SHIPPING COAL TO NEW CASTLE: ARE SRIC *POPULUS* PLANTATIONS A VIABLE FIBER PRODUCTION OPTION FOR THE CENTRAL HARDWOODS REGION?

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Abstract: Production costs for short rotation, intensive culture (SRIC) *Populus* biomass were developed from commercial-sized plantations under investigation throughout the eastern U.S. *Populus* hybrid planted on good quality agricultural sites at a density of 850 cuttings/acre was projected to yield an average of 7 ovendry (OD) tons/acre/year. Discounted cash-flow analysis of multiple rotations showed pre-harvest production costs of $15/ton (OD). Harvesting and transportation expenses would increase the delivered cost to $36/ton (OD). Although this total cost compared favorably with the regional market price for aspen (*Populus tremuloides*), future investments in SRIC systems will require the development of markets specific to this biomass output.

INTRODUCTION

Foreign restrictions of oil imports to the U.S. during the 1970s resulted in a review of energy-use policies and an allied search for alternate energy sources. The perceived energy crisis brought about an accelerated exploration for domestic sources of fossil fuels and an investigation into the use of solar energy and allied forms of renewable energy (OTA 1980).

Woody biomass was evaluated as a supplemental fuel source, both in terms of expanded supplies from domestic forests and from short rotation, intensive culture (SRIC) energy plantations. During the 1970s wood provided a small portion of U.S. energy supplies, amounting to 2% of annual energy needs (OTA 1980). Most of this biomass was used for residential heating. In terms of the future, an expanded use of forest growth, mortality, and urban wood waste, above current forest industry usage, could provide about 8% of U.S. energy needs (Peterson 1983). An additional 6% of our energy needs could be developed by converting one-tenth of the nation's private forest, range, and pasture lands to SRIC plantations (OTA 1980). However, one of the unresolved questions is whether woody biomass could compete, cost-wise, with other fuel sources.

Most of the early proposals regarding the expanded use of wood energy were tied to the direct combustion of biomass for electric generation (Skelton et al. 1982). However, under current and near-future world prices for coal and petroleum, biomass-dedicated conversion

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systems cannot compete with large scale, coal- and oil-fired systems (Strauss et al. 1988). Woody biomass would have a better option as a feedstock for ethanol production. Liquid fuels are in strategic short supply within the U.S., making this country vulnerable to supply and/or price disruptions (Wright 1988). The production of ethanol from woody biomass has been proposed under several processes, with the final product considered to be cost competitive under open-market situations (Wright and d'Agincourt 1984, Bergeron et al. 1988). Biomass from SRIC *Populus* plantations would be particularly well suited to these conversion processes on the basis of material characteristics and supply capabilities (Ranney et al. 1987, Strauss et al. 1988).

SRIC production is designed to promote high biomass yields at a young stand age. The most cost-effective cultural approaches have included the use of improved clonal material, intensive site preparation and weed control, planting densities of 600 to 1600 trees/acre, fertilization, coppice regeneration, and two to three harvest cycles of five to eight years each (Ranney et al. 1987). In order to facilitate these cultural designs and secure a maximum output, most of the SRIC plantations have been placed on good agricultural lands. Hardwoods have been preferred due to their rapid early growth, good stress tolerance, and strong coppicing ability. Major attention has been directed to the poplars (*Populus* spp. and hybrids), eucalypts (*Eucalyptus* spp.), silver maple (*Acer saccharinum*), sweetgum (*Liquidambar styraciflua*), sycamore (*Platanus occidentalis*) and black locust (*Robinia pseudoacacia*). Willows (*Salix* spp.) have been investigated in Canada and northern U.S., involving "wood grass" strategies with over 10,000 stems/acre and ultra-short rotations of one to three years (Wright et al. 1988).

Research on SRIC technology in the U.S. was initiated in the mid-1960s, with major improvements secured through numerous experimental trials. Much of this work was funded or co-funded by the U.S. Department of Energy and coordinated through its Short Rotation Woody Crops Program (SRWCP) (Wright et al. 1989).

