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Short Rotation Woody Crops Program: Annual Progress Report for 1986

J. W. Ranney
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P. A. Layton
W. A. McNabb
C. R. Wenzel
D. T. Curtin

Environmental Sciences Division
Publication No. 2839

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SHORT ROTATION WOODY CROPS PROGRAM: ANNUAL PROGRESS REPORT FOR 1986

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CONTENTS

Page

ABSTRACT v

EXECUTIVE SUMMARY vii

LIST OF TABLES ix

LIST OF FIGURES xi

1. INTRODUCTION 1

2. IMPROVEMENT OF BIOMASS PRODUCTION IN WOODY PLANTS 9
   2.1 TREE-LEVEL ECOPHYSIOLOGICAL GROWTH MODEL 10
   2.2 THE STAND-LEVEL ECOPHYSIOLOGICAL GROWTH MODEL 13
   2.3 COPPICE EVALUATIONS 15
   2.4 STAND COMPETITION MODELS 17
   2.5 GENETIC IMPROVEMENT 19
   2.6 SUMMARY OF BIOMASS YIELDS IN SRWCP RESEARCH PLOTS 22
   2.7 NUTRIENT STUDIES 26

3. SPECIFIC CHARACTERISTICS OF SHORT-ROTATION INTENSIVELY CULTURED WOOD 27
   3.1 SPECIFIC GRAVITY 28
   3.2 LIGNIN AND EXTRACTIVE CONTENT 30
   3.3 ASH CONTENT 30

4. HARVESTING AND HANDLING 33
   4.1 SPECIFIC DEVELOPMENTS 33

5. TECHNOLOGY TRANSFER AND RELATED ACTIVITIES 37

LITERATURE CITED 39

APPENDIX I - Conversion Factors 43

APPENDIX II - Latin and Common Names of Woody Species 45

ABSTRACT

This report describes accomplishments in the Short Rotation Woody Crops Program (SRWCP) for the year ending September 30, 1986. The program is sponsored by the U.S. Department of Energy's Biofuels and Municipal Waste Technology Division and consists of research projects at 29 institutions and corporations. The SRWCP is an integrated program of research and development devoted to a single objective: improving the productivity, cost efficiency, and fuel quality of wood energy crops as feedstocks for conversion to liquid and gaseous fuels. SRWCP directives have shifted from species-screening and productivity evaluations to large-scale viability trials of model species selected for their productivity potential and environmental compatibility. Populus was chosen the lead genera of five model species, and initial steps were taken toward organizing a Populus Research Consortium. Production yields from SRWCP research plots and coppice studies are discussed along with new efforts to model growth results and characteristics on a tree and stand basis. Structural and chemical properties of short-rotation intensive culture (SRIC) wood have been evaluated to determine the desirability of species traits and the potential for genetic improvements. Innovative wood energy crop handling techniques are presented as significant cost reduction measures. The conclusion is that new specialized wood energy crops can be feasible with the advances that appear technically possible over the next 10 years.

EXECUTIVE SUMMARY

This report is a synthesis of technical progress and activities of the Short Rotation Woody Crops Program (SRWCP) through fiscal year 1986. The SRWCP has undergone extensive metamorphosis since 1985 in response to advancing research knowledge in both the production and conversion of wood energy crops. For example, there is less emphasis on spacing/rotation field studies and species screening trials in favor of (1) more focused research on model species and (2) monoculture viability trials.

Since 1978, 142 species have received preliminary screening evaluations through SRWCP funding. However, development of SRIC technology may be best advanced at present with greater emphasis on selected or model species then on continued species screenings. The *Populus* hybrids have shown the highest productivity of any species evaluated for SRIC in the continental United States. Besides the *Populus* genera, SRWCP research efforts are being focused on other model species including *Robinia psuedoacacia*, *Platanus occidentalis*, *Liquidambar styraciflua*, *Acer saccharinum*, and *Eucalyptus* spp.

The productivity potential, ease of vegetative propagation, and wide natural range of *Populus* hybrids has made it the lead model genera. As a result, a *Populus* Consortium was formed to encourage a directed and focused exchange of ideas and study findings among nine institutions conducting basic, applied, and theoretical research on the genera. This initiative demonstrates the progress and potential that can be accomplished from cooperative efforts in advancing wood energy crop research. Already, there has been a greater integration and transfer of physiological and genetic technologies.

An evaluation was conducted to determine which of seven major regions across the United States was most highly suited for initiating scale-up SRIC monoculture viability trials. The Lake States region achieved the highest priority ranking based on a number of general environmental and technological considerations. The Southeast and Pacific Northwest, respectively, were second and third in ranking priority as a function of high productivity and low risk factors. The Great Plains states followed with abundant private interest and land availability. The Northeast, while low in overall priority, remains an important region for SRIC with its great energy needs and limited fuel alternatives.

In previous years, extensive economic analyses have been conducted to estimate concept viability and aid in focusing research. This year such evaluations were conducted by subcontractors on specific sites. ORNL concentrated on issuing Requests for Proposals (RFP), negotiating contracts, synthesizing growth data, developing conceptual growth models, linking to conversion pathways, and responding to DOE inquiries. Finite accomplishments for the year have been:

- A stand-level growth model based on programmatic data was developed.
- A tree-level physiological growth model based on leaf photosynthesis and carbon allocation was developed.
- *Populus* was selected as the lead genera (of five model species), and initial steps were taken toward organizing a *Populus* research consortium.
- It was determined that single, longer rotations of 4 to 6 years generally produce more biomass than 2 shorter rotations (i.e., 2- to 3-year rotations, including 1 coppice rotation) totaling the same number of years. Second-year productivity of coppice is often extremely high.
- A technique for significantly reducing severance costs for small-diameter trees was verified.
- Links were made with conversion technology researchers to help define desirable traits for improvement through genetics, culture, and materials handling.
- Somaclonal screening resulted in the isolation of putative herbicide-tolerant tree tissues.
- The Lake States area was identified as the top priority region for wood energy crop development.
- Two requests for proposals, one for model species genetics and physiology research and the other for monoculture viability tests, were released for competitive bids; awardees were selected.

LIST OF TABLES

Table		Page
1	Short Rotation Woody Crops Program projects	3
2	Short Rotation Woody Crops Program planned projects	6
3	Most recent yield data as of March 1986--experimental yields based on at least 100 trees per replicate	24
4	Most recent yield data as of March 1986--exploratory yields based on less than 100 trees per replicate	25
5	Characteristics of 4-year-old hybrid *Populus* biomass components	29
6	Effects of cultural treatments on nutrients in SRIC wood	31
7	Spacing and tree size influence harvest costs, as shown for the Canadian-designed FB-7 short-rotation harvester (Curtin 1986)	33

LIST OF FIGURES

Figure		Page
1	Research plan for the Short Rotation Woody Crops Program	2
2	Short Rotation Woody Crops Program project locations	5
3	General structure of a tree-level ecophysiological growth model for Populus developed by the USDA Forest Service in cooperation with Michigan State University and the University of Washington.	11
4	Computer output generated by a tree-level ecophysiological model showing leaf orientation from the side and top	12
5	Relationship of total biomass produced at time (t) as a function of total radiant energy absorbed. Solid line indicates maximum slope of the data based on the irrigation and fertilization treatment; the dashed line indicates the minimum slope based on the control treatments	14
6	(a) Frequency distribution of 42 comparisons of age 2 coppice yields to age 2 establishment yields, with the results ranked and divided into percentile groups. The percent coppice yield increase was calculated as follows: (2C - 2E yields/2E yields) x 100. (b) Frequency distribution of 48 comparisons of total yields obtained by harvesting every 2 years against yields harvested at age 4, with the results ranked and divided into percentile groups. The percent coppice "system" yield increase was calculated as follows: (2E + 2C yields - 4E yields/4E yields) x 100.	16
7	A size-density relationship for SRIC trees based on data sets where self-thinning (mortality) had begun to occur. The maximum size-density relationship is estimated by eye and is calculated to have the equation ln W = ln 13.4-1.25 ln p, where W = weight and p = density	18
8	Leaf sections of Populus hybrid clone NC-5339 were dipped in several levels of the herbicide glyphosate	20
9	Biomass crusher developed by the Forest Engineering Research Institute of Canada	35

1. INTRODUCTION

This report is a summary of both technical progress and direction within the Short Rotation Woody Crops Program (SRWCP) during 1986. This research program, sponsored by the Biofuels and Municipal Waste Technology Division, U.S. Department of Energy (DOE), has the goal of increasing the availability of woody biomass for energy. Short-rotation intensive culture (SRIC) of woody crops was identified in 1977 as the major initiative for program research. Developing SRIC feedstocks will (1) help ensure against interruption of U.S. energy supplies, (2) diversify U.S. energy resources in meeting total energy demands, (3) avoid adverse impacts on wood-based industries, and (4) offer economical alternatives to fuels that have environmentally undesirable effects or are regionally limited by cost or inadequate supply. The SRWCP is managed for DOE by the Environmental Sciences Division (ESD) of the Oak Ridge National Laboratory (ORNL).

The ESD conducts both program management and supportive research for the SRWCP. Management activities consist of coordinating and directing a national research and development program in wood energy crop production. Research conducted at ESD focuses on energy crop nutrient cycling, growth modeling, physiology, programmatic data synthesis, economic evaluation, and international cooperation. The subcontracted work in the SRWCP supports research on the production of new wood energy crops for use as feedstocks for conversion to liquid and gaseous fuels. Improved productivity, cost-effectiveness, environmental acceptability, and feedstock quality are the measures of progress, whereas research thrusts are in genetics/biotechnology/physiology, cultural aspects, harvest/handling, biomass composition, and economics (see Fig. 1).

This report synthesizes the status of research and development of SRIC for energy. Progress reported has come from 19 institutions and agencies that participate in the SRWCP (see Table 1 and Fig. 2). New projects, some already initiated as a result of two RFPs in FY 1986 (Table 2), are not advanced enough to contribute information for this report. Work by other institutions is discussed, since the research sponsored by DOE is complemented by other U.S. research as well as international research and development activities that contribute to improving SRIC viability.

Recent annual reports have devoted their attention to spacing-rotation relationships, economics, and the basic concepts underlying SRIC. These issues continue to be important areas of research for the SRWCP, resulting in several important conclusions regarding productivity gains and cost reductions:

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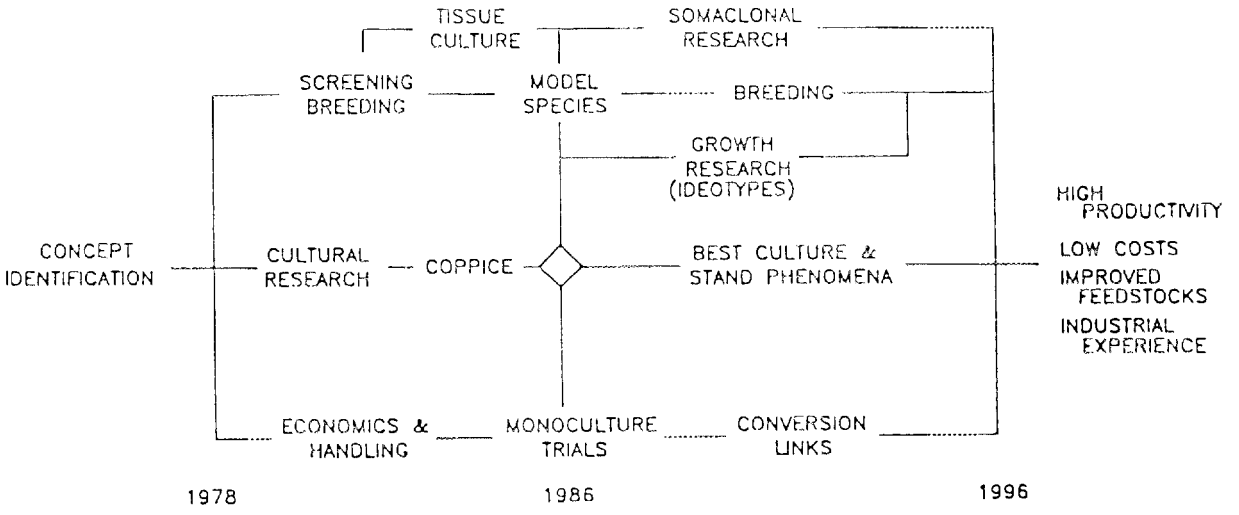

Fig. 1. Research plan for the Short Rotation Woody Crops Program.

