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Financial and Energy Costs of Supplying Woody Biomass to Conversion Sites

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ABSTRACT

A series of short rotation *Populus* plantations involving four management strategies were evaluated in tandem with alternate harvest and storage strategies to determine the least cost method for supplying biomass to conversion sites. All inputs were itemized on both a financial and energy basis to establish the unit output costs for commercial-scale systems.

The control strategy had the lowest production costs, at \$28.74 Mg^{-1} (ovendry), and 5,455 MJ Mg^{-1}(OD). The addition of harvest and storage costs, based on existing and proposed technologies within the forest product industries, increased the total supply cost for biomass to \$59.61 Mg^{-1}(OD) and 7,233.1 MJ Mg^{-1}(OD). On a financial basis, the proposed cost was 17% more expensive than a projected price for biomass from an ethanol plant and was also higher than the general prices for aspen from domestic markets. However, on an energy basis, the gross heat of combustion for the *Populus* biomass was 2.7 times greater than its total energy costs.

Index Entries: Woody biomass; economics; financial costs; energy costs.

INTRODUCTION

Biomass has received increased attention as a supplemental energy source following the oil and natural gas crises of the 1970s. Projections of biomass consumption within the United States indicate 5–15% of our total energy requirements could be obtained from biomass by the year 2000

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(1,2). This would represent an annual consumption of 130–350 million metric tons (Mg) of biomass.

Woody biomass represents a major component of this proposed aggregate supply. The current annual consumption of wood energy in the United States is 1.5 to 1.8 trillion megajoules (MJ), or approximately 2% of our energy needs (3). This role could be expanded through the increased uses of forest growth, forest mortality, and urban wood wastes, above and beyond current industrial roundwood needs. These particular sources could provide about 8% of our estimated US energy needs during the next decade (4). Additional wood energy could be realized from plantation systems designed to maximize biomass production. Nearly 5 trillion MJ could be obtained annually from energy farms by the year 2000 (5). However, a basic question concerning these short rotations, intensive culture (SRIC) systems is their financial capability of competing with other energy sources.

Some of the early cost estimates by Inman et al. (6) on the production of woody biomass from SRIC plantations using *Populus* hybrid placed the delivered cost at 20–\$31 Mg^{-1}(OD). Further evaluations of the regional variations in the supply cost for hardwood biomass throughout the US by Fege et al. (7) indicated potential delivered costs could range from 22–\$38 Mg^{-1}(OD).

The fertilization of *Populus* hybrid plantations was estimated by Pfeiffer (8) and Barron et al. (9) to increase the delivered cost of biomass to between 38–\$55 Mg^{-1}(OD). A similar increase in delivered cost was also identified by Vyas and Shen (10) in their modeled production of *Populus* biomass from fertilized plantations. Using alternate tree spacings and rotation lengths, their estimated delivered cost for biomass ranged from 42–\$56 Mg^{-1}(OD). Throughout the majority of these studies harvest and transportation costs represented 10–\$25 Mg^{-1}(OD), or 20–40% of the total delivered cost.

The financial and energy requirements for supplying biomass from SRIC plantations are being evaluated by the School of Forest Resources at The Pennsylvania State University in cooperation with the US Department of Energy. This project has provided financial and energy analyses of *Populus* hybrid grown under four production strategies on two dissimilar sites (11). These production alternatives were also analyzed in tandem with harvesting and storage options to determine the least cost configuration for an integrated biomass supply system. This report identifies the financial and energy costs for several proposed supply systems and the economic feasibility of using this woody biomass within two alternative conversion processes.

