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Cost Parameters Affecting Multiple Rotation SRIC Biomass Systems

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ABSTRACT

Short rotation intensive culture (SRIC) plantations were analyzed to determine a least-cost method of supplying feedstock for liquid fuel manufacturing. The plantations were based upon *Populus* hybrid, nonfertilized and fertilized strategies and a spacing of 21,000 trees/ha. Financial analyses indicated a 3-y rotation would minimize production costs for the particular design of these plantations.

Under a 3-yr rotation, nonfertilized plantations averaged 10 metric tons, ovendry, per hectare per year (Mg(OD)/ha/yr) and developed plantation costs of $28/Mg (OD). The fertilized strategy obtained 13 Mg(OD)/ha/yr and costs of $30/Mg(OD). For the nonfertilized strategy, production costs were divided equally among three input areas: equipment and materials, labor, and land, whereas with fertilization, nearly 50% of the cost was tied to equipment and materials. Additional costs of $30–42/Mg(OD) were forecast for the harvest and storage of biomass, with 75% of these costs placed in equipment and materials.

Index Entries: Economics; woody biomass; plantations; harvesting; storage.

INTRODUCTION

One of the more promising feedstocks available for conversion to liquid fuels is woody biomass. Its production can be sustained under photosynthetic principles and in a manner that compliments world environmental

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standards. Biomass represents a safe, combustible product and a unique source of fiber, cellulose, and sugars. Consumption could reach 5–15% of total US energy requirements by the year 2000 (*1,2*). Woody biomass represents a major component of this supply, with conventional sources having the potential of providing 3–4 exajoules of energy annually by the year 2010 (*3*). Additional energy, in the range of 4 exajoules annual, could be obtained from short rotation intensive culture (SRIC) plantations designed specifically for biomass production (*3,4*). However, a basic concern with SRIC systems is their ability to compete with other energy sources.

Production costs for SRIC plantations include: site preparation, planting, weed control, pest control, fertilization, and administration and overhead costs. Dutrow and Saucier's (*5*) analysis of high density sycamore plantations in Georgia found the fixed costs of establishment to be $383/ha. with total establishment costs ranging from $485–994/ha. Variations in total costs were attributed to the increased cost of planting higher density stands. DeBell and Harms (*6*) found the planting of *Populus* plantations to be the largest single production cost, representing up to 40% of the total. In an evaluation of 15-yr rotation *Populus* plantations, Lothner et al. (*7*) placed site preparation and planting at $318/ha, with planting representing 46% of these costs.

Fertilization, where required, usually represents a significant cost input. Rose (*8*) estimated fertilization costs of *Populus* plantations at $62–370/ha, depending on site quality. Inman et al. (*9*) evaluated a wide range of SRIC plantations and found fertilization to comprise 20% of the total biomass cost, including harvest. Pfeiffer (*10*) found fertilization to be 30% of preharvest costs.

The harvest of woody biomass represents a major addition to total supply costs. Initial studies of harvesting have shown costs of $18–20/Mg(OD), representing 30% of the product's total delivered cost (*9,11*). However, much of this equipment was inefficient because it was originally designed for the harvest of either agricultural crops or domestic timber. Recent evaluations of equipment designed for the harvest of small diameter, closely spaced trees in SRIC plantations have reported costs in the range of $10–14/Mg(OD) (*4,12*).

The economics of SRIC plantations serve as a focal point for investigations organized by the School of Forest Resources at The Pennsylvania State University in cooperation with the US Department of Energy's Short Rotation Woody Crops Program. The project evaluated *Populus* hybrid grown under nonfertilized and fertilized strategies on two dissimilar sites (*13,14*). These management alternatives were analyzed in tandem with harvesting and storage options to determine the least-cost method of supplying feedstock to an ethanol conversion facility. This paper identifies the level and sources of production costs during the first two rotations of these plantations.

