White ash
<i>Leucaena retusa</i>	Leucaena
<i>Liquidambar styraciflua</i>	Sweetgum
<i>Pinus radiata</i>	Monterey pine
<i>Pinus taeda</i>	Loblolly pine
<i>Platanus occidentalis</i>	American sycamore
<i>Populus balsamifera</i>	Balsam poplar
<i>Populus deltoides</i>	Eastern cottonwood
<i>Populus tremuloides</i>	Quaking aspen
<i>Populus trichocarpa</i>	Black cottonwood
<i>Prosopis alba</i>	Mesquite
<i>Pseudotsuga menziesii</i>	Douglas-fir
<i>Quercus rubra</i>	Northern red oak
<i>Robinia pseudoacacia</i>	Black locust