METHODS

Plantation Production

Biomass yields were developed from a series of *Populus* hybrid plantations established on two central Pennsylvania agricultural sites, representing favorable and unfavorable growing conditions. Each plantation site (1.2 ha) used six replications (.2 ha each) of four production strategies (.05 ha each for control, fertilization, irrigation, and fertilization-irrigation units). Half of the plantations were established in 1980, with the remainder planted in 1981. All trees were *Populus* hybrid NE-388 (*Populus maximowiczii* × *trichocarpa*) and were planted .6 m apart in rows spaced at .8 m. These spacings were designed for 4-yr rotations of the plantation, with five such rotations expected from the initial root stock planting.

Although the fertilization of *Populus* plantations has been evaluated on a research basis (*8–10*), there are no available standards for cost efficient rates of application. As an alternative, fertilizer was applied on designated strategy units at a rate that would achieve a maximum annual corn silage output of 47 Mg ha^{-1} (field wt). The fertilization treatments also provided the units with a balanced N-P-K-Ca-Mg nutrient set for equal enhancement of available macronutrients on both sites. A trickle irrigation system was installed on designated units to deliver a nonlimiting supply of water for tree growth. Moisture values in the upper 20 cm of soil were used to determine the frequency and volume of irrigation.

The Biomass Supply System

The three basic stages to the supply system, identified as production, harvest, and storage, were cost analyzed on a commercial scale basis using both financial and energy measures of the various inputs.

Within the production stage, each technical operation was analyzed on the basis of the rate of production for the central equipment units, the number of such units required for a particular operation, and the number of secondary equipment units required for complementary operations. The configuration of equipment needs and the seasonal time frame for certain operations placed the optimal commercial size of a plantation unit at approximately 900 ha. The combination of four plantation units and a satellite nursery represented 3750 ha and could sustain an annual production of 32,000–40,000 Mg (OD) of woody biomass. An associated set of managerial costs was developed for the business and technical operation of the plantation system.

Two potential harvesting strategies were considered; a harvest/baling system and a harvest/chipping approach. In the harvest/baling strategy, as proposed by Schiess (*12*) and Stuart et al. (*13*), trees would be cut, crushed, field dried, and baled before loading and transporting to the storage/conversion site. This particular system was field tested on the project's *Populus* plantations and provided production rates similar to those reported in the literature (*13*). The size and scale of the various equipment units were also considered appropriate for the diameter range, number, and spacing of stems on these plantations.

The second strategy has been described by Massey et al. (*14*) and Sirois (*15*), and involves a simultaneous harvest/chipping operation using larger scale field equipment, followed by the transportation of chips to the storage/conversion site. Although this proposed system can achieve a higher rate of harvest output than the first strategy, it is also dependent on larger scale equipment investments. Potentially, this system may represent a certain over-design for the more closely spaced and smaller diameter trees realized from four year rotations.

The two strategies provided a range of costs among somewhat diverse, but applicable, approaches to harvesting. The first strategy involved smaller scale equipment and a baled delivery of crushed stems, whereas the second strategy had larger scale equipment and the more conventional chipped form of biomass. Biomass recovery under both strategies was set at 90% of gross plantation yields.

Transportation of the harvested biomass was based on a round trip truck haul of 80 k from the plantation site to the point of conversion. The general structure of the financial and energy parameters for this operation were organized from previous studies on the truck transport of woody biomass (*16,17*).

Several storage and drying alternatives were proposed as preutilization strategies for the conversion site. Since the plantations would be harvested during fall and winter periods, a sizable inventory of biomass would be required for the year-round operation of a conversion facility. The specifics of the storage alternatives reflected the conversion requirements of the woody biomass. For example, in the production of ethanol, a high moisture content would be desirable. However, for direct incineration, moisture levels should be below 25% (ovendry wt basis) to maintain a higher conversion efficiency.

Cost Analysis

The financial evaluations of the biomass systems used an accounting-type model rather than a cash flow model, with the initial cost of establishing the plantation prorated over the planned series of five rotations. In addition, all costs incurred during any given rotation were compounded to the end of the rotation. This provided the means for evaluating the unit cost of the biomass output and a basis for aggregating the subsequent costs of harvesting, transportation, and storage. All financial values were for the base period 1980–1981, with a 5% real rate of interest used in compounding values over time.