Table 1
Investment and Operating Costs for SRIC Plantations in Central Pennsylvania[a]

	Initial costs, $/ha	Annual costs, $/ha/yr	Cost Distributions: Equipment, %	Fuel and Materials, %	Labor, %	Land, %
Investment						
Land	1,712.10					100.0
Establish						
Site Prep.	44.12		54.8	13.3	31.9	
Herbicides	290.13		1.2	97.5	1.3	
Planting	916.75		18.2	30.8	50.0	1.0
Operating						
Maintenance						
Insect.-Fung.		26.70	16.6	77.8	5.5	
Land Taxes		11.93				100.0
Managerial		52.60	3.5	1.7	94.7	.2
Amendments						
Fertilization		84.41	8.2	89.8	2.1	
Irrigation		663.01	61.8	3.7	34.5	

[a] 1988 values.

METHODS

The Supply System

For cost analysis purposes, the proposed biomass system was divided into three stages: plantation, harvest, and storage. Within each stage, all technical operations were evaluated on a commercial scale basis. Costing procedures followed an accounting format organized along traditional variable and fixed-cost categories and further stratified in terms of the basic inputs: equipment, materials, labor, and land (*14*). All values reported herein are for the 1987–1988 base period, with a 5% real rate of return used in assessing the interest cost of investments.

Since the plantation stage involved an initial set of establishment costs, these investments were prorated at a 5% interest charge over the expected life of the plantation. In addition, an evaluation was made of the annual maintenance and operating costs required by the individual management strategies (Table 1). Companion sets of investment, operating, and maintenance costs were developed for the harvest and storage of biomass.

Plantation Design and Strategies

Plantation operations were patterned from a system of research plantations established in central Pennsylvania on two agricultural sites, representing good and moderate growing conditions. All trees were *Populus* hybrid NE-388 (*Populus maximowizii* × *trichocarpa*), planted at a spacing of 0.48 m^2 for intended 4-yr rotations, with 5 rotations expected from the initial root stock planting. Half of the plantations were established in 1980, with the remainder planted in 1981. Details on the establishment and operation of the plantations have been previously reported (*15*).

Four management strategies were included within the research design: control, fertilization, irrigation, and fertilization–irrigation. Fertilizer prescriptions were developed from soil analyses and applied on designated strategy units at a level that would have achieved a corn silage output of 47 Mg/ha (field weight). A trickle irrigation system was installed on designated strategy units to deliver a nonlimiting supply of water for tree growth.

The sequence and timing of establishment operations placed the plantation's optimum commercial size at approximately 900 ha (*14,15*). In order to insure a constant annual flow of biomass from the plantations, four 900-ha plantations would be established sequentially to provide a balanced-age production unit. This configuration could sustain an estimated output of 30,000–40,000 Mg(OD)/yr.

Harvest and Storage

Several harvest and storage strategies were evaluated through literature surveys and field inspections of commercial and research systems. Two harvesting strategies were selected for commerical-level cost analysis: a harvest-baling system developed by Schiess (*16*) and Stuart (*17*) and a harvest-chipping system reported by Sirois (*18*) and McKenna (*19*). In the harvest-baling system, trees would be cut, crushed, field dried, and baled, with the bales transported to the storage-conversion site by way of flat-bed trucks. Biomass was chipped prior to storage. The second strategy involved a simultaneous harvest-chipping operation, followed by transportation of the chips in tractor trailers. Transportation under both strategies was based on a round-trip truck haul of 80 km from the plantation site to the point of conversion. Technical parameters for the trucking operations were organized from previous transportation studies of woody biomass (*20*). Net biomass fiber recovery under both strategies was set at 90% of gross plantation yields.

Several storage systems were proposed as preutilization strategies. Since the plantations would be harvested during fall and winter periods, a 6-mo inventory of biomass would be required for the year-round operation of a conversion facility. Wet and dry storage strategies were evaluated to reflect the higher moisture content requirement of biomass used in the production of ethanol and, conversely, the below 25% moisture content (ovendry weight) requirement of biomass used in direct combustion.