In order to encourage the commercialization of SRIC programs, the economics of plantation systems are being evaluated under two general stages of research. These include feasibility studies of proposed commercial-sized systems (Perlack et al. 1986, Strauss et al. 1988) and, more recently, the scale-up analysis of actual commercial plantations (Wright, in press). This latter effort includes economic and viability trials of 50-acre or larger monoculture plantations established by several research institutions and private companies through cost-sharing programs. Much of the work in both stages was completed in the northcentral and northeastern regions of the U.S. and has focused on various *Populus* hybrids (Wright, in press).

This paper develops a general production model from these combined research efforts; focusing on the establishment and maintenance of commercial-sized *Populus* plantations. Unit costs for biomass are developed and compared to the current market price of similar wood supplies from domestic forests.

PROCEDURES

Research sponsored by SRWCP over the past decade provided a nation-wide appraisal of various silvicultural designs for SRIC biomass plantations. In an effort to summarize the central findings of these investigations, a woody biomass production model was developed and evaluated under a discounted cash-flow design.

Plantation Design and Operations

The design for the SRIC system uses *Populus* hybrid planted on good agricultural sites at a density of 850 trees/acre. Rotation length was expected to fall in the range of five to eight years, with two to three rotations anticipated from the initial planting. Selection of the optimum-length rotation was dependent on a discounted cash-flow analysis of production costs.

The establishment of SRIC plantations is similar to the procedures used for agricultural row crops, involving a fall preparation of the site and spring planting of the poplar cuttings (Perlack et al. 1986, Grado et al. 1988). During the fall period, the site receives a total- kill herbicide and mowing operation to remove old field vegetation, followed by offset disking to prepare the soil for planting. Lime may be added at this time, depending on soil acidity. In the spring, the soil is disk harrowed, with a pre-emergent herbicide applied to counter residual weed sources. In order to insure an adequate nutrient base for tree growth, a complete nitrogen-phosphorus-potassium fertilizer prescription is applied prior to planting, with additional nitrogen supplemented throughout the rotation (Table 1). Machine planting was assumed within the cost structure of the model, with the poplar cuttings produced at a self-owned nursery (Grado et al. 1988).

Additional herbicide applications were scheduled at the beginning of the first and second summer periods to limit weed growth. Protection from insect and canker attack was provided through a biennial insecticide/fungicide spray program. This represented an insurance cost in reducing the susceptibility of monoculture systems to infestations, such as cottonwood leaf beetle (*Chrysomela scripta*) and *Septoria* canker (Ostry et al. 1988).

Annual charges were also assessed for land rent, property taxes, and the managerial supervision of the entire production effort. In this manner, land and management were identified as specific inputs to the production system.

Table 1.--Establishment and maintenance costs for SRIC plantations, 1987-88.

Operations	Cost Components	$ /acre
FALL ESTABLISHMENT:		
Total kill herbicide	machine and labor	2.
	materials (1.3 lb/a)*	30.
Mowing/brushing	machine and labor	8.
Plowing	machine and labor	14.
Liming	machine and labor	3.
	materials (1 ton/a)	28.
Total		85.
SPRING ESTABLISHMENT:		
Disking	machine and labor	5.
Pre-emerg. herbicide	machine and labor	2.
	materials (1.6 lb/a)*	36.
Fertilization	machine and labor	6.
	materials (50 lb/a each N,P,K)	18.
Planting	planter and labor	9.
	materials (850 cuttings/a)	42.
Total		118.
SUMMER ESTABLISHMENT:		
Herbicide-year 1	machine and labor	2.
	materials (1.0 lb/a)*	22.
Herbicide-year 2	machine and labor	2.
	materials (1.0 lb/a)*	22.
Total		48.
MAINTENANCE:		
Insecticide/fung.	machine and labor	1.
(years 2,4,6)	materials (1.4 lb/a/appl.)**	9.
Fertilization	machine and labor	3.
(years 3,5,7)	materials (110 lb/a/appl. of N)	11.
Land rent	(5.0% of $690/a)	35.
Land taxes	(0.75% of $690/a)	5.
Managerial	labor and facilities	14.
	av. annual	66.

* combination of linuron/glyphosate.

** combination of Sevin/Dylox.

Plantation Yields

Growth and yield functions were developed from SRWCP data sets. These included yield information from partial and first rotations of several *Populus* systems planted at 700-1400 trees/acre and one double rotation system planted at 8500 trees/acre.