Table 1. Short Rotation Woody Crops Program projects

Institution	Investigator	Title
BioEnergy Development Corporation	T. B. Crabb	Eucalyptus plantations for energy in Hawaii
Crown Zellerbach Corporation	D. Rice	Short-rotation intensive culture program
Energy/Development International	S. Hale, Jr. R. D. Kirmse	Species screening and genetic selection at sites in Arizona, New Mexico, and Texas
University of Florida	D. L. Rockwood	Woody species for biomass production in Florida
Iowa State University	R. B. Hall	Breeding *Alnus* for intensive culture of biomass for energy
Kansas State University	W. A. Geyer	Great Plains energy forest
Michigan State University	J. W. Hanover	Tree species and management strategies for biomass production in the Lake States
North Carolina State University	D. J. Frederick R. C. Kellison R. Lea	Silvicultural and harvesting systems for producing fuels from woody biomass in the southeastern United States
Oklahoma State University	C. G. Tauer	Evaluate *Populus* selections for fuelwood
Pennsylvania State University	P. R. Blankenhorn T. W. Bowersox C. H. Strauss	Economic analyses for coppice dynamics for a *Populus* hybrid grown under four management strategies and genetic variation in NE parentages
Plant Resources Institute	C. M. McKell E. S. Wurtele M. Balandrin	Tissue culture of elite biotypes of *Atriplex canescens* as a short-rotation crop
Tennessee Valley Authority	D. T. Curtin	Short-rotation woody crops harvesting and field handling

Table 1. (continued)

Institution	Investigator	Title
Texas A&I University	P. Felker	Production of woody biofuels from mesquite
Tuskegee University/Carver Research Foundation	M. E. M. Tolbert	Nutrient optimization in short-rotation energy plantations
USDA FS North Central Forest Experiment Station	E. A. Hansen	Increasing yields of *Populus* energy plantations
USDA FS Pacific Northwest Forest and Range Experiment Station	D. S. DeBell	Increasing the biomass production of alder and cottonwood plantations in the Pacific Northwest
USDA FS Pacific Southwest Forest Experiment Station	C. D. Whitesell	Eucalyptus plantations for energy production in Hawaii
University of Washington	R. F. Stettler	Indo-U.S. poplar studies
University of Washington/ Washington State University	R. F. Stettler P. E. Heilman	Genetic improvement of black cottonwood for short-rotation coppice culture

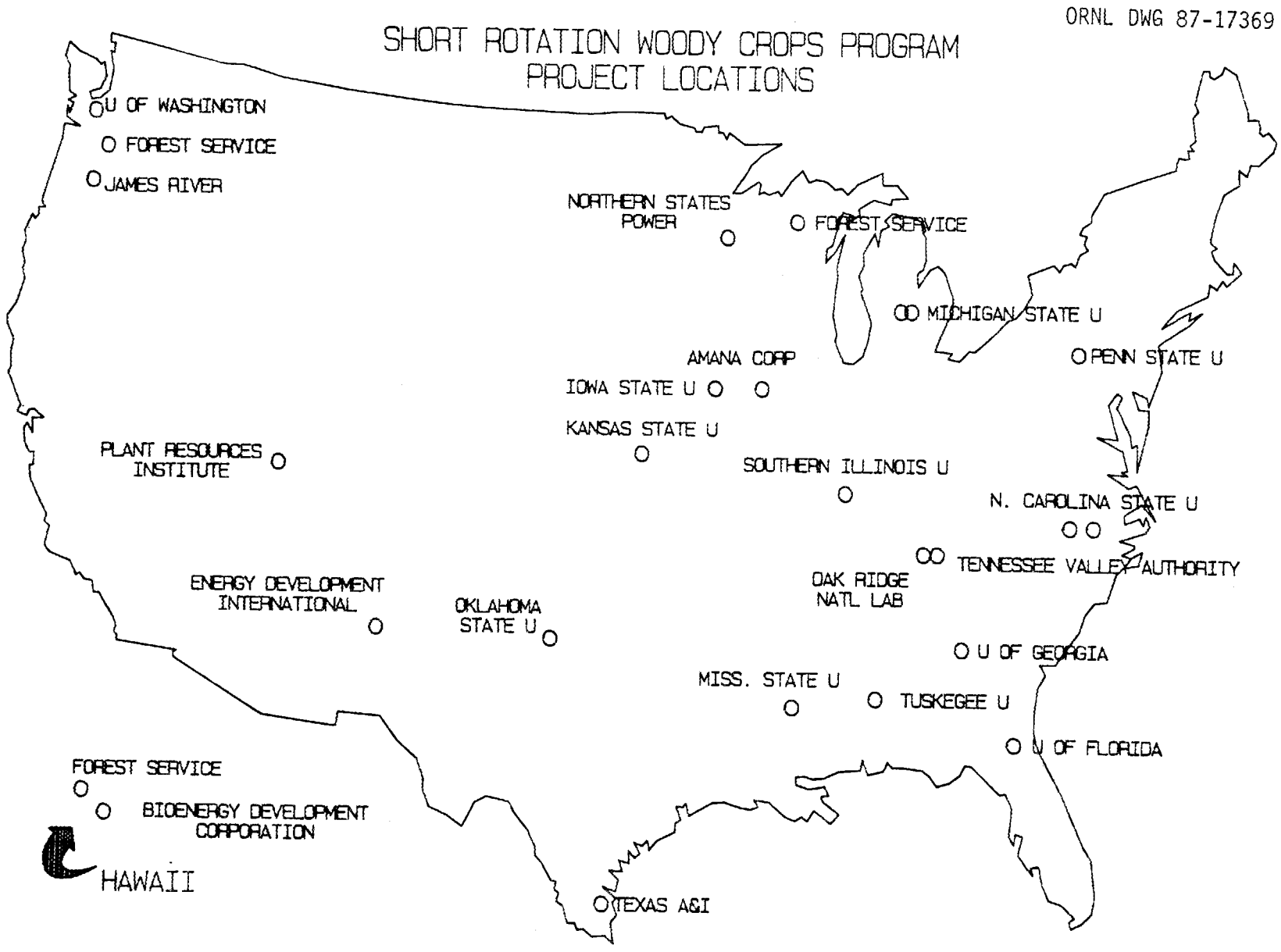

Fig. 2. Short Rotation Woody Crops Program project locations.

Table 2. Short Rotation Woody Crops Program planned projects

Institution	Investigator	Title
Amana Society/Iowa State University	D. Shoup	Monoculture viability trials
University of Georgia	B. C. Bongarten	Optimizing energy yields in black locust through genetic selection
Michigan State University	D. I. Dickmann	Net assimilation and photosynthate allocation of *Populus* clones grown under SRIC
Mississippi State University	S. B. Land, Jr.	Early selection criteria and clonal propagation systems
North Carolina State University/First Colony Farms	R. Lea	Monoculture viability trials
Northern States Power/USDA FS North Central Station	L. D. Ostlie	Monoculture viability trials
Southern Illinois University	W. C. Ashby	Genetic biomass and growth analysis of clonal silver maple in several locations
University of Washington/ Crown Zellerbach Corp.	W. A. Atkinson	Monoculture viability trials

Major increases in productivity rates will come through genetic manipulation of growth functions, tree architecture, and a tree's ability to cope with environmental stresses. For example,

1. Growth functions within a tree and within a monoculture must be better understood to enable research prioritization.

2. New and more rapid methods for genetic research can now be used in combination with classical approaches to attain desired ends.

3. Tree improvement, biotechnology, and defining the genetic variability of wood energy crops must be focused on the highest priority species and regions to provide significant advances for private sector scrutiny.

Major cost reductions must be made primarily through a combination of genetic advances and wood-handling improvements. For example,

1. Harvest, handling, and packaging for transport are areas where costs can be most efficiently reduced through innovative recombinations of forest and agricultural engineering.

2. Genetic manipulation, while increasing productivity, must also concentrate on ways of making crops easy to manage (minimizing cultural and financial crop management costs such as herbicides, fertilizers, plantlet cost, pesticides, irrigation, etc., on a wide variety of sites).

3. Improving energy traits (and thereby productivity and cost) will rely on improved handling methods (physical treatment) as much as on the genetic manipulation of wood composition for conversion efficiencies.

These findings have played heavily in the presentation of material in this report, which contains the rationale for the research priorities and direction in which the SRWCP is now headed. The next few years are expected to be similar to FY 1986 (see Fig. 1) in that they will see (1) the synthesis and conclusion of much of the spacing-rotation research; (2) preparatory research in genetics, physiology, and biotechnology for prioritizing genetic traits for improvement; (3) coordination with biomass conversion technologies to assess important wood traits for improvement; (4) breeding and genetic improvement of model species as a result of the foregoing; (5) evaluation of nutrient use efficiency; and (6) opportunistic studies of equipment for improved SRIC handling.

The sections that follow begin with the more basic areas of research in genetics and physiology, progress toward the more applied aspects of culture, energy traits, harvesting and handling, and conclude with technology transfer activities. All of these topics overlap with others and are presented in recognition of this fact.

2. IMPROVEMENT OF BIOMASS PRODUCTION IN WOODY PLANTS

Growth (productivity) of wood energy crops is influenced by a complex set of environmental and genetic variables. Much of the early SRWCP research was oriented toward obtaining a general understanding of species differences in growth patterns and a more detailed understanding of the effect of site, stand characteristics, and cultural treatments on productivity levels (Ranney et al. 1986). The research was valuable in that it identified promising species with considerable genetic variability, and also demonstrated that site amendments and intensive management can result in significant yield increases. Further improvements in the productivity of SRIC stands will come by closely integrating studies of genetic variability with evaluations of the effects of site characteristics and cultural treatments on biomass production.

A major accomplishment in FY 1986 was the release of a Request for Proposals (RFP) for work on model species to initiate the necessary integrated research approach toward improving productivity. Successful bidders to the RFP have proposed new work on Populus spp., Acer saccharinum, Platanus occidentalis, and Robinia pseudoacacia*. The emphasis on the model species focuses SRWCP research toward identifying and understanding what characteristics make SRIC stands more effective at "collecting" solar energy and what parameters affect dry matter partitioning ("stored" solar energy in the tree or stand). Characteristics and parameters must be well understood to target traits for genetic improvement.

Research is being conducted to develop two different but complementary computerized ecophysiological growth simulation models to better understand growth processes and to offer specific direction for the genetic improvement of wood energy crops. At the level of the individual tree, J. G. Isebrands of the USDA Forest Service North Central Forest Experiment Station (USDA-NCFES) is coordinating an effort within the SRWCP to develop an ecophysiological growth model for Populus. Field studies to test and verify the model are or will be ongoing at three institutions under contract to the SRWCP. These include the USDA-NCFES in Rhinelander, Wisconsin; the University of Washington; and Michigan State University.