Table 2
Biomass Production (Mg(OD)/ha) from First and Second Rotations of SRIC Plantations in Central Pennsylvania[a]

	Year 1	Year 2	Year 3	Year 4
First Rotation[b]				
Control	1.0	10.3	20.3	33.5
Irrigation	.9	9.0	21.0	33.3
Fertilization	.9	12.3	27.1	40.4
Fert.-Irrig.	1.0	12.7	27.1	42.1
Second Rotation[c]				
Control	6.2	19.0	30.8	35.3
Irrigation	6.8	18.5	29.9	36.9
Fertilization	4.8	19.0	38.3	41.4
Fert.-Irrig.	5.0	21.6	34.2	43.5

[a] Total tree yields (ovendry weight) at the end of each growing season, including mainstem wood, bark, and branches (25).
[b] 1981 planting only.
[c] 1980 and 1981 plantings.

RESULTS

Plantation Output

Yields reported in Table 2 represent an average from the two sites (*13, 21*). Although the two sites were initially selected as examples of good and moderate growing conditions, comparisons of the four strategies over two rotations have shown inconsistent yields, with the composite advantage on the better site held to 5%.

First rotation yields are from the second planting (1981) owing to the 1980 planting developing a growth lag from first year weed competition. This problem was effectively countered by a herbicide program used in the 1981 planting. Second rotation yields are an average from the two plantings. The growth lag, evident in the first rotation of the 1980 planting, was not repeated in the second rotation.

Overall, second rotation yields were only 5% greater than first rotation yields. Irrigation had the greatest first-to-second rotation gain (11%), with the remaining three strategies averaging less than a 5% gain.

Unit Production Costs

Unit costs for the biomass output were developed from a least-cost model proposed by Clutter et al. (22) and modified for the particular design of this study's SRIC plantations (23)

$$C = ((L + T/i + A/i) + E(1 + i)^n/(1 + i)^n - 1)) / Y_t/ (1 + i)^t - 1$$

where, C = biomass cost, per unit of yield; L = land costs, per unit area; T = annual maintenance costs, per unit area; A = annual fertilization and/or irrigation costs, per unit area; E = establishment costs, per unit area; Y_t = yield, per unit area; t = rotation age in years; i = real interest rate; and n = plantation life expectancy in years.

This formula established the unit cost of biomass as a function of the discounted cash flows for the establishment, operation, and maintenance of the SRIC system and the discounted yields from the plantation. Individual rotation lengths were analyzed in perpetuity. Evaluations of alternate rotation lengths have shown the least-cost solution for the particular design and spacing of the Penn State plantations to be 3 yr (*23*).

Unit costs for control and fertilization under the 3-yr rotation were decidedly lower than the remaining two strategies (Table 3). Control was least expensive at $28/Mg(OD). Although fertilization resulted in 24% more output than control, a 30% increase in production costs placed its unit costs at $30/Mg(OD). The tripling of production costs for irrigation, in combination with its minimal gain in production, resulted in unit costs of $99/Mg(OD) for irrigation and $94/Mg(OD) for fertilization-irrigation.

Cost distributions for the control strategy showed a near balance among: equipment and materials, labor, and land (Table 3). Fertilization, as a separate amendment, involved a 90% cost commitment to materials, with the total strategy allocating 48% of its costs to equipment and materials, 26% to labor, and 25% to land. Irrigation was capital intensive, with the entire strategy having over 55% of its costs in equipment and materials, 34% in labor, and the remaining 10% in land. Fertilization-irrigation included the cost influences of both amendments, with nearly 60% of its costs originating from equipment and materials, 30% from labor, and 10% from land.

Harvest and Storage Costs

Harvesting and transportation costs for the two proposed systems were comparable to other findings (*16–19*). The harvest-baling strategy had an estimated cost of $20/Mg(OD), with the more expensive harvest-chipping strategy placed at $35/Mg(OD) (Table 4). Nearly $8/Mg(OD) was required for the transportation of biomass under both strategies, based upon an 80 km round trip haul.

Both harvesting strategies were capital intensive, with labor representing the second highest expense. The smaller scaled harvest-baling strategy had 55% of its costs in equipment, whereas the more complex harvest-chipping strategy had 73% in equipment. Labor represented 27% of the total cost in harvest-baling and 17% in harvest-chipping.