The depreciation and interest costs for equipment operations were developed as annuity payments based upon the equipment's total principal cost, operating lifetime, and a 5% real interest charge. Material and labor costs for the various operations were organized from the technical requirements of each operation and the current market value of these inputs.

The charge for land was expressed as an opportunity cost, or economic rent, and represented the annual net revenue available from corn production. Corn prices were based on competitive market quotations. The capitalized value of the annual economic rent agreed with the range in land values quoted for Pennsylvania farm real estate during the period 1976–1981 (*18*). Property taxes were assigned in accordance with these capitalized land values and regional taxing procedures.

Energy costs were organized in a standard variable and fixed cost accounting convention. The variable energy costs for material inputs, such as fuel, herbicide, pesticide, and fertilizer products, were based on the energy to weight ratios for the product, multiplied by the volume of material used in their respective operations. The energy cost of human labor was itemized but proved to be a small energy input.

The fixed costs for equipment operations were patterned from a methodology proposed by Pimentel (*19*). This approach divided energy costs into

1. Those embodied in the equipment's basic materials,
2. Those employed in the fabrication of the equipment,
3. Those embodied in repair parts.

These basic energy investments were divided over the equipment's operating lifetime and itemized for each operation on the basis of equipment operating time.

The energy equivalent for land rent was the net energy return from corn production foregone by the use of the site for SRIC plantations. These values were organized for central Pennsylvania agricultural sites through the development of energy budgets for corn production. Although corn is not a traditional biofuel it did represent the primary field crop for this region. The annual net energy return of 41,943.7 MJ ha^{-1} for corn production, compared favorably to the results reported by Pimentel (*19*) for four growing regions in the northeastern US. The energy equivalent for property tax was the energy to financial cost ratio for land rent, multiplied by the financial cost of the tax.

RESULTS

Plantation Production Costs

The end-of-rotation financial costs ranged from \$1014.62 ha^{-1} for the control strategy to \$3646.08 ha^{-1} for fertilization-irrigation on the better site* (Table 1). For the control strategy, land rent and taxes represented nearly one-third of the financial costs. The prorated establishment cost was 31% of the total production costs, and managerial costs amounted to 24% of the total. Fertilization added 49% to the base cost of the control strategy, whereas irrigation nearly tripled the financial charges from the control program.

From an energy accounting standpoint, land rent and taxes were the dominant costs; amounting to 96% of the total. Although this amount of

*The less favorable site averaged 15% greater costs for the fertilization and irrigation strategies and 6% lower yields; thereby removing this site from further consideration.

Table 1
Production Costs For First Rotation Biomass Plantations

Operation/strategy	Financial costs,[a] $ ha^{-1}	Energy costs, MJ ha^{-1}	Financial to energy ratios, $ GJ^{-1}
Operational Costs			
Establishment[b]			
Site preparation	13.10	238.6	54.90
Herbicides	72.74	644.6	112.84
Planting	233.47	2,197.7	106.23
	319.31	3,080.9	103.64
Maintenance			
Insect.-fung.	85.94	3,951.6	21.75
Land rent and tax	361.66	185,506.8	1.95
Management	247.71	20.9	11,852.15
	695.31	189,479.3	3.67
Cultural amendments			
Irrigation	2,132.81	21,989.1	96.99
Fertilization	498.65	51,600.8	9.66
	2,631.46	73,589.9	35.76
Total strategy costs			
Control	1,014.62	192,560.2	5.27
Irrigation	3,147.43	214,549.3	14.67
Fertilization	1,513.27	244.161.0	6.20
Fert. = irrg.	3,646.08	266,150.1	13.70

[a]Costs compounded to end of four year rotation at 5% annual rate.