An estimated growth curve was developed for an 850 trees/acre plantation, having, as a targeted yield, 7 ovendry (OD) tons/acre/year. This production level was consistent with current research results and was considered a conservative estimate of future SRIC yields (Ranney et al. 1987). Recent summaries of record SRIC small-plot yields for *Populus* hybrid have shown production levels in the range of 6-9 tons (OD)/acre/year (Hansen 1988).

Biomass Costs

The unit cost of biomass was developed from a least-cost model for SRIC plantations (Strauss et al. 1990):

$$C=\frac{\left(\frac{R}{i}+\frac{T}{i}\right)+\left(\frac{E(1+i)^n}{(1+i)^n-1}\right)}{\frac{Y_t}{(1+i)^t-1}} \tag{1}$$

where,

C = biomass cost, per unit of yield
R = annual land rent and taxes, per unit area
T = annual maintenance costs, per unit area
E = establishment costs, per unit area
Y_t = yield, per unit area
t = rotation age in years
n = plantation life expectancy in years
and i = real interest rate.

Under this formula, unit costs are a function of the discounted cash flows originating from the establishment and annual operations of the SRIC system and the discounted yields of the plantation. Annual costs, including land rent, taxes, and maintenance, were discounted as annual perpetual series. Established costs were compounded to end of the plantation's life expectancy and then discounted as periodic perpetual series. It was assumed that the requirements and costs of reestablishing a new plantation would approximate those followed in the original establishment phase. Yields were discounted as perpetual periodic series specific to their individual rotation lengths. The plantation's life expectancy was based on the number and length of rotations in any given analysis.

A 5% real rate of return was used throughout the analysis. This represented a compromise between the 6% historic real rate identified for corporate capital (Klemperer 1979) and the 4% real rate expected on new long-term investments (Row et al. 1981).

Establishment and Annual Operating Costs

Estimated costs for the individual operations were developed from the SRWCP data base and are reported in U.S. dollars for the 1987-1988 period (Table 1). Contract charges for the establishment and annual operations of commercial-sized plantations compared well to previous models of SRIC systems (Lothner et al. 1985, Perlack et al. 1986, Grado et al. 1988). Variations in costs were largely attributed to the differences in equipment and prescribed materials used on alternate sites. The final budget reflected the establishment and annual operations of a site having good aspect and soil quality.

Establishment costs totaled $250/acre, including the discounted cost of the second-year herbicide operation (Table 1). Herbicide operations were 47% of establishment costs, with materials constituting over 90% of this expense. Land preparation and planting were 31% of establishment costs, with 54% of this expense tied to the poplar cuttings (Grado et al. 1988). First-year liming and fertilization constituted the final 21% of establishment costs.

Annual maintenance included additional fertilization on an alternate year basis ($14/acre/application) and the application of insecticides/fungicides on an alternate year schedule ($10/acre/application). In addition, an annual managerial cost of $14/acre was assessed for administrative and personnel requirements (Strauss et al. 1988).

Annual rent was assessed at 5% of the land value, with annual property taxes estimated at 0.75% of land value. Land was valued at $690/acre, representing the capitalized net return of a good corn production site (110 bu corn/acre/year). This was representative of the land values from several SRIC projects and was 20% above the 1988 U.S. average for farm real estate (USDA ERS 1988).

Growth and Yield

The projected growth of *Populus* hybrid represented an average function for first and second rotations (Table 2). Typically, the above-ground growth secured during the initial portion of the first rotation will be 20-40% lower than for comparable points in the second rotation due to the concurrent development of root systems in the first rotation.

Current annual increment (CAI) was projected to accelerate during the first five years, reaching a maximum of 10.5 tons (OD)/acre in the 5th growing season. As expected, mean annual increment (MAI) increased at a more gradual rate, attaining the targeted maximum of

7.0 tons (OD)/acre/year after the 6th growing season. The narrow range of MAI values in the 5th to 8th years reflected the high CAIs in the 3rd to 6th growing seasons.

Table 2.--Yields and cost of biomass for SRIC plantations.

Year	Yields (ton(OD)/acre)	Cost* - 2 Rotations ($/ton(OD))	Cost* - 3 Rotations ($/ton(OD))
3	13.4	27.11	23.80
4	23.4	19.28	17.35
5	33.9	16.03	14.68
6	42.4	15.11	14.02
7	48.9	15.19	14.23
8	53.3	15.95	15.07

* Discounted cash flow analysis at 5%.