Storage costs for a 6-mo period ranged from $10–28/Mg(OD), with dry storage involving the higher costs (Table 4). Equipment costs, tied to the movement and handling of wood chips, represented the major expense

Table 3
Production Costs from SRIC Plantations in Central Pennsylvania[a,b]

		Cost Distributions			
Strategy	Cost, \$/Mg(OD)	Equipment, %	Materials, %	Labor, %	Land, %
Control	28.37	7.9	24.3	32.3	35.5
Irrigation	99.13	45.9	9.8	33.8	10.5
Fertilization	29.77	8.0	39.6	25.2	27.2
Fert.-Irrig.	94.45	42.8	16.4	31.2	9.6

[a]Least cost analysis of 3-year rotation.
[b]1988 values.

Table 4
Harvesting and Storage Costs for Alternate Strategies[a]

		Cost Distributions			
Strategy	Cost, \$/Mg(OD)	Equipment, %	Materials, %	Labor, %	Land, %
Harvesting[b]					
Harvest-Baling[c]	20.06	55.0	17.8	27.2	0.0
Harvest-Chipping	34.70	72.6	10.0	17.4	0.0
Storage					
Wet storage of chips	10.24	54.0	23.5	22.0	0.5
Wet storage of chips, then dried	27.92	74.4	9.8	15.7	0.2
Dry storage of wet chips, then dried	16.87	60.4	17.2	22.1	0.3

[a]1988 values.
[b]Based on net plantation yield of 32.7 Mg(OD)/ha.
[c]Including chipping of biomass before storage.

in all three strategies; ranging from 54–78% of the total. The increased cost of dry storage strategies originated from drying equipment and associated energy inputs.

Total Cost Proposals

Total costs for the aggregate biomass system were developed from the more feasible strategies found within the three stages (Table 5). Plantation costs were based upon the lower costing control and fertilization strategies. The two harvesting strategies represented small- and large-scale systems currently under development. Finally, green and dry storage strategies were used to represent alternate specifications for delivered biomass.

Table 5
Biomass Costs for Alternate Supply Systems[a]

System and Strategies	Costs, $/Mg(OD)	Cost Distributions Equipment, %	Materials, %	Labor, %	Land, %
System 1					
Control production[b]	31.52	7.9	24.3	32.3	35.5
Harvest-baling	20.06	55.0	17.8	27.2	
Wet storage	10.23	54.0	23.5	22.0	0.5
Total	61.82	30.8	22.1	28.9	18.2
System 2					
Fertilization production[b]	38.08	8.0	39.6	25.2	27.2
Harvest-chipping	34.70	72.6	10.0	17.4	
Dry storage	16.87	60.4	17.2	22.1	0.3
Total	84.65	44.9	23.0	21.4	10.7

[a] 1988 values.
[b] Average net cost based on 90% recovery of total yield.

Two systems were built from the six options; a rudimentary system composed of control/harvest-baling/wet storage and an upgraded system organized from fertilization/harvest-chipping/dry storage. Total costs for the two proposed systems were $62 and 85/Mg(OD), respectively (Table 5). In the first system, 51% of the cost was for plantation production, 32% for harvesting, and 17% for storage. As the supply system was technically upgraded by way of fertilization, harvest-chipping, and dry storage, costs became more dependent on equipment and materials inputs.

On an input basis, the first system had 53% of its costs in equipment-materials, 29% in labor, and 18% in land. Harvest and storage were the primary sources of equipment and material costs. In the second system, an even larger commitment was made to equipment-materials (68%), leading to a proportionate reduction in labor and land costs.

DISCUSSION

A stated goal of the US Department of Energy's Short Rotation Woody Crops Programs is to develop specialized wood-energy crops for the production of liquid and gaseous fuels (*4*). This is in contrast to previous, more traditional proposals tied to the direct combustion of biomass for electric generation (*24*). Under current and near-future world prices for coal and petroleum, the conventional conversion of biomass to electricity cannot compete with large scale, coal- and oil-fired systems (*24*). In contrast, liquid fuels are in strategic short supply within the US, with about half imported, making this country vulnerable to supply and/or price disruptions (*25*).