[b]Financial costs of establishment were prorated over 20-yr plantation life at a 5% annual rate. Energy costs of establishment were divided uniformly over 20-yr plantation life.

energy (185,506.8 MJ ha^{-1}) was not actually expended in production, it did represent an accounting debit for the amount of net energy expected from biomass production. Failure to meet this expected return would be sufficient cause for returning the land to corn production.

For the 7,053.4 MJ ha^{-1} of energy actually used in the control strategy, 56% was for the biennial application of insecticides and fungicides and 44% was for the amount of planting costs proportioned to the first rotation. In the fertilization strategy, the fertilizer materials represented seven times more energy than was actually used in the entire control strategy. Irrigation was another energy intensive operation but only required about 40% of the energy used in fertilization. About 5% of irrigation's energy cost was for pumping water to the trees, with the remainder tied to the energy embodied in irrigation equipment.

The relative financial costs of the energy inputs used in the various operations were evaluated by way of their financial to energy cost ratios, expressed on the basis of dollars per thousand megajoules (gigajoules) of energy input ($GJ^{-1}). Low cost ratios were identified in land rent and taxes, fertilization, and the insecticide/fungicide operations (Table 1). Land's energy cost of \$1.95 GJ^{-1} was obtained by the division of the financial cost of land rent by its comparable energy cost. This relatively low ratio represented the moderate net financial returns expected from corn production in comparison to its major net energy returns. The cost ratios for fertilization (\$9.66 GJ^{-1}) and insecticide/pesticide operations (\$21.75 GJ^{-1}) reference to the materials used within each operation. In both instances, the materials has relatively low financial costs and high energy costs.

In contrast, the highest cost ratio was for managerial operations (\$11,852.1 GJ^{-1}). Here, the substantial financial charge for human labor was in sharp contrast to its modest energy requirement. Most of the operations using substantial amounts of labor also had relatively high cost ratios, with irrigation and the various establishment operations having ratios in the vicinity of \$100 GJ^{-1}.

The composite of all operations represented within the four plantation strategies had cost ratios ranging from \$5.27 GJ^{-1} for control to \$14.67 GJ^{-1} for irrigation. The generally low values for these cost ratios reflected the dominant position of land within the energy accounting process. A reanalysis of the strategies, net of the financial and energy charges for land, placed fertilization with the lowest cost ratio (\$19.63 GJ^{-1}); followed by fertilization-irrigation (\$40.73 GJ^{-1}), control (\$92.57 GJ^{-1}), and irrigation (\$95.92 GJ^{-1}). This ranking correlated with the relative increase in the financial cost of labor among the control and irrigation strategies.

Unit Production Costs

The first rotation ovendry biomass yields reported in Table 2 on an overdry tonne basis (Mg [OD]) include all wood, bark and branchwood above a 15 cm stump height. These ranged from 32.65 Mg (OD) ha^{-1} for the irrigation strategy to 43.0 Mg (OD) ha^{-1} for fertilization-irrigation. Basically, the addition of fertilizer to these sites increased biomass output, either as a separate amendment or in combination with irrigation.

Table 2
Total Biomass Yields and Unit Production Costs from First Rotation Plantations

Management Strategy	Biomass Yields,[a] Mg (OD) ha^{-1}	Unit financial cost, \$ Mg^{-1} (OD)	Unit energy cost, MJ Mg^{-1} (OD)	Financial to energy ratios, \$ GJ^{-1}
Control	35.3	28.74	5,455	5.27
Irrigation	32.6	96.55	6,581.3	14.67
Fertilization	42.5	35.61	5,745	6.20
Fert. = irrg.	43	84.79	6,189.5	13.70

[a]Four year total tree yields, ovendry weight.

However, irrigation by itself, was redundant with the normal rainfall and groundwater supplies available to this site and resulted in lower yields than the control strategy.