At the stand level, modeling efforts were initiated jointly between ORNL, the Commonwealth Scientific and Industrial Research Organization of Australia, and others using the data generated in the SRWCP. Research currently being conducted at the USDA Forest Service Pacific Northwest Forest and Range Experiment Station (USDA-PNW) in Olympia, Washington, at the USDA-NCFES in Rhinelander, and at Pennsylvania State University

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*Latin names are used throughout this report; common names are provided in Appendix B.

should contribute strongly to improving the model. Both of these models will be described in more detail.

2.1 TREE-LEVEL ECOPHYSIOLOGICAL GROWTH MODEL

The tree-level ecophysiological growth model for Populus is unique in that it maintains the individual leaf as the principal biological unit for photosynthetic production (Michael 1984; Michael et al. 1985). The model uses actual field data to determine the effect of leaf orientation, light interception, and temperature on the photosynthate production of individual leaves, and then integrates the photosynthate from all leaves and distributes them to the competing growth centers of the tree. Total tree production is estimated by combining the hourly and daily net photosynthate production (i.e., photosynthesis loss respiration) of individual Populus leaves, the distribution of the accumulated photosynthates throughout the plant, respiration of plant components, and conversion of photosynthates into dimensional growth. The general structure of the ecophysiological model for poplar is given in Fig. 3. The model, although complex, can run on any MS-DOS-based microcomputer equipped with a hard disk. Once the site and microclimatic conditions are defined for a particular environment, the model requires relatively few input variables to describe the morphological and phenological characteristics of a clone. The model then quickly generates an hourly report on total cumulative photosynthesis per leaf and per tree. Through an iterative process, the model can provide an estimate of the biomass production of the clone for the year, as well as other dimensional output, such as height, diameter, and volume.

The tree-level model is expected to be a useful tool to geneticists for identifying juvenile traits in Populus that strongly influence yield. The present model is limited to a 1-year-old tree with less than 100 leaves, but even at this stage, early selection criteria provided by this model can be helpful for breeders. The model provides a graphic output of the leaves to enable the user to visualize the effects of changes in leaf orientation and size on solar radiation interception and photosynthate production (Fig. 4). The model can be used to test hypotheses regarding how modification in crown architecture and carbon allocation patterns may affect first-year production rates in a given environment. It can also help test how a given clone of specific crown architecture performs under different environmental conditions--including stress. Thus, the model can be used to design the "ideal" tree for a particular environment. If field-tested clones perform according to model predictions, the model could be used to reduce the number of clones that are field tested in a given environment. At this stage of development the model does not yet satisfy all the needs of the SRWCP because it cannot predict the growth of larger trees and cannot assess how interactions between trees in a stand affect total production per unit area. The model could be expanded to address those needs, or it could be linked with a stand-level model to take advantage of the strengths of both approaches.

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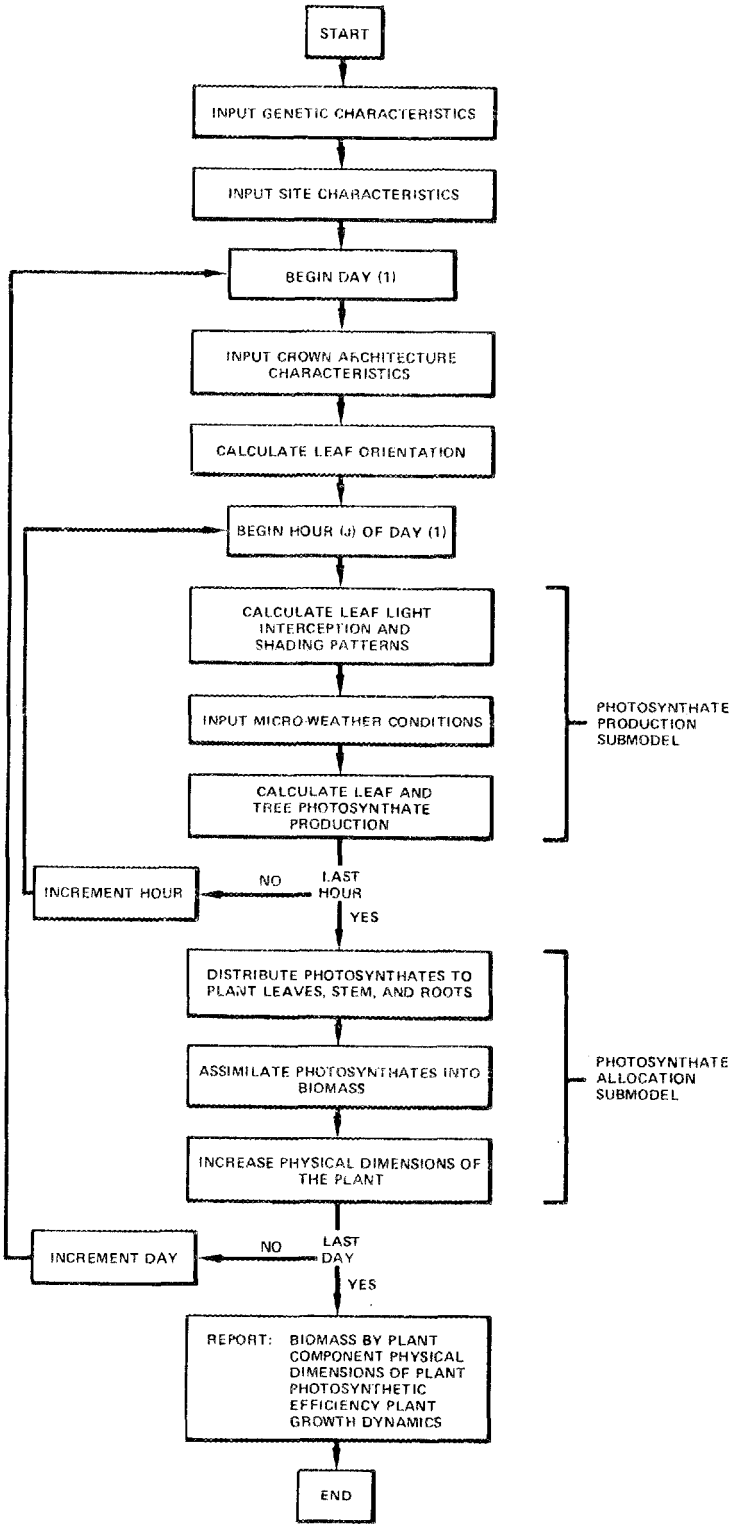

Fig. 3. General structure of a tree-level ecophysiological growth model for Populus developed by the USDA Forest Service in cooperation with Michigan State University and the University of Washington.

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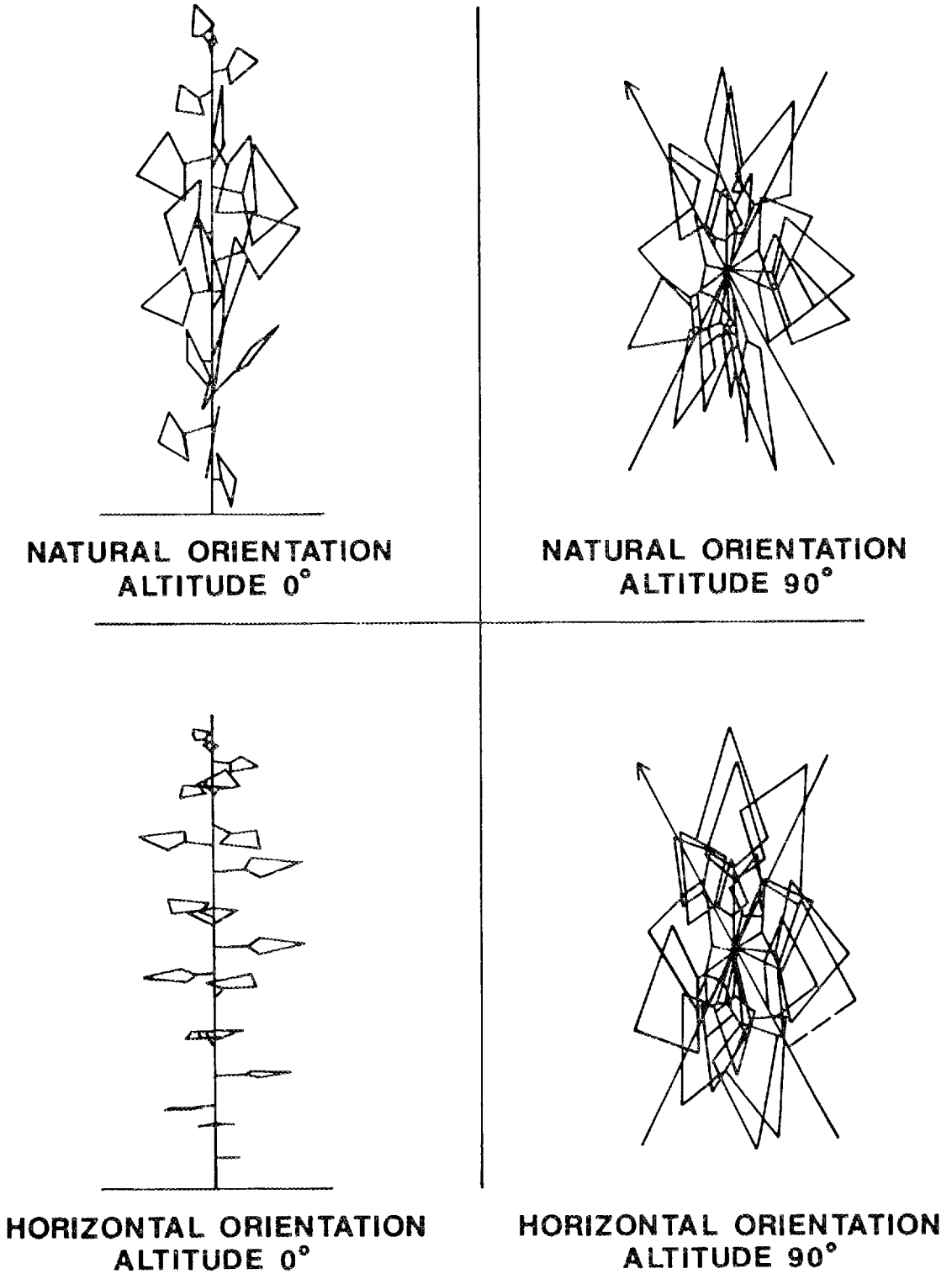

Fig. 4. Computer output generated by a tree-level ecophysiological model showing leaf orientation from the side and top.
Source: Hansen et al. 1986.

2.2 THE STAND-LEVEL ECOPHYSIOLOGICAL GROWTH MODEL

The premise of the stand-level ecophysiological conceptual model is that dry matter production in plant communities is proportional to the radiant energy absorbed by the canopy. The model developed from this premise differs from the tree-level model in assuming that the canopy of a stand can be adequately described in a simplistic manner. Model development was performed by J. J. Landsberg, a senior scientist with the Division of Forest Research in the Australian Commonwealth Scientific and Industrial Research Organization, while on sabbatical at Oak Ridge National Laboratory. The basic equation of the model is

$$\frac{dW_T}{dt} = \mathcal{E} \phi_{s.abs}, \qquad (1)$$

where W_T is net dry matter (biomass), t is time, $\mathcal{E}$ describes the efficiency with which the crop converts radiant energy (light) into biomass, and $\phi_{s.abs}$ is the absorbed flux of short-wave radiant energy**. The data required to test the conceptual model includes estimates of biomass increments per unit ground area over some suitable time interval and measurements or estimates of radiant energy absorbed. Since measurements of radiant energy absorbed are not readily available, a relatively simple radiation interception model is used to estimate radiant energy absorbed. The radiation interception model requires information on the dynamics of leaf area development over the growing season, but no other canopy parameters. Where frequent measurements on leaf area index are not available, the time course of leaf area index over a season can be simulated using an equation constrained by maximum leaf area, the date of leaf emergence, and the end of leaf fall. Once total absorbed energy is calculated, it is plotted against total aboveground biomass produced (stems, branches, and leaves). If the data conform to the conceptual model by producing a straight-line relationship, then the efficiency of converting of radiant energy into biomass can be determined. Data from Pennsylvania State University (PSU) (Fig. 5) and from the USDA-NCFES produced the expected straight-line relationships. An energy conversion efficiency of 0.00016 kg/MJ was estimated based on 1-year-old production data from PSU. For 2-year-old and older crops, data from both PSU and USDA-NCFES resulted in a conversion efficiency of 0.0007 kg/MJ for the best cultural conditions. A limitation of the model is that there is no accounting for energy allocation to roots. It is speculated that one reason for the lower apparent conversion efficiency of plants in the first year of growth is that much of the absorbed energy is being partitioned into root dry matter.