The production of ethanol from woody biomass has been proposed by Bergeron et al. (*26*) and Wright and d'Agincourt (*27*) using several dilute acid hydrolysis processes, with net production costs ranging from $.34–.49/L. Wood costs in these proposals were placed at $42–46/Mg(OD), on a delivered to the mill basis, with wood representing 44–48% of the total manufacturing costs. Storage costs for biomass were incorporated as a general plant charge and not assessed specific to the raw material input. Alternative processes, as proposed by Wright (*25*), are based on an enzymatic breakdown of woody biomass and could secure even higher yields of ethanol. Projected production costs for the enzymatic process are in the range of $.44–.47/L, with the wood input at a $46/Mg(OD) price, dropping to 20% of the total conversion costs.

By comparison, SRIC biomass at $52/Mg(OD), also excluding storage, would be 13–24% higher than the costs targeted in the preceding ethanol conversion studies. SRIC biomass would raise ethanol manufacturing costs 10–15% in the dilute acid processes and 3–5% in the enzymatic process. However, to its credit, the more homogeneous physical and chemical charcteristics of *Populus* hybrid would provide a better quality feedstock for the sensitive ethanol conversion processes. Furthermore, this biomass could be supplied at a constant and sustained rate from SRIC plantation systems.

Sensitivity analysis was introduced to evaluate cost parameters having the greatest impact on SRIC biomass. The analysis was based on a proposed system composed of fertilization, harvest-baling, and wet storage. Operational factors having the greatest cost effect were: harvesting, plantation maintenance, and establishment, with an even greater impact realized from variations in plantation output (Fig. 1). A further address of these four factors was considered.

Currently, most SRIC harvesting strategies represent either developing technologies or adaptations of existing equipment used in domestic forests. Cost reductions in harvesting are anticipated, as equipment designs are specifically adapted to the functional needs of biomass plantations (*28*). However, a current stalemate seems to exist in the development process owing to the lack of markets for SRIC machinery. In turn, market development is largely constrained by the limited investments in SRIC plantations and allied conversion technologies. In all likelihood, the commercial feasibility of SRIC systems will need to be resolved first before further attention is placed on harvesting equipment.

Maintenance costs within the SRIC model included land use, managerial coordination of plantation work, and insecticides and fungicide applications. In total, nearly 50% of the cost within the fertilization strategy was from these sources. Although certain reductions could be made in terms of the quantity and quality of resources employed, any such cutbacks might also impinge on the output from the system.

One potential means for reducing maintenance costs would be realigning the model from a vertically-integrated, corporate-owned status to a

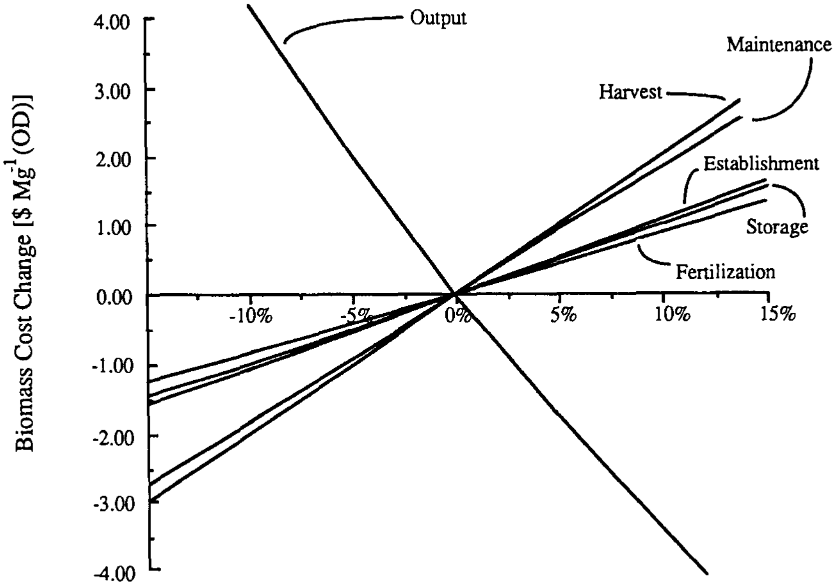

Fig. 1. Impact of percentage changes in operational costs and output upon the total biomass cost for the fertilization/harvesting-baling/wet store system.