RESULTS

Unit Costs of Biomass

The discounted cash-flow analysis of pre-harvest production costs under a two rotation system placed the least-cost solution in the 6th year at $15.11/ton (Table 2). Optimum rotation coincided with maximum MAI due to the compression of the plantation's growth function into a relatively short period. During this period, annual growth changes were more volatile than the respective increases in cost, with the short time span also reducing the effects of discounting. Of further interest, extending the plantations into the 7th growing season increased the output cost by less than 1%. This reflected the modest decline of CAI in the 7th year.

The principal cost in the SRIC model was land rent and taxes, amounting to 42% of the total. Managerial costs, fertilizer and lime, and herbicides each represented about 14-15% of the total. The composite of land preparation, planting, and insecticide/fungicides was the final 15% of expenses.

If the plantations could support a third rotation under the same yield pattern, the least-cost solution would also occur in the 6th year, with the unit cost reduced to $14.02/ton (Table 2). The 7% cost reduction resulted from the extended prorate of the establishment costs over the additional rotation.

Harvesting costs were based on a feller/buncher unit designed for closely-spaced, small-diameter trees (Stokes et al. 1986, Woodfin et al. 1988, Strauss et al. 1988). The harvested material would be chipped in the field, and transported 25 miles with tractor-trailer units. Under this design, harvesting and transportation costs were estimated at $18/ton (OD). A final delivered cost of $36/ton (OD) was established for the two rotation system on the basis of an 85% net delivery of plantation yields.

DISCUSSION

Marketing and Pricing Considerations

Given the financial profile for SRIC wood production, some question remains as to whether this venture represents a viable option for northeastern U.S. In terms of fiber production, our hardwood forests are typically overstocked with respect to available markets. Softwoods are the principle force in pulpwood markets, with the short-fibered hardwoods representing a certain drudge on the market. On the basis of stumpage prices, softwoods typically carry two to three times the value of hardwoods (Peterson 1990).

An exception to this hardwood situation is provided by aspen (Populus tremuloides) in the Lake States. This lighter weight and faster growing species has generated a major roundwood market among the particleboard and paper industries. Current prices for delivered, unpeeled aspen in the Lake States are $38-40/ton (OD) (Peterson 1990). Of interest, aspen shares many of the mechanical and chemical properties of the hybrid poplars, with both species groups adaptable to the production of ethanol. Several ethanol-conversion studies have established feedstock prices in the range of $38-42/ton (OD) (Wright 1989, Bergeron et al. 1989). As such, SRIC biomass at $36/ton (OD), delivered, would be competitive with domestic aspen and also meet the expected feedstock prices for ethanol production.

In many respects, *Populus* biomass is a unique product. It is homogeneous in terms of either physical or chemical properties and can be genetically engineered for sensitive chemical processes (Blankenhorn et al. 1984). Furthermore, SRIC designs would permit a constant and sustained rate of production. Probably the best example of commercial SRIC *Populus* production in the U.S. is the 7000 acres of plantations developed by the James River Corporation along the Columbia River in Oregon. These plantations were initiated in 1984 in response to hardwood shortages among Pacific Northwest paper mills (Stanton 1987). Their general design and estimated output levels parallel the SRIC model presented in this paper.

Plantation and Allied Production Costs

Sensitivity analysis was used to evaluate the parameters having the greatest impact on pre-harvest and delivered costs. The pre-harvest cost was most sensitive to land costs and biomass yields, with harvesting and transportation having the greatest effect on total delivered cost. A further address of these factors was considered.

The general SRIC model included land rent and taxes as specific cost requirements. These charges, representing 42% of pre-harvest costs, were a direct reflection of land's value in other agricultural pursuits. In order for the SRIC proposal to compete for this resource, comparable or higher net returns will be required from the biomass enterprise. The option of using lower priced, marginal lands for SRIC plantations would reduce this cost impact but, in all probability, would also lower yield potentials. Further investigations of the economic niche of SRIC production within the various gradients of land may be required.