**Metric units are used throughout this report; conversion factors are provided in Appendix B.

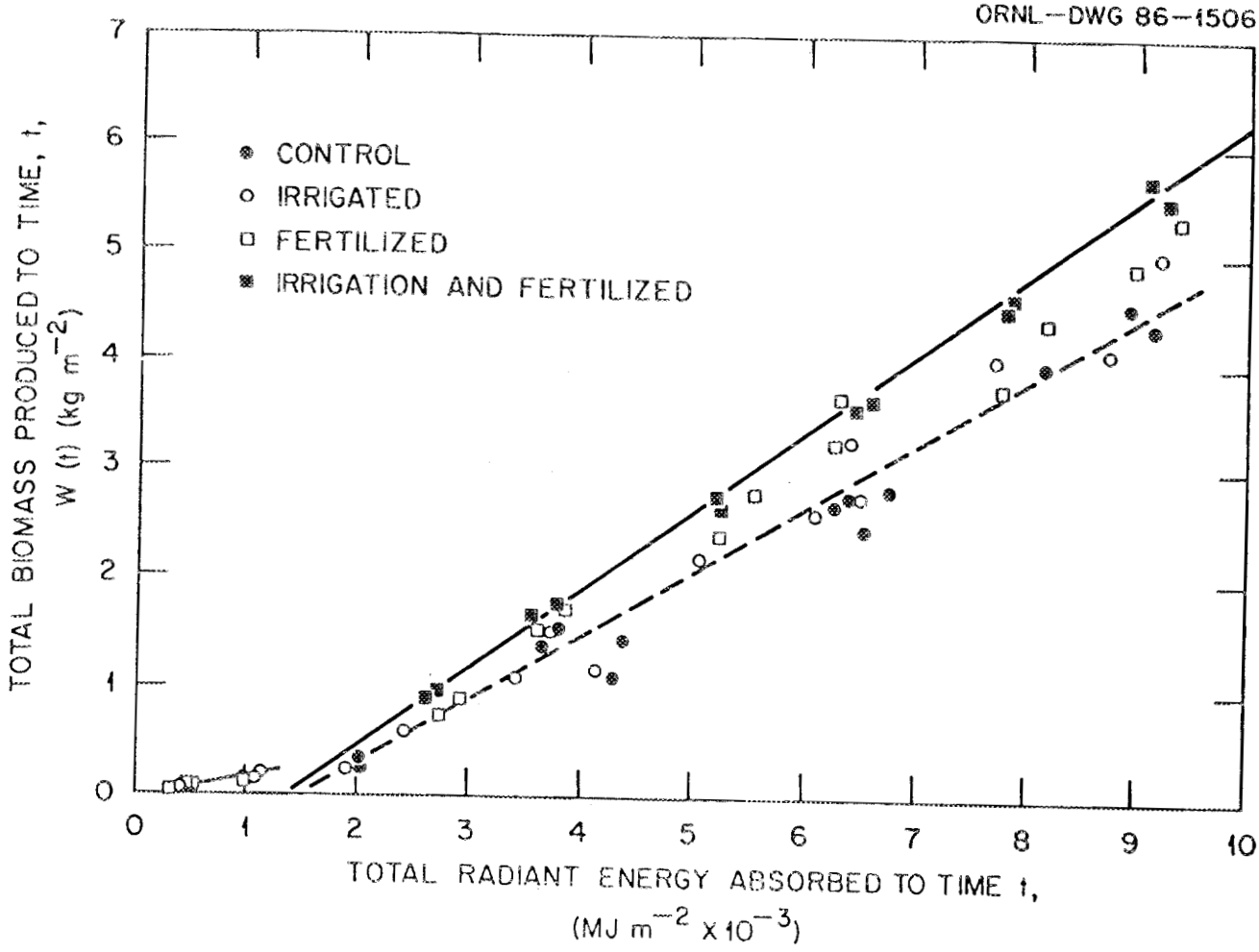

Fig. 5. Relationship of total biomass produced at time (t) as a function of total radiant energy absorbed. Solid line indicates maximum slope of the data based on the irrigation and fertilization treatment; the dashed line indicates the minimum slope based on the control treatments. (Original data from Blankenhorn et al. 1986a.)

The data from PSU and USDA-NCFES were used to parameterize a computer simulation model that calculates the total dry matter produced (based on estimates of absorbed energy) and partitions the dry matter into leaves and stems (including branches). The simulation process demonstrated that dry matter partitioning to leaves must be high early in the growing season in order to produce the leaf masses actually observed in stands at PSU and USDA-NCFES. This agrees with carbon allocation patterns determined in ^{14}C tracer studies (Isebrands and Nelson 1983). The growth curves produced by the simulation model provide realistic crop estimates for Wisconsin and Pennsylvania. Although in theory a stand-level model such as this could predict yield obtainable from any area (with input of actual radiation data for that area), the model needs to be tested with other data bases and factors (e.g., fertility levels, density) affecting the parameter values investigated before it can be used with any confidence in predicting obtainable yields in a given area. However, the model can be used now to perform sensitivity analysis such as evaluating the effect of changing radiation levels or leaf area dynamics on dry matter production. Since the parameters that describe leaf area dynamics (e.g., dates of leaf emergence and leaf fall and maximum leaf area) are traits under genetic control, this stand-level model can also be useful to geneticists in establishing ideal traits for maximizing productivity.

2.3 COPPICE EVALUATIONS

Yield evaluations between coppice regrowth and first-rotation SRIC stands and harvesting schedules continue to be an important consideration within SRWCP. Comparisons of observed first-rotation and coppice yields were made with data sets [Fig. 6, (a) and (b)] derived primarily from SRWCP contractors. The data sets include *Populus* data from Pennsylvania and Washington (Blankenhorn et al. 1986b, Heilman and Peabody 1981, Hansen et al. 1986); *P. occidentalis*, *Quercus phellos*, and *Liquidambar styraciflua* data from Alabama (Torreano 1986, Torreano and Frederick, manuscript being revised); *P. deltoides* and *Acer saccharinum* data from Kansas (Geyer 1981, Geyer 1986); *P. occidentalis* data from Georgia (Steinbeck and Brown 1980) and Mississippi (Kennedy 1980); and *Salix* data from Ireland (McElroy and Dawson 1986).

Data from the SRWCP suggest that coppiced minirotations (2 years or less) at best equal but do not exceed the productivity rate of the establishment growth in short-rotation (3-10 years), intensively cultured hardwoods on an average annual basis. In trials where rotation lengths of 2 and 4 years were imposed, the 2-year rotation treatment resulted in total yields equal to or lower than the 4-year establishment rotation treatment in 40 of 48 comparisons. Coppice systems with rotation lengths greater than 2 years, and single rotation systems followed by replanting of genetically improved stock need to be considered as options for short-rotation, intensively cultured (SRIC) systems. SRIC should be designed to maximize biomass production by using proper weed control, selected species or clones, and optimum fertilizer and water for the most appropriate rotation length and density strategy. When such practices are followed, increased yields will be obtained.

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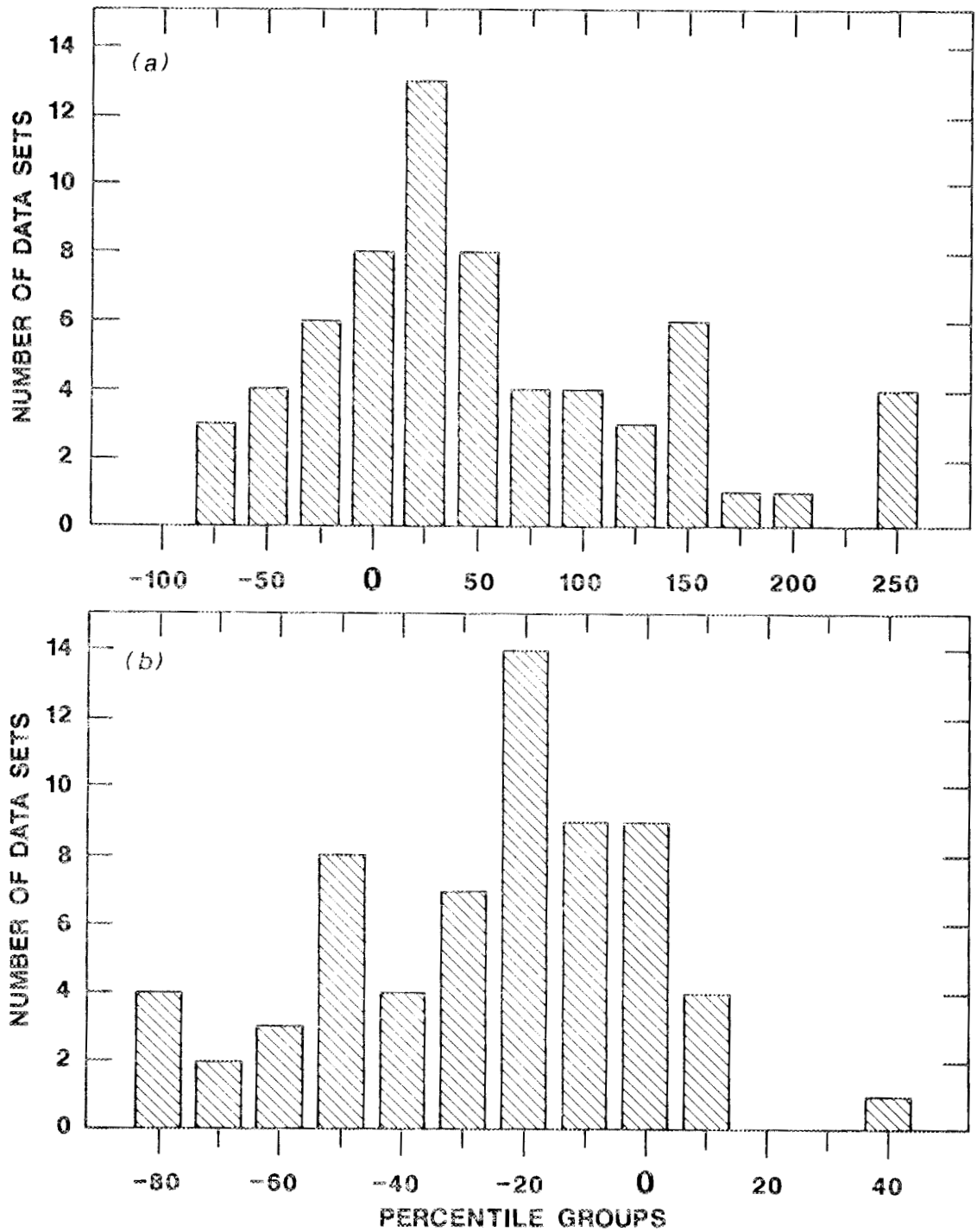

Fig. 6. (a) Frequency distribution of 42 comparisons of age 2 coppice yields to age 2 establishment yields, with the results ranked and divided into percentile groups. The percent coppice yield increase was calculated as follows: (2C - 2E yields/2E yields) x 100. (b) Frequency distribution of 48 comparisons of total yields obtained by harvesting every 2 years against yields harvested at age 4, with the results ranked and divided into percentile groups. The percent coppice "system" yield increase was calculated as follows: (2E + 2C yields - 4E yields/4E yields) x 100.