nonintegrated, farm ownership base. This format could provide a certain continuity and efficiency in the production and harvesting operations common to agricultural and SRIC systems. Two potential sources of cost reduction within a farm-based SRIC system would be the managerial infrastructure and the expected returns to land. Potentially, agricultural management could be employed on SRIC projects in a more efficient manner and at a lower expected rate of pay. However, some caution must be taken when evaluating this farm-based scenario in terms of the actual availability of human and land resources, their associated market value, and the overall problems of coordinating a decentralized production effort. Although marginal land and labor might be provided at lower market prices, the caliber and quantity of resources required for commerical-scale SRIC operations could surpass these margins.

The cost of land, as projected by this study, was organized as an annual net return from corn production, with the capitalized value of this annual return agreeing with current land prices (*29*). To a certain degree, these returns are positively affected by various farm subsidy programs. Similar programs might be organized for the joint purpose of encouraging biomass production while, at the same time, limiting farm surpluses and maintaining the long-term potential of agricultural sites. To a large degree, the rationale for any new subsidy programs will depend on the cost tradeoff between existing and proposed subsidy programs and society's eventual need for biomass.

Establishment represented a third critical cost factor within the model. These expenses were largely controlled by the plantation design and the expected operational life of the plantation. The closely-spaced design used in this project required nearly 21,000 cuttings/ha, with the total planting cost representing 73% of the establishment charge. Although wider spacings would reduce planting costs, this would subsequently impact on rotation length, yields, and harvesting procedures. Several studies have suggested more economical designs in the range of 2000–7000 cuttings/ha, with rotation lengths of 5–10 yr (*4,28,30,31*).

A more direct approach to securing cost reductions would be increasing biomass output. Within the existing model, a 10% change in output would secure a $3–4/Mg(OD) shift in cost (Fig. 1). However, changes in production for any given strategy are largely controlled by plantation design, including the selection of any given *Populus* clone.

Considerable attention has been directed to the development of genetic hybrids as a means of increasing biomass yields. Production levels of 30–40 Mg(OD)/ha/yr have been suggested as an attainable biological goal (*4*). A recent summary of record SRIC small-plot yields from *Populus* hybrid has shown production levels in the range of 15–20 Mg(OD)/ha/yr (*32*). Although these research results were 4–7 times higher than earlier commercial field yields, future commercial yields of 10–12 Mg(OD)/ha/yr were considered attainable through the use of improved genetic material and cultural strategies (*32*). Further increases in commercial yields may be possible, with advancements dependent on cultural and breeding research.

Yields realized by this study at 13 Mg(OD)/ha/yr were within the range of expected field yields for commercial plantations for this region of the US. However, the actual attainment of commercial production at these levels may still be some years in the future, with further increases requiring added research and time.

SUMMARY

Economic evaluations of closely spaced *Populus* plantations under 3-yr rotations have shown an ability to produce biomass at a total cost of $65/Mg(OD), including harvest and storage of the material and a 90% recovery of gross plantation yields. Plantation costs of $32/Mg(OD), before harvest, were estimated for a control strategy averaging 10 Mg(OD)/ha/yr. Equipment-material, labor, and land inputs represented near equal portions of production costs. Plantation costs for the fertilization strategy were $2/Mg(OD) higher than control, even though growth averaged 13 Mg(OD)/ha/yr. Harvesting and storage required additional costs of $20 and $10/Mg(OD), respectively.

Under final analysis, the $65/Mg(OD) cost for SRIC biomass was 20–30% higher than current domestic wood prices. However, plantation costs were specific to the closely-spaced design and specific strategies used in these particular plantations. Various improvements and allied cost savings are expected in the future design, culture, and harvest of SRIC plantations.

Organization of biomass supply systems within the agricultural sector, as opposed to a vertically-integrated, corporate structure, could also provide a more economical source of management and land resources. This proposed shift in biomass production should be assessed in terms of available resources and the added costs of coordinating a more dispersed, farm-based supply system. Finally, increases of biomass output through genetic improvements should provide dramatic reductions in production costs. However, attainment of these goals, in terms of actual commercial applications, will require further research.

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