The financial and energy costs for each strategy were determined on a per unit output or stumpage basis (Table 2). The financial and energy cost rankings for the strategies were identical. Least expensive was control ($28.74 and 5,455.0 MJ Mg^{-1} [OD]). The relative increase in financial and energy costs for fertilization were not matched by an equivalent gain in output, resulting in higher per unit costs ($35.61 and 5,745.0 MJ Mg^{-1}[OD]). Irrigation had the highest per unit financial and energy costs ($96.55 and 6,581.3 MJ Mg^{-1}[OD]). The combined fertilization-irrigation strategy achieved some cost reductions over irrigation because of an increased output. Here, the relative increase in fertilizer's financial and energy costs were exceeded by its gain in output. Although the margin from fertilization was cost effective, the composite venture was still cost prohibitive ($84.79 and 6,189.5 MJ Mg^{-1}[OD]).

Harvesting and Storage Costs

The financial costs for harvesting the proposed biomass systems compared favorably to other published findings (*8–10*). The harvest/baling strategy had an estimated financial cost of $19.08 Mg^{-1}(OD) and the harvest/chipping strategy a cost of $33.30 Mg^{-1}(OD) (Table 3). Both systems used similar amounts of energy; 937.6 MJ Mg^{-1}(OD) for harvest/baling and 996.2 MJ Mg^{-1}(OD) for harvest/chipping.

Table 3
Harvesting Costs for Alternate Strategies[a]

Operation/strategy	Financial costs, $ Mg^{-1} (OD)	Energy costs, MJ Mg^{-1} (OD)	Financial to energy ratios, $ GJ^{-1}
Harvest/Baling Strategy			
Harvester, Tractor	3.93	100.5	39.10
Baler	3.54	113.0	31.33
Loader-Unloader	4.00	293.0	13.65
Tractor-Trailer (bales)	4.53	171.6	26.40
Plant Chipper, Conveyor	3.08	259.5	11.87
Total	19.08	937.6	20.35
Harvest/Chipping Strategy			
Harvester/Chipper	14.34	380.9	37.65
Forwarder	8.22	251.2	32.72
Transfer Utility	2.60	54.4	47.79
Tractor-Trailer (chips)	7.52	288.8	26.04
Unloader, Conveyor	.62	20.9	29.66
Total	33.30	996.2	33.43

[a]Based on net plantation yield of 32.7 Mg ha^{-1}

In the harvest/baling strategy, transportation was the largest financial cost (24%), followed by loading-unloading (21%), and the harvester (21%). The major financial costs for the harvest/chipping strategy were the harvest/chipper (43%) and its accompaniments (33%). These two equipment items were responsible, in large part, for the cost differential between the alternate strategies. From an energy standpoint, the harvest/baling strategy had nearly 60% of its costs in the loader-unloader and plant chipper whereas the harvest/chipping strategy had 67% of its energy cost in the harvester/chipper and tractor-trailer.

The variation in the financial and energy costs among the storage strategies was dependent on the particular characteristic of the storage technique, with total financial costs ranging from 8.60–$24.35 Mg^{-1}(OD) (Table 4). Strategies involving the drying of green wood chips had the highest financial and energy costs.

Total Supply Costs for Biomass

Various strategies were selected from each stage in the supply system to develop the probable range of total financial and energy costs for biomass at the conversion center. Plantation costs were based on the two minimal cost strategies, control and fertilization.

Both harvesting strategies were used in this final stage of analysis as examples of a least cost, but developmental, harvest/baling system and a more expensive, but largely available, harvest/chipping system. Finally, two storage strategies were selected to meet alternate material specifications. The conversion of biomass to ethanol via hydrolosis/fermentation would require wet storage, thereby insuring biomass with a high moisture content. In contrast, incineration of biomass for electrical generation would place a priority on lower moisture contents and dry storage.