Plantation yields had the greatest impact on pre-harvest unit costs. If, for example, yields were reduced by 25%, plantation costs would increase by 32%. In contrast, a 25% increase in output would decrease pre-harvest costs by over 20%. A comparison of record experimental yields to actual field yields among agricultural crops and for SRIC Populus plantations (Hansen 1988) suggested that the immediate field potential for commercial SRIC plantations may only be within the range of 4.5 - 5.5 ton/acre/year. Further increases were considered possible, with the realization of future gains dependent on cultural and breeding research. More recent estimates of growth in commercial-sized *Populus* plantations by Wright (in press) point to the 7 - 9 ton/acre/year range as an attainable objective. This range has also been verified by results from commercial-sized field trials in northcentral U.S.

The particular design of a SRIC plantation is paramount in determining production success. This involves a careful matching of clonal hybrids to the particular growing site and a successful implementation of the prescribed cultural strategy. Attention to these design prerequisites will, in large measure, enhance the degree of success in SRIC ventures.

In order to move SRIC biomass to the market, major harvesting and transportation costs have to be met. These costs, plus those associated with material loss, more than doubled the final delivered cost of biomass in the SRIC model. Currently, most SRIC harvesting systems represent either developing technologies or adaptations of existing systems used in native forests. Cost reductions can be anticipated, as harvesting equipment is better designed for the needs of biomass plantations (Stokes et al. 1986, Woodfin et al. 1988). However, a current stalemate exists in the development process owing to the lack of investments in SRIC plantations and allied conversion technologies. In all likelihood, the feasibility of energy and fiber technologies need to be first resolved before further attention is placed on SRIC harvesting equipment.

SUMMARY AND CONCLUSIONS

A general model of a commercial-sized SRIC biomass plantation was developed from a series of research programs coordinated by the U.S. Department of Energy's Short Rotation Woody Crops Program. The model centered on the use of *Populus* hybrid, planted on good quality agricultural sites at a density of 850 cuttings/acre. Establishment costs amounted to \$250/acre, with weed control and planting representing 47% and 21%, respectively, of this total expense. Average annual maintenance, including the prorated cost of land, amounted to \$66/acre/year.

Plantation yields were projected to reach a maximum MAI of 7 tons (OD)/acre/year by the sixth year. Discounted cash-flow analysis of cost and growth parameters indicated that two 6-year rotations would achieve a pre-harvest unit cost of $15/ton. Land was the dominant cost factor, representing 42% of the unit cost. Managerial costs, fertilizer and lime, and herbicides each contributed about 15% to the unit cost. Additional harvest and transportation requirements placed the delivered cost of *Populus* biomass at $36/ton.

In its proposed operational form, SRIC biomass would be competitive with aspen from domestic forests and also fulfill the cost requirements of a feedstock for ethanol production. The major cost of land within the financial model suggests the need for evaluating less expensive and lower quality land resources. However, the linkage between site quality and yields represents a critical balance in the cost equation. Although improvements in harvesting and transportation technologies could provide major cost reductions, further developments will probably depend on some form of industrial commitment to biomass production.

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LITERATURE CITED

Bergeron, P. W., J. D. Wright, and C. E. Wyman. 1988. Dilute acid hydrolysis of biomass for ethanol production. In: Energy from Biomass and Wastes XII. Institute of Gas Technology. Chicago, IL pp. 1277-1297.

Blankenhorn, P. R., T. W. Bowersox, C. H. Strauss, G. L. Stimely, C. A. Hornicsar, and M. L. DiCola. 1984. The characteristics of hybrid poplar as a potential feedstock for fermentation to ethanol. In: Proceedings of TAPPI 1984 Research and Development Conference. Appleton, WI pp. 43-44.

Grado, S. C., C. H. Strauss, P. R. Blankenhorn, and T. W. Bowersox. 1988. Short rotation woody biomass plantations: Technical requirements and costs for establishment. Biomass 17(4):277-289.

Hansen, E. A. 1988. SRIC yields: A look to the future. In: Economic Evaluations of Short-Rotation Biomass Energy Systems. International Energy Agency. Duluth, MN pp. 197-207.

Klemperer, W. D. 1979. Inflation and present value of timber income after taxes. J. For. 77:94-96.