2.4 STAND COMPETITION MODELS

An understanding is needed of stand competition processes to select species and clones tolerant to competition and to optimize densities and rotation lengths for obtaining high yields in both seedling and coppice stands. Competition is, therefore, seen as the integrating phenomenon for individual tree and stand-level models. Our current approach to evaluating competition processes (and its effect on production levels) is to look at regression relationships between density and parameters that are affected by density, such as average tree weight or diameter breast height. This approach has been used successfully to develop management schemes for species such as Pinus radiata (Drew and Flewelling 1977) and Pseudotsuga menziesii (Drew and Flewelling 1979). These and other investigators have found that maximum size-density relationships normally conform to a relationship that has been labeled the -3/2 power law of self thinning. Negative three-halves is the slope of the line that estimates maximum mean tree weight as a function of density in stands where substantial mortality is occurring, thus maintaining the maximum condition.

Based on a preliminary analysis of data from SRIC stands where mortality has been observed, a similar size-density relationship may exist for several hardwood species (Fig. 7). A relatively small proportion of the growth information generated by the SRWCP was suitable for this analysis since most stands are being harvested before competition-induced mortality is evident. Using more suitable data from stands with spacings (densities) ranging from 1,000 to 100,000 trees per hectare, the resultant slope of the line was somewhat less (-1.25) than would normally be expected (-1.5) from the 3/2 generalized power law. Data from some specific density ranges (20,000 to 50,000 trees per hectare) did not conform so well. Thus, the relationship is not sufficiently substantiated by the available data to use it for making management decisions. However, the analysis suggests that different hardwood species may have relatively similar size-density relationships. The species evaluated (Populus spp., Eucalyptus spp., Alnus rubra, Elaeagnus umbellata, and Platanus occidentalis) all share a trait of intolerance to competition (especially shading). Similar evaluations need to be made with SRIC species that are more tolerant to competition, such as Acer saccharinum, and with improved genotypes of intolerant species. One example of an improved genotype plotted on the graph (at approximate density of 7000 trees per hectare) shows the maximum size exceeding the predicted value before any mortality is observed. This type of result suggests that improved competition tolerance and/or improved growth characteristics will either increase the size of the trees before stands reach a self-thinning phase or that the self-thinning phase will be reached sooner.

The use of maximum size-density relationships to evaluate competition or stockability will be more meaningful when applied to data from a single species or clone and cultural treatment at a wide range of densities. Such data are currently being generated for Populus clones and Alnus rubra families by the USDA Forest Service in the Pacific Northwest and

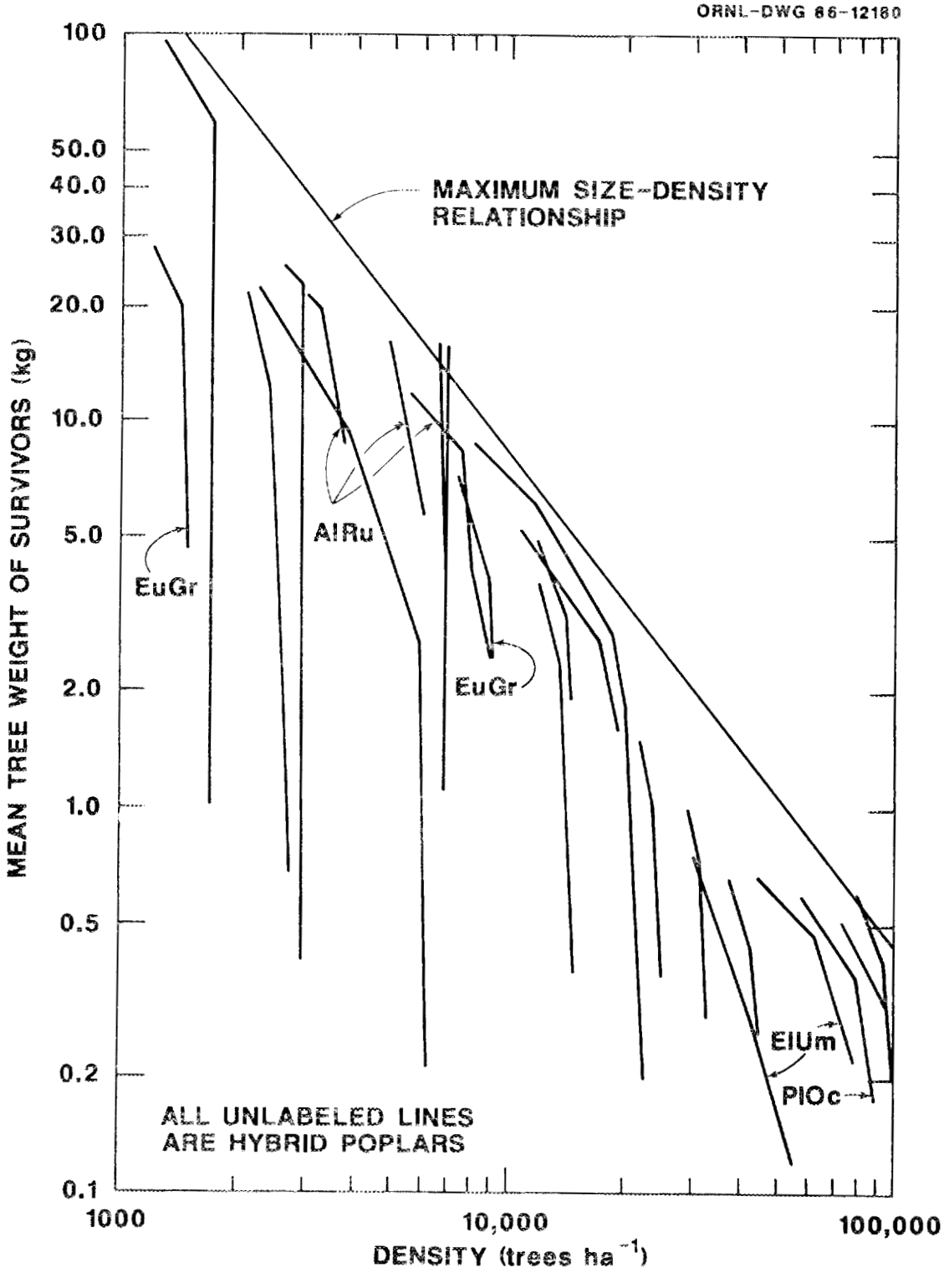

Fig. 7. A size-density relationship for SRIC trees based on data sets where self-thinning (mortality) had begun to occur. The maximum size-density relationship is estimated by eye and is calculated to have the equation $\ln W = \ln 13.4 - 1.25 \ln p$, where W = weight and p = density.

the North Central regions. These relationships could be very helpful in developing cost-effective management strategies for SRIC crops.

2.5 GENETIC IMPROVEMENT

Advanced genetic improvement of hardwood species for energy production is continuing. During the last year there were several significant accomplishments that will be discussed later. Biotechnology, using screening for herbicide tolerance and disease resistance, has provided one of these accomplishments. Biotechnology, using gene insertion, is less promising for short-term gains because of a lack of genes with known responses in trees, costs, and government regulation of field trials. For example, in the last year, a gene was inserted into a tree at an estimated cost of $1 million.

The USDA-NCFES tree improvement efforts have been concentrated on collecting and testing three species of Populus for use in the Lake States area. The species are Populus trichocarpa, P. deltoides, and P. balsamifera. Populus balsamifera is a relatively new addition to their breeding program. It was added because of its native growth, resistance to diseases, and desirable energy traits. Over 3000 clones of P. trichocarpa are being tested in this program. Growth, cold tolerance, and disease resistance (especially to septoria canker) are factors considered in the screening and selection of clones for future breeding or release to the public.

Disease is perhaps the most serious biological risk. An in vitro screening method using leaf discs exposed to a spore suspension of the septoria pathogen in a nutrient agar medium has been developed by M. E. Ostry, USDA-NCFES, St. Paul, Minnesota. Leaf discs with 50% or less necrosis after 20 days of exposure are considered resistant. If high correlations are found to exist between field tests and the leaf disc screening method, this procedure can be used to quickly and inexpensively screen clones for resistance to septoria canker. Hybrid poplar clones with P. trichocarpa as one of the parents are generally considered highly susceptible to infection by the septoria fungus (Hansen 1983). Therefore, confirmation of the in vitro screening methods and their effectiveness will enhance the use of P. trichocarpa and its hybrids.

Weeds are major factors affecting successful hardwood plantation establishment and early growth. Hardwoods are extremely sensitive (vulnerable) to currently registered herbicides (Cantrell 1985); therefore, weed control is a serious management problem. Somaclonal screening is used by the USDA-NCFES to test for herbicide resistance in Populus spp. Figure 8 shows a shoot forming from a leaf that was dipped in toxic levels of a herbicide. The existence of this shoot indicates putative resistance to the herbicide and, thus, if field validated, may allow effective and easier chemical weed control without hurting tree growth. The ability to use herbicides can greatly increase the productivity of biomass energy plantations. For example, Hansen (1986)

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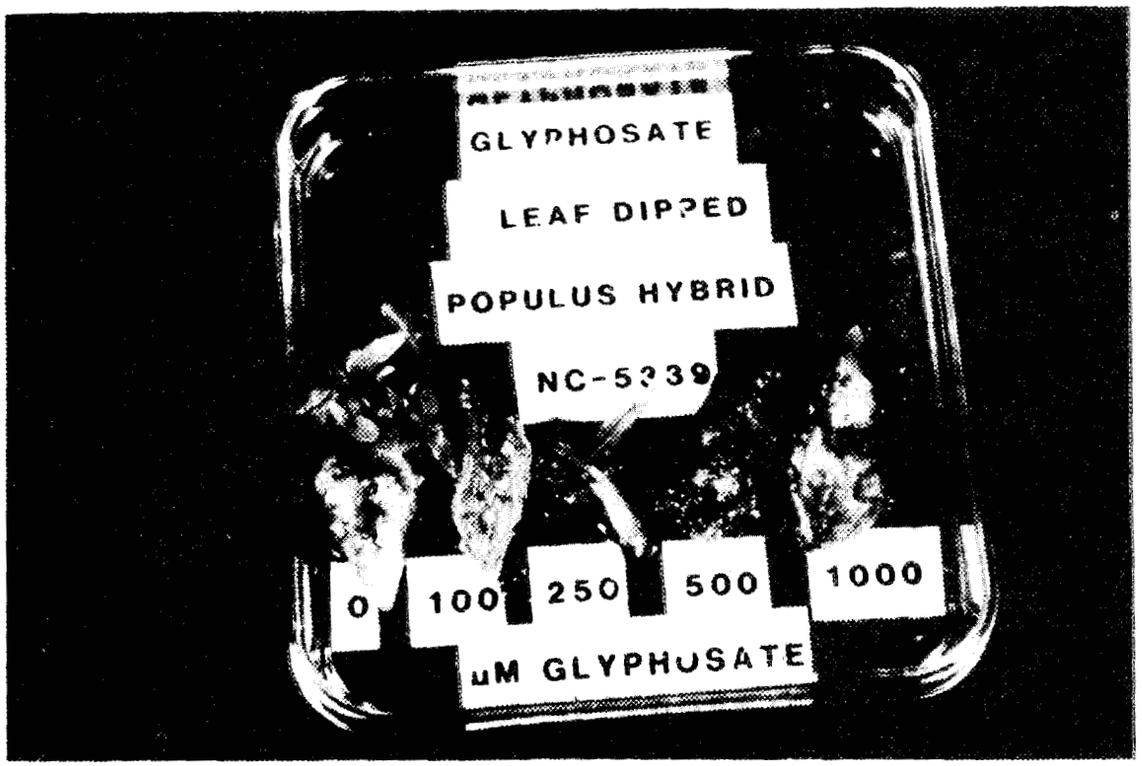

Fig. 8. Leaf sections of Populus hybrid clone NC-5339 were dipped in several levels of the herbicide glyphosate. The shoot forming on the middle leaf disc apparently has some level of tolerance to the herbicide.

found that improved cultural techniques, mainly weed control, almost doubled biomass productivity from 2.6 to 4.5 Mg ha^{-1} $year^{-1}$.