The least cost system, consisting of control production, harvest/baling, and wet storage, had unit cost of $59.61 Mg^{-1}(OD) and 7,233.1 MJ Mg^{-1}(OD) (Table 5). In contrast, the maximum cost system, composed of fertilization production, harvest/chipping, and dry storage, had costs of $87.89 Mg^{-1}(OD) and 7,484.2 MJ Mg^{-1}(OD).

Table 4
Storage Costs for Alternate Strategies

Strategy	Financial costs, $ Mg^{-1} (OD)	Energy costs, MJ Mg^{-1} (OD)	Financial to energy ratios, $ GJ^{-1}
Wet storage of chips	8.60	234.4	36.69
Wet storage of chips, then dried	24.35	309.8	78.60
Dry storage of wet chips, then dried	15.02	104.7	143.46
Chips dried and dry storage	15.93	213.5	74.61

Table 5
Biomass Costs for Alternate Technological Systems

System/operations	Financial costs, \$ Mg^{-1} (OD)	Energy costs, MJ Mg^{-1} (OD)	Financial to energy ratios, \$ GJ^{-1}
System #1			
Control production[a]	31.93	6,061.1	5.27
Harvest/baling	19.08	937.6	20.35
Wet storage	8.60	234.4	36.69
Total	59.61	7,233.1	8.24
System #2			
Fertilization production[a]	39.57	6,383.3	6.20
Harvest/chipping	33.30	996.2	33.43
Dry storage	15.02	104.7	143.46
Total	87.89	7,484.2	11.74

[a]Net costs based on 90% recovery of total yield.

In the least cost system, 54% of the financial cost was from plantation production, 32% from harvesting and the 14% from storage. As the supply system was technically upgraded by way of fertilization, harvest/chipping, and dry storage, the financial costs increased and were more dependent on equipment. For fertilization, 98% of the increased cost was tied to materials and equipment. Similarly, harvest/chipping had 96% of its increased cost tied to equipment. The conversion from wet to dry storage found 77% of the added cost in equipment and material inputs.

Maximum Values for Biomass

The economic feasibility of using *Populus* biomass within an electric generation facility or an ethanol production center was evaluated on the basis of the maximum price that could be paid for biomass by either conversion system. A maximum residual price was developed by subtracting all manufacturing costs for the conversion process, including the return to capital, from the gross revenue earnings for the energy products. This residual price would be the maximum available for covering the costs of plantation production, harvesting, transit, and storage. This type of pricing strategy assumed that the buyer of biomass would have the dominant market position, similar to that found in many timber markets.

The electric generation facility was based on a 50 megawatt, wood-fired system proposed by Skeleton et al. (*20*). However, this type of venture presented major financial limits within the structure of existing energy markets. Financial evaluations showed plant costs of \$.067 kWh^{-1} (kilowatt hour) exceeding the regional industrial market price for electricity by \$.009 kWh^{-1}. Since these comparative small scale p lants would not be competitive with larger scale, coal-fired plants, they were removed from further consideration.

The conversion of woody biomass to ethanol provided a stronger potential. A proposal by Wright and d'Agincourt (*21*) for manufacturing ethanol from aspen under a high temperature, hydrolysis system established annual financial and operating parameters for a 190 million L capacity plant. Plant costs, inclusive of a by-product credit, were \$.151 L^{-1}. With the commercial market price for fermented ethanol at \$.42 L^{-1}, the maximum residual price for biomass was equivalent to \$51.02 Mg^{-1}(OD). This particular price was comparable to the delivered (and stored) prices for aspen (*Populus tremuloides*) in western and Lake State markets (*21,22*). However, in comparison, the *Populus* biomass from the least cost system, delivered and stored at a cost of \$59.61 Mg^{-1}(OD), would be 17% higher in cost than the maximum residual price.