Lothner, D. C., H. M. Hoganson, and P. A. Rubin. 1985. Examining Short-Rotation Hybrid Investments using Stochastic Simulation. USDA For. Serv. N. Cent. For. Exper. Sta. Duluth, MN 31 p.

Office of Technical Assessment. 1980. Energy from Biological Processes. U.S. Congress Off. of Tech. Assess. OTA-E-124. Washington, DC 195 p.

Ostry, M. E., L. F. Wilson, H. S. McNabb, and L. M. Moore. 1988. A Guide to Insect, Disease, and Animal Pests of Poplars. Ag. Hdbk. 677. U.S. Dept. Ag. Washington, DC 118 p.

Perlack, R. D., J. W. Ranney, W. F. Barron, J. H. Cushman, and J. L. Trimble. 1986. Short-rotation intensive culture for the production of energy feedstocks in the US: A review of experimental results and remaining obstacles to commercialization. Biomass (9):145-159.

Peterson, R. M. 1983. Managing wood for energy within the multiple use concept. In: The Sixth International Forest Products Research Society Industrial Wood Energy Forum '82. Proc. 7334, Vol. 1:2-5. Madison, WI.

Peterson, T. A. 1990. Wisconsin Forest Product Price Review, Boltwood Edition. April 1990. University of Wisconsin-Extension. Madison, WI 4 p.

Ranney, J. W., L. L. Wright, and P. A. Layton. 1987. Hardwood energy crops: The technology of intensive culture. J. For. 85(9):17-28.

Row, C., F. Kaiser, and J. Sessions. 1981. Discount rate for long-term Forest Service investments. J. For. 79:369-376.

Skelton, J. C., E. S. Lipinsky, W. J. Sheppard, C. K. Badger, E. H. Hall, D. E. Lenerz, M. P. Pease, K. A. St. John, and C. K. Wagner. 1982. The Role of Biomass in Electric Utilities. Battelle, Columbus, OH 184 pp.

Stanton, B. J. 1987. Establishing and maintaining short-rotation, intensively cultured plantations of hybrid cottonwood in the Pacific Northwest. James River Corp. Unpublished paper from DOE SRWCP Contractor's Meeting. Tacoma, WA 29 pp.

Stokes, B. J., D. J. Frederick, and D. T. Curtin. 1986. Field trials of a short-rotation biomass feller buncher and selected harvesting systems. Biomass 11:185-204.

Strauss, C. H., S. C. Grado, P. R. Blankenhorn, and T. W. Bowersox. 1988. Economic evaluations of multiple rotation SRIC biomass plantations. Solar Energy 41(2):207-214.

Strauss, C. H., S. C. Grado, P. R. Blankenhorn, and T. W. Bowersox. 1990. Financial selection of rotation age for SRIC plantations. Biomass 23(1):55-69.

USDA Economic Research Service. 1988. Agricultural Land Values and Markets: Situation and Outlook Report. AR-10. USDA ERS. Washington, DC 30 p.

Wright, J. D. 1988. Evaluation of enzymatic hydrolysis processes. In: Energy from Biomass and Wastes XII. Institute of Gas Technology, Chicago, IL pp. 1247-1277.

Wright, J. D., and C. G. d'Agincourt. 1984. Evaluation of Sulfuric Acid Hydrolysis Processes for Alcohol Fuel Production. SERI/TR-231-2074. Solar Energy Research Institute. Golden, CO 111 p.

Wright, L. L., D. R. DeBell, C. H. Strauss, W. A. Geyer, L. Sennerby-Forsse, and L. Zsuffa. 1988. Panel discussion on the relative merits of woodgrass and SRIC. In: Energy from Biomass and Waste XII. Institute of Gas Technology. Chicago, IL pp. 261-274.

Wright, L. L., J. H. Cushman, and P. A. Layton. 1989. Dedicated energy crops: Expanding the market by improving the resource. Biologue 6(3):12-19.

Wright, L. L. (in press). Commercialization of short-rotation intensive culture tree production in North America. In: Energy from Biomass and Waste XIII. Institute of Gas Technology, Chicago, IL.

Woodfin, S. L., L. L. Wright, and D. T. Curtin. 1988. SRIC: Integration of production and harvesting system costs. In: Economic Evaluations of Short-Rotation Biomass Energy Systems. International Energy Agency. Duluth, MN pp. 115-150.