The clone in Fig. 8 was also used by researchers at Calgene and the University of Wisconsin in transformation experiments. Using Agrobacterium tumefaciens as a vector, Fillatti et al. (1986) reported that they successfully introduced a gene for glyphosate resistance (aroA) into plantlets (ramets) of this clone. For trees, this is the first reported insertion of a commercially important gene, as well as one of the first successful insertions.

Currently, the procedures for somaclonal screening and plantlet regeneration from groups of cells in Populus have been defined for only a few clones, and these vary among clones and species. Future efforts will include developing the methodology for Populus trichocarpa clones. These techniques will enhance the future genetic improvement of Populus in the Lake States, the Pacific Northwest (University of Washington), and in other areas of the country. Populus trichocarpa genetic improvement in the Pacific Northwest is continuing with the production of 235 new P. trichocarpa x P. deltoides hybrids and 652 interpopulation crosses of P. trichocarpa. Analysis of the 2-year-old seedlings showed a highly significant superiority of hybrids in volume growth and Melampsora rust resistance, which is a serious Populus disease in the Pacific Northwest. Variations in these traits existed both within and among families studied, thus demonstrating that a large potential exists for genetic improvement via selection of the best individuals from the best families. Cloning of these selections will provide immediate improvement in growth and rust resistance.

Physiology studies that complement the University of Washington's breeding program and the tree-level ecophysiological model have provided new insights into the morphological explanations of the hybrid vigor that exists in P. trichocarpa x P. deltoides. These studies include the number and sizes of cells, the location and amount of leaf mesophyll layers, and leaf orientation (Isebrands and Michael 1986, Stettler et al. 1986).

Four new subcontracts (Table 2) were initiated from an RFP soliciting genetics and physiology research projects on model species. The overall objective of these projects is to produce genetically improved clones for each of the species. The exception is the Michigan State University project, which will be to evaluate clones for various physiological and biomass parameters, with a special emphasis on root growth. Researchers will be working with the Populus breeding program at the USDA-NCFES, and their results will benefit studies with the tree-level ecophysiological model. All four projects are required to use similar methodology for biomass data collection to ensure that results will be comparable and applicable on a broad scale. The development of tissue culture propagation techniques is ongoing in species that cannot be propagated easily from nonrooted cuttings.

In one of the new genetic projects, Southern Illinois University will focus on developing clonal propagation methods for Acer saccharinum via tissue culture. The plantlets will then be used in provenance tests. In ongoing research projects, Plant Resources (Native Plants, Inc.) developed an auxiliary bud regeneration method for Atriplex canescens, but was unsuccessful in developing a callus regeneration system (Wurtele et al. 1986). Somatic embryos of A. canescens were obtained under some culture conditions but did not develop into plants. Callus and suspension cultures of four selected Eucalyptus grandis clones were established at the University of Florida, but no plantlets were produced. North Carolina State University began preparations for developing a tissue culture system for Liquidambar styraciflua. The ability to clone this and other species will provide significant amounts of gain in biomass productivity that cannot be captured otherwise.

In general, Populus species research activities are in an advanced stage compared with the non-Populus model species. Populus models will serve as prototypes for future research with other model species. In Populus, the ideal traits emerging as important are narrow crowns with small limbs, larger upper leaves and smaller lower leaves, indeterminate growth, pest resistance, and drought tolerance. Although common efforts are conducted on the identification of ideal traits or "ideotype," breeding must be specific for regional traits such as climate and soil types. As our knowledge of genetic variation, growth, culture, and conversion technologies improves, genetic improvement of more specific traits will take place.

2.6 SUMMARY OF BIOMASS YIELDS IN SRWCP RESEARCH PLOTS

The Short Rotation Woody Crops Program has numerous field sites around the United States where biomass yields are being evaluated. The goals of the program are to demonstrate that mean annual biomass yields of 20 Mg ha^{-1} $year^{-1}$ are feasible or that SRIC systems for energy at lower yields are profitable. The program's high-yield goal has been exceeded in the first rotation in very small research plots of Populus hybrids in the Pacific Northwest on very high quality agricultural sites (yields ranged from 16.1 to 30.1 Mg ha^{-1} $year^{-1}$ at age 4). Industrial plantings of the same clones on several hundred hectares in Oregon are achieving early growth rates that suggest similar high yields will be attained by rotation age (4 to 6 years). Yields exceeding the goal of 20 Mg ha^{-1} $year^{-1}$ have also been obtained in a few trials with first-rotation Eucalyptus in Hawaii and Florida. At most other sites in the United States, maximum yields in the range of 6 to 14 Mg ha^{-1} $year^{-1}$ are more common. Tables 3 and 4 summarize the most recent yield estimates available as of March 1986. The yields are reported for a number of sites that vary considerably in quality, climatic conditions, species, level of intensity of culture, and purpose of the tests. Although all tests are providing valuable information that will be useful in shaping intensive culture techniques for various regions of the country, not all test sites are currently producing at the optimum rate known to be attainable for the species and site types involved.

This is largely because some of the yield data are coming from older plots that were established 5 to 10 years ago before effective techniques for weed control were well known. New tests on a larger scale currently being initiated by the SRWCP, should provide the best indication of the kinds of yields that can be obtained, given our current state of knowledge on establishing and managing SRIC systems.

Tables 3 and 4 provide a general indication of the type, locations, age, and numbers of studies in progress that are designed to provide yield information. The data are not entirely from the 1985 growing season, since some projects prefer to report only measured yields from harvested plots, and their most recent harvest occurred before 1985. Much of the data are preliminary, and the yield estimates may be revised at a later date. The yields reported result from the aggregation of sets of treatments such as a range of planting densities (spacings), cultural treatments, sites, planting years, or different species. The average yield was calculated from reported treatment yields that are, in turn, averages of replicate yields. Maximum and minimum yields represent the average value for the best and poorest treatment within the aggregated set. Total number of replicates involved are listed to provide an indication of the extent of the information base being summarized by these tables.

To facilitate comparisons between coppiced and uncoppiced stands, both root age and stem age are given. In first-rotation stands, root and stem age are equal, whereas in second rotation stands, stem age is younger than root age. Average yields for the second rotation are based only on second-rotation stem growth.

The maximum yields in experimental trials, defined as 100 or more trees per treatment plot (Table 3), were obtained with a variety of species and treatment conditions. In Pennsylvania, the best yields were obtained with fertilizer additions on abandoned agriculture fields in a bottomland location. Yield differences between the two sets of data are a function of age differences. In Wisconsin, the best yields were obtained in an age 5 clone/spacing/irrigation trial with a hybrid (NE41) at 10,000 trees/ha and irrigated conditions. The Alnus spacing trial in Washington was established with a very low intensity of culture, and by age 11, yield performance was relatively similar at all spacings; however, the best yields occurred at the 1.2 x 1.2 m spacing (13,449 trees/ha). In the Hawaiian spacing trials the most dense spacings (e.g., 5000 to 6666 trees/ha) generally produced the highest yields at a young age. However in the age 6 trial, there was no significance difference in mean annual biomass yield densities of between 2000 and 5000 trees/ha. The species mixture trial showed quite high yields when Eucalyptus saligna was mixed in a 50:50 ratio with Albizia falcataria.

The maximum yields in exploratory trials, arbitrarily defined as less that 100 trees per replicate plot (Table 4), showed similar yields to those found in larger plots. The Kansas tests consisted of Nelder

Table 3. Most recent yield data as of March 1986--experimental yields based on at least 100 trees per replicate

ST	Species	Test type	Root age	Stem age	No. trts[a]	No. reps[b]	Yield ($Mg\ ha^{-1}\ yr^{-1}$) Av.	Min	Max
PA	*Populus* hybrid	Culture	6	2	8	24	10.5	8.8	12.8
		Culture	5	1	8	24	7.1	5.2	8.2
WI	*Populus* hybrids	Clone/spacing	5	5	18	36	6.8	0.4	11.0
		Spacing	9	9	2	8	8.5	8.2	8.8
		Rotation length	var	var	4	4	8.8	8.2	9.4
		Irrigation	5	5	4	12	6.5	5.7	7.0
WA	*Alnus rubra*	Spacing	11	11	5	10	6.0	5.2	7.3
HI	*Eucalyptus saligna*	Spacing	4.0	4.0	4	16	8.9	5.4	14.4
		Spacing	6.1	6.1	4	20	13.2	10.7	15.5
	Mixed	Species mix	5.4	5.4	3	9	11.2	6.8	17.3
		Species mix	4.0	4.0	7	28	20.7	15.8	24.5

[a]Trts = treatments.
[b]Reps = total number of replicates of treatments.

Table 4. Most recent yield data as of March 1986--exploratory yields based on less than 100 trees per replicate

ST	Species	Test type	Root age	Stem age	No. trts[a]	No. reps[b]	Yield ($Mg\ ha^{-1}\ yr^{-1}$) Av.	Min	Max
KA	*Populus deltoides*	Species/site	6	6	5	15	8.8	5.6	13.9
	Robinia pseudoacacia	Species/site	6	6	5	15	8.0	6.9	9.6
	Acer saccharinum	Species/site	6	6	3	9	7.5	5.8	8.5
	Ulmus pumila	Species/site	6	6	3	9	8.8	6.7	11.4
IA	*A. glutinosa*	Provenance	5	5	10		3.4		
		Provenance	6	1	10		5.8		
TX	*Prosopis alba*	Production	2	2	1	3	8.8	8.3	9.5
		Production	3	3	5	15	1.4	1.2	1.6
NC	6 species	Species/spacing	7	7	21	105	3.4	0.7	7.5
	6 species	Rotation length	4	2	18	90	1.0	0.1	3.0
	5 species	Species/spacing	6	6	15	90	2.0	0.2	9.6
AL	3 species	Species/spacing	4	4	9	54	5.7	3.8	7.2
		Rotation length	4	2	9	54	4.4	2.1	6.2
HI	*Eucalyptus saligna*	Spacing	4	4	6	24	17.4	12.0	27.0
		Spacing	2	2	4	16	15.4	11.2	23.4
		Fertilizer	6	6	4	16	12.9	2.2	22.8
		Fertilizer	6	6	5	20	8.0	3.4	13.4
		Fertilizer	4.5	4.5	12	48	19.0	11.0	26.6
	Eucalyptus grandis	Spacing	2	2	6	24	5.3	1.5	14.8
		Fertilizer	2	2	16	64	4.7	1.0	18.3
WA	*Populus trichocarpa*	Provenance	4	4	9	45	14.6	9.9	18.7
	Populus hybrids	Clonal	3	3	3	15	24.6	16.1	30.1
	Populus/Alnus	Species mix	4	4	12	60	15.4	12.0	18.8

[a]Trts = treatments.
[b]Reps = total number of replicates of treatments.

plots located throughoutthe state. The highest yields were obtained from Populus deltoides, which only performed well in the eastern, wetter part of the state. Robinia pseudoacacia and Acer saccarinum performed better over a range of sites. Iowa data were compiled from provenance trials where only an average from the whole trial was provided. The main point of interest in the Iowa trials is that the first-year coppice results were higher than age 5 establishment average yields. In Texas, the best yields for Prosopis alba were obtained with select clonal material planted in the South Texas coastal region with an average annual rainfall of approximately 70 cm per year. Much lower yields were obtained at the drier inland site more representative of much of the semiarid South west. On a bottomland site in North Carolina, Liquidambar styraciflua is producing the highest yields in both the age 7 establishment and the age 2 coppice rotations. On a different bottomland site, age 6 Pinus taeda is producing about five times more biomass than the next best species. Survival and yields of most of the species under investigation in North Carolina are very low because of poor weed control and drought problems during the establishment years. In Alabama, on an old-field site, Platanus and Quercus are producing the best yields by age 4. Platanus is performing only slightly better than Quercus in the coppice rotation by the second year of growth. The small plot trials in Hawaii are primarily testing optimum fertilizer application rates and types. These tests have shown that nitrogen is a limiting factor even on "good" caneland. Best yields have occurred with application of nitrogen fertilizers every six months during the first four years. The Populus trichocarpa and hybrid trials conducted in Washington have been conducted on very fertile bottomland soils. Best yields have been obtained with three Populus trichocarpa x deltoides hybrids commonly known as Hybrid 11, 8, and 5. These clones are being studied extensively to determine the physiological reasons for their high yields.