A net energy evaluation of *Populus* biomass was developed by comparing its inherent gross energy potential to the total energy costs of supplying this feedstock to a conversion center. Although this method did not include any measures from a secondary conversion process, as organized in the financial evaluations section, this approach was more consistent with the development of energy costs for land rent. These particular energy costs were organized from the gross energy of corn rather than any net energy measures taken from a secondary process or food chain system. With land rent and taxes representing over 80% of the energy costs in the biomass budgets any effort to evaluate *Populus* on the basis of its net energy from secondary processing rather than gross energy would place it at a decided disadvantage.

The energy value for *Populus* was based on its gross heat of combustion, with the weighted value for the wood and bark components measured at 19,392.5 MJ Mg^{-1}(OD) (*11*). As such, the potential energy output from biomass was 2.7 times greater than the total budgeted energy from the least cost system (7,233.1 MJ Mg^{-1}[OD]). This substantial increase in energy, over and above all energy inputs, including those for land use, represented the photosynthetic gain realized by these forest systems over their four year growing period.

DISCUSSION

The total cost of producing biomass from SRIC plantations displayed a considerable variation among the alternate management strategies during their first rotation. Least expensive, on a financial and energy basis, was the control strategy, with total costs, before harvest, of \$28.74 Mg^{-1}(OD) and 5,455 MJ Mg^{-1}(OD). Fertilization increased these financial costs by 24% and the energy costs by 5%. Irrigation was an unrealistic option for this region, either as a singular strategy or in combination with fertilization. The use of irrigation increased the financial costs to between \$85 and \$100 Mg^{-1}(OD) and the energy costs to between 6200 MJ and 6600 MJ Mg^{-1}(OD), respectively.

Two biomass supply systems were evaluated—a least cost system adaptable to an ethanol plant, and a moderate cost system adaptable to an electric generation facility. In the least cost system, harvesting represented 32% of the total financial costs and storage 14% of the total costs. For the moderate cost system, harvesting was 38% of the total financial costs and storage was 17%. Overall, harvest, transit, and storage represented close to 50% of the total financial costs in either system.

The conversion of *Populus* biomass to ethanol provided the strongest financial potential for these raw material supply systems. However, based on a projected maximum price that could be offered for biomass, the least cost system would still exceed this price by 17%.

Reductions in the unit cost of biomass could be obtained by either a decrease in input costs or an increase in plantation output. Within the production stage of the system, land was a major input cost. Although certain cost savings could be obtained through the use of marginal agricultural sites, their production capability would most likely be below those sites used in this project. As proposed, the scale of operations for commercial plantations will require major blocks of good quality land. Thus SRIC plantations will be in direct competition with alternate agricultural pursuits and, therefore, must have the financial capability of making a competitive return to these sites.

Although the control strategy was nearly \$7 Mg^{-1}(OD) less than fertilization, there remains some question as to whether the control strategy's nutrient drain will sustain the same output over continued rotations. Fertilization may be required to maintain a near constant flow of output from the plantations. However, there is some potential for reducing the amount of fertilizer used in these strategies without impeding the rate of growth of the *Populus*. Evaluations of the actual nutrient uptake by the *Populus* hybrids have indicated that the trees used less nutrient materials than was supplied (*11*). Reductions of nitrogen and phosphorus by 20 to 30% seem feasible and will be further evaluated by this project.

One of the best potentials for securing further cost reductions would be through increased plantation production. The total supply costs reported by this study would meet the proposed price for biomass if production was increased in the control strategy by 37% or in fertilization by 70%. Currently, the second rotation, midterm production levels for the project's plantations are 50% above their comparable first rotation levels. These gains have the potential of partially offsetting the higher costs recorded during the first rotation. Further evaluations will be made on the best means for optimizing biomass yields and allied financial returns through the manipulation of production strategies and rotation periods.

Harvesting is another critical stage to the proposed biomass supply systems, representing nearly one-third of the total financial costs. Most harvesting strategies, including those analyzed by this study, are largely representative of either developing technologies or adaptations from the harvest of domestic forests. As such, further cost savings might be anticipated as more functional and efficient harvest equipment is developed for future biomass plantations.

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