2.7 NUTRIENT STUDIES

The main thrust of biomass research at ORNL is nitrogen use efficiency of new energy crops. The approach is one of defining the physical, chemical, and biological actions of a nitrogen-enriched soil on nitrogen availability to, and growth of, these new energy crops. Energy crop physiology, photosynthate production, allocation, and root-symbiont interactions are part of this interdisciplinary effort. A pilot study began in March 1986; however, little data are available for reporting. This research is partially replicated at Tuskegee University for the purpose of validating field results and facilitating research exchange with an historically black university.

Other major efforts at ORNL include the compilation of a complex wood energy crop data base from which syntheses are now being conducted, evaluation of lignocellulosic herbaceous crop growth capacities under limited management inputs, and comparative economic evaluations of energy crop production strategies.

3. SPECIFIC CHARACTERISTICS OF SHORT-ROTATION INTENSIVELY CULTURED WOOD

The improvement of desirable wood energy qualities in dedicated energy crops is complex. Energy qualities refer to desired wood traits that make the conversion of wood to liquid and gaseous fuels more cost efficient. These traits are not the same for the different thermochemical and biochemical conversion processes. The complexity of improving energy qualities is found within the multiple gene-controlled traits of interest, that is, the "playing off" of one trait against another, and the multiplicity of biofuel conversion pathways, many of which remain open to major engineering changes. To further complicate the improvement process, productivity, energy qualities, and tolerance of environmental adversities must all be simultaneously improved for maximum energy at minimum cost. Productivity can be expressed in terms of dry tons per hectare per year without leaves (suitable for thermoconversion) or with leaves at the time of harvest (for anaerobic digestion); as dry tons of cellulose and hemicellulose for conversion to fermentable sugars; as dry tons of lignin-, bark-, and mineral-free material; and as feedstocks of a given moisture content. Other qualitative traits, including specific gravity; extractives content and quality; calcium, sulfur, and nitrogen content; and ratios of carbon, hydrogen, and oxygen in various wood components may also be of concern. Each is related to a specific conversion technology and its efficiency in the production of liquid and gaseous fuels. It is unclear how feedstock traits specifically affect conversion efficiency in terms of cost per liter, since the conversion processes themselves are under development. The ability of various conversion technologies (1) to use part or all of the feedstock, (2) to use raw or extensively pretreated feedstock, (3) to convert efficiently, and (4) to produce high-valued fuels affect both the value and cost of feedstocks. This section will discuss how productivity can be improved and costs can be reduced from the perspective of aiding conversion technologies. However, it must be acknowledged that insufficient information exists about conversion technologies to determine specific efficiency improvements and cost reductions.

An analysis of 4-year-old hybrid Populus (NE 388) grown under SRIC conditions and producing 10 dry tons ha^{-1} $year^{-1}$ (leaf weight was an additional 3.25 dry tons ha^{-1} $year^{-1}$) yielded important compositional characteristics to be converted to liquid and gaseous fuels. For example, cellulose is the most desired component in wood for conversion to ethanol, whereas lignin is usable only in thermochemical conversion to gas, ethers, and nonethanol products. The ash content of 4-year-old hybrid Populus is so low that it is of little concern (Table 5). The compositional characteristics listed in Table 5 are representative of many hardwood species grown under intensive culture. There are two overpowering concerns in these data. The material is very bulky (low specific gravity) and has a high water content (50%, dry basis). Specific gravity must be considered in all energy pathways and transport costs, whereas moisture content is of most concern in thermal conversion pathways and in transport/storage costs. The present cost

of wood drying suggests that conversion processes that accept wet feedstocks will be preferred until such time that field drying can economically fit into production costs. Specific gravity and moisture content are frequently inversely related, although dense wood is often slower to dry. In Table 5, alpha cellulose and hemicellulose are components of holocellulose, and lignin is expressed on an extractives-free basis; therefore, percents add up to more than 100%. Also, samples for testing each component were not all from the same set of trees.

3.1 SPECIFIC GRAVITY

Specific gravity has proven to be a highly heritable (clonal) trait with expression across sites and age, although there is a trend toward higher specific gravity at older ages. Anderson et al. (1985) compared the average specific gravity of the native Populus balsamifera (wood only), 0.325, to that of a specific hybrid clone, TRICH-20 (wood and bark), 0.369, thus demonstrating the clear heritability of specific gravity. Higher specific gravity and reduced variability are extremely desirable in improving and refining biomass fuel pathways. Although specific gravity can be increased even more, the selection process for high productivity, tolerance to environmental stress, and other energy traits may require compromises with this trait for maximum energy production per hectare per year.

Mroz et al. (1986) found the specific gravity of young wood (less than 9 years old) in Acer saccharinum, Quercus rubra, Fraxinus americana, and Betula pendula to vary between 0.46 and 0.59. Specific gravity for similar aged P. tremuloides and Robinia pseudoacacia varied between 0.32 and 0.37. The increased productivity of the latter species, however, yielded greater energy per hectare per year than the denser material. Better cost figures will help determine the balance in this trade-off.

Cultural practices also have an effect on specific gravity. Selected Populus coppice wood and bark at the age of one year have a combined average specific gravity of 0.31, which is highly variable between individual trees (0.24 to 0.38). As the coppice material ages, specific gravity increases and its variability decreases, a phenomenon also associated with first-rotation wood crops. Studies by the University of Florida to evaluate the effects of spacing on Eucalyptus grandis found that tight spacings increase moisture content and reduce specific gravity in 2.5-year-old material (spacings 1,600 and 10,000 trees per hectare). Coppice material showed no strong changes from first-rotation material in these characteristics. Of the many other species screened in the SRWCP, it appears that the fastest growing fertilized species (Mg ha^{-1} $year^{-1}$) (Populus spp., Eucalyptus spp.) have low specific gravity (below 0.40), which can be significantly genetically improved.

Table 5. Characteristics of 4-year-old hybrid *Populus* biomass components

Component	S.G.[a]	M.C.[b] (%)	Heat of combustion[c] (cal/gm)	Ash[d] (%)	Extractives[e] (%)	Holo-cellulose[f] (%)	Alpha cellulose[g] (%)	Lignin[h] (%)
Wood	0.37	98.0	4590	0.51	5.36	82.78	46.68	16.47
Bark	0.34	111.2	4737	5.31	41.32	43.99	45.34	13.95
Wood-Bark	0.37	103.1	4650	1.20	10.87	75.73	46.51	17.30

[a]S.G. - specific gravity.
[b]M.C. - moisture content on a dry weight basis (USDA Forest Service, Forest Products Lab., No. 2014, 8 pp.).
[c]Heat of combustion (ASTM D 2015-66, oven-dry basis).
[d]Ash content (ASTM D1102, oven-dry basis).
[e]Extractives (ASTM D 1105-56, oven-dry basis).
[f]Holocellulose (acid chlorite method, Browning, B. L. 1967, oven-dry basis).
[g]Alpha cellulose (ASTM D 1106-56, oven-dry basis).
[h]Lignin content determined on an extractives-free basis (ASTM D 1103-60, oven dried Klason).

3.2 LIGNIN AND EXTRACTIVE CONTENT

Energy content per unit weight of wood is another factor of significant concern that is closely related to lignin and extractives content because these components contain a high energy per unit weight. These components are best screened within species, since wood lignin content may vary from 12 to 23% among species. Bark lignin content is higher and even more variable among species. Lignin content apparently changes little with respect to cultural practices, a phenomenon corroborated (Mroz et al. 1986) for seven hardwood species. Even though lignin content per unit volume of wood may be reduced in fast-growing, short-rotation material, it remains relatively constant, and the increased bark content (containing higher lignin concentrations) of smaller-diameter material may actually raise lignin (energy) concentrations in the feedstock. There is sufficient evidence to believe that both lignin and extractives content can be genetically improved and have their variability narrowed through clonal screening and breeding within species, although the amount of improvement is still in question. Studies of Populus spp. (Anderson et al. 1984) have shown that members of the Tacamahaca group (balsam) generally have a higher energy content than the Aigeiros (cottonwoods) and Leuce (aspen) groups, a factor of considerable concern in Populus energy breeding programs. Savidge (1985), in his study of the anatomical and biochemical characteristics of woody cells and their development, concluded that a feature such as lignin can be manipulated through genetics without affecting volumetric growth. This finding has far reaching implications for improving the energy qualities of wood (high or low lignin content) while maintaining dry weight productivity.

3.3 ASH CONTENT

The ash content of bark is of significant concern to all conversion pathways but is of much less concern in combination with wood. Compared with any other biomass feedstock, wood (including bark) has the lowest ash content. Cultural experiments using fertilization and short rotation show undesirable (although minor) increases in ash content on the order of 1 or 2% of total dry weight. These figures are dwarfed by the effects of increased bark content in smaller-diameter material. Bark can account for more than 60% of the dry weight of 1-year-old material; however, drops to less than 20%. Because of bark's high extractives and ash content and related low holocellulose content, it may be an undesirable feedstock for biological conversion pathways, especially ethanol production. Bark's higher heat of combustion, however, makes it more desirable for thermal conversion pathways.

It is well documented that whole aboveground tree feedstocks exclusive of foliage vary in quality with age. However, these changes at early ages under SRIC conditions are not well identified. Pennsylvania State

University, in their study of hybrid Populus NE 388, found some interesting effects of culture (Table 6).

Nitrogen, a possible contributor to nitrous oxides in thermochemical conversion and a needed nutrient in anaerobic digestion, increased over 100% in kilograms per hectare of biomass harvested. Changes in other minerals were not as significant. Calcium concentrations appear to be so low that effects on hydrolysis in acid neutralization and recovery are of little consideration. Other sources (Anderson et al. 1985) reported that sulfur increased almost threefold as a result of fertilization. Emission concerns are undetermined for sulfur and nitrogen. Bark characteristics (in the same study) were quite different from wood in SRIC material. Not only did rotation age affect the bark content in whole-tree feedstocks, but two other factors also varied: (1) holocellulose increased from 64 to 74% of dry weight, and (2) ash decreased from 2.2 to 1.1% as the SRIC Populus trees aged from the first to the fourth year.

Table 6. Effects of cultural treatments on nutrients in SRIC wood

Treatment	N		P		K		Ca		Mg	
	Dry wt (%)	kg/ha	Dry wt (%)	kg/ha	Dry wt (%)	kg/ha	Dry wt (%)	kg/ha	Dry wt (%)	kg/ha
Fertilized (4 year)	0.12	40	0.02	7	0.09	29	0.09	31	0.01	5
Unfertilized (4 year)	0.08	18	0.02	5	0.07	15	0.08	19	0.01	3

4. HARVESTING AND HANDLING

4.1 SPECIFIC DEVELOPMENTS

In this section, we report new developments with regard to reducing the cost of harvesting and handling SRIC material. While the SRWCP is not directly involved in designing or testing prototype equipment for SRIC applications, efforts are made to keep abreast of new techniques and hardware that are being used elsewhere in the forest industry. Some of the cost reduction measures identified to date include:

1. Use continuous harvesting principles;
2. Use saws as severance mechanisms;
3. Minimize power requirements in the field (e.g., avoid chipping);
4. Use attachments for existing tractors;
5. Dry biomass in the field;
6. Produce bundles or bales for efficient handling;
7. Minimize field passes with equipment; and
8. Use adjacent sites for storage and perhaps drying.

Recently completed joint studies (industry-university-DOE) of the Hyd-Mech feller buncher (FB-7) prototype developed by the National Research Council of Canada (Ranney et al. 1986) have resulted in the most favorable harvesting costs to date. Theoretical figures (in parentheses in Table 7) account for adjustments for larger trees (not actually cut) at wider spacings to assess their impact on costs.

Table 7. Spacing and tree size influence harvest costs, as shown for the Canadian-designed FB-7 short-rotation harvester (Curtin 1986)

Spacing (m)	Density (trees/ha)	Tree wt (kg)	No. harvested (trees/h)	Severance rate (tons/h)	Severance cost ($/ton)
1.4 x 2.4	2959	24.2	615	14.9	1.23
2.8 x 2.4	1461	24.2 (75.7)[a]	1195	28.9 (90.5)	0.64(0.20)
4.2 x 2.4	974	24.2 (160.0)	635	15.4(101.6)	1.20(0.18)

[a]Figures in parentheses are estimated based on the assumption that larger trees will occur at wider spacings.

Even with these low severance costs, efficiencies can be improved for the narrower-spaced trees. However, as these results indicate, it appears that the greatest cost challenges occur with the collection and handling of harvested material. Whole-tree bundling and whole-tree chipping have been under examination, but crushing, drying, baling, or chunking are now being explored because of certain advantages.

The biomass crusher, developed by the Forest Engineering Research Institute of Canada (FERIC), was tested in the United States by several institutions (see Fig. 9). The FERIC crusher is a prototype for solely investigating the crushing process (DuSault 1984). Studies conducted by the U.S. Forest Service at Auburn, Alabama, indicated that a crushing rate of approximately 15 linear meters per minute could be achieved on stems up to 21 cm in diameter (Ashmore et al. 1986). Using only 11 kw (15 hp) of power, the crushing technique requires significantly less power than conventional chipping operations. Also crushing short-rotation (small-diameter) material has shown that wood can be passively field dried, thus losing 90% of its moisture in 6 days (Du Sault 1984). Crushing and rapid field drying offers four important advantages: (1) much less energy is required to crush material than to chip it, (2) much less unproductive weight has to be transported (cost reduction), (3) fuel costs for heat drying (the major cost in many conversion pathways) is eliminated, and (4) wood cell respiration is stopped immediately, thus reducing losses to feedstock degradation common in chips.

There are other possible advantages of crushing and drying presently under investigation. The use of existing cylindrical hay balers with only minor modifications may solve unit handling, transport, and dry outdoor (field or on-site) storage of harvested material. Minor recrushing after field drying may also separate bark from wood before baling, providing a more homogeneous feedstock while leaving much of the nutrients and ash components in the field.

Conclusions are that:

1. Field chipping should be avoided because of power requirements;

2. SRIC crushing and bunching offer significant advantages over chipping;

3. Stand spacing, harvest age, tree size at harvest time, and harvest costs must be considered together when assessing how best to minimize/reduce costs.

ORNL Photo 4996-84

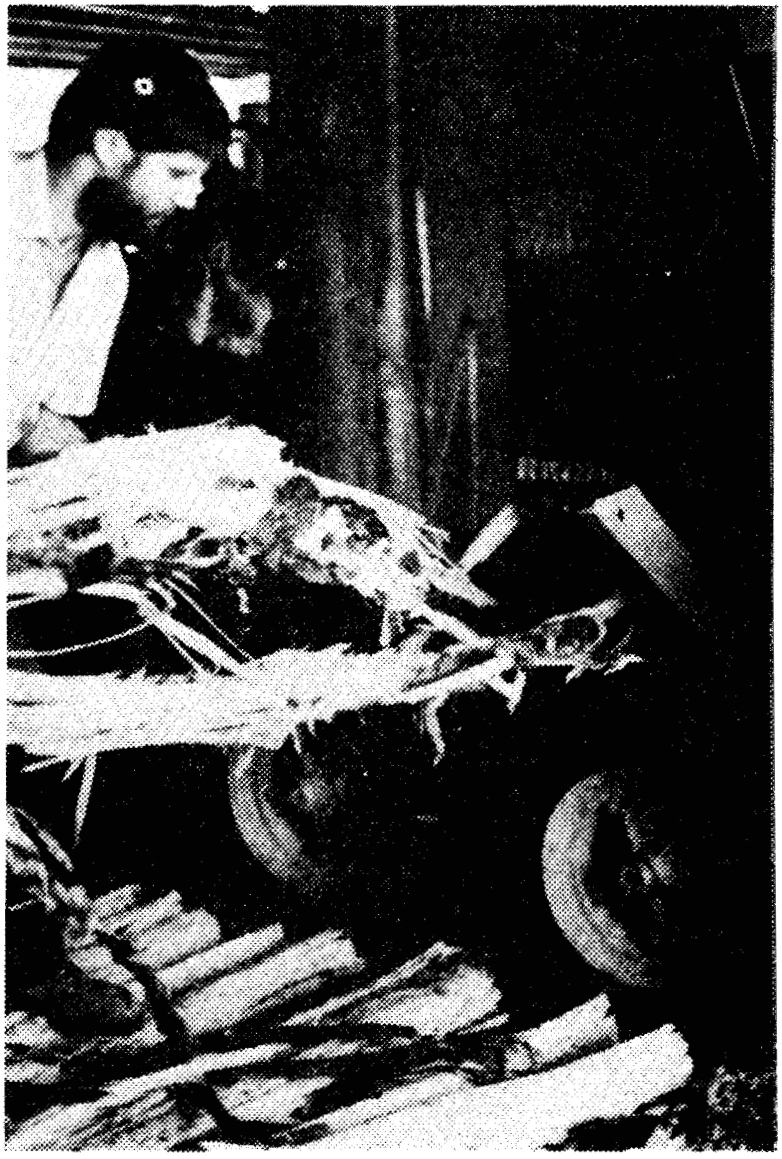

Fig. 9. Biomass crusher developed by the Forest Engineering Research Institute of Canada.

5. TECHNOLOGY TRANSFER AND RELATED ACTIVITIES

The SRWCP is actively involved in the collection and dissemination of accurate practical information that will help develop a strong biomass energy industry based on renewable energy crops. Programmatic research is primarily geared toward the improvement of wood energy crops for gaseous and liquid fuel pathways, which are still very much in the future. In these cases, linkages with conversion research on feedstock requirements, feedstock improvement, and the relevance of those improvements to conversion operations and pathway costs have been initiated with sister research laboratories. ORNL is directly involved with the Battelle Pacific Northwest Laboratory and, in turn, with the Solar Energy Research Institute in evaluating the effect of feedstock qualities on various conversion strategies. ORNL is also informally dispensing SRIC feedstocks on a small scale to those who wish to conduct direct tests on them. Selected SRWCP subcontractors are involved in qualitative assessments of SRIC feedstocks and the effects that culture and genetics have on them. In the past, both ORNL and subcontractors have worked with the National Bureau of Standards to develop biomass standards specifically for such testing, although no standards have been formally adopted at this early stage of biomass energy research.

The wood energy plantation independent of conversion technologies is a concept relatively untested for viability. Risks of low or variable productivity, disease outbreaks, cultural inefficiencies, and inaccurate cost estimates have not been assessed in monocultural trials larger than research plots. Rather than add the risk of linking with untested conversion technologies, monoculture viability trials have been initiated with industries using mature direct-combustion technology. The industries involved are Northern States Power, Crown Zellerbach Corporation, the Amana Society, and First Colony Farms. These efforts, in cooperation with four other institutions (Table 2) on a 50-50 cost-sharing basis with DOE, are structured to infuse state-of-the-art knowledge from research into the pragmatic evaluation processes of energy-conscious industries and utilities. Thus, in all cases, university and/or USDA Forest Service groups are associated with the work and, in two cases, serve as the primary contractor. The monoculture viability trials are as much a training activity as a concept viability trial. ORNL involvement during the planning phase has been strong.

A recurrent problem over the past few years has been the lack of availability of SRIC consultants to interested industries on a long-term basis, and the awareness of extension and advisory people about SRIC, its potentials, and its limitations. In solving this problem, the SRWCP has been providing assistance and support to SRIC training courses under the organization and guidance of the Great Lakes Regional Program. The target audience has been extension specialists and professional consultants. The Great Lakes Region was targeted because interest in SRIC outside the research community is highest in this region and because the Coalition of Great Lakes Governors identified such training as an important need in the development of biomass energy in the region.

An important aspect of technology transfer is having respected and visible representatives speak on behalf of SRIC for energy at major meetings. The SRWCP has been fortunate in this respect and has been represented at practically every forestry and biomass energy meeting in the country over the past year as a result of subcontractor involvement.

Involvement of the SRWCP staff and subcontractors in the International Energy Agency/Forest Energy Agreement (Annex II and others), as well as other international encounters (Reagan/Gandhi Agreement), has enabled two-way technology transfer in SRIC research and development. The primary gains for the United States have been in Populus breeding material, knowledge of clonal adaptivity ranges (important for breeding improvement), SRIC harvesting technology, involvement in the development of internationally acceptable species-testing protocols, identification of desirable wood characteristics for conversion, and in access to gene clone banks of Populus, Alnus, and Salix species. Less tangible benefits have involved the identification of productive research avenues and techniques in species improvement for energy. Lessons have also been learned from Canada and Sweden on training (motivating) private landowners in growing SRIC crops. An increasingly important area of exchange involves biotechnology, with the United States having much to gain.

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APPENDIX I

Conversion Factors

1 Mg ha^{-1} $year^{-1}$ = 0.44 ton $acre^{-1}$ $year^{-1}$

\$1/GJ = \$1.05/MBtu

1 GJ/ha = 96,699 kcal/acre

1 cm = 0.394 in.

1 g = 0.0022 lb

1 m^3/ha = 14.3 ft^3/acre

1 ha = 2.47 acre

1 m = 3.28 ft

1 Mg = 1.00 tonne

1 Mg = 1.102 ton

1 m^3 = 35.31 ft^3

1 km = 0.62 mile

1 kJ/kg = 0.43 Btu/lb

1 J = 0.00095 Btu

1 GJ = 0.95 x 10^6 Btu

1 dm^3 = 3.53 ft^3

1 kPa = 0.01 Bar

APPENDIX II

Latin and Common Names of Woody Species

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

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