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An Inventory Control Model for Supplying Biomass to a Processing Facility

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ABSTRACT

An inventory control model was developed to determine the least cost approach for supplying biomass to a processing plant. Model applications were made for the plantation, harvest, and manufacturing components of woody biomass to ethanol supply systems to assess efficiency and financial performance.

Model solutions determined the optimum inventory policy for hybrid poplar plantations grown over rotation lengths of 4 through 8 yr. The harvest occurred during a 6-mo time frame after the growing season. All biomass was directed to an ethanol manufacturing facility capable of processing 10,000 Mg(OD) of harvested raw materials/mo^{-1}. At this level, the facility was required to meet an output demand of just over 3,000,000 L/mo^{-1}.

An evaluation of model solutions led to an optimum biomass rotation length of six yr and an ethanol production cost of \$0.376 L^{-1}. The least-cost policy established the harvesting requirements and storage schedules for standing trees, harvested raw materials, and ethanol. Inventory control had a major impact on production costs, with alternate strategies within the rotation increasing ethanol costs by as much as 62%.

If biomass is to compete as a viable feedstock for alternative fuel or chemical production, additional cost reductions will be necessary. These can be realized through the inventory control of standing trees, harvested materials, and final product.

Index Entries: Inventory control; storage; biomass; shortage costs; harvesting.

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INTRODUCTION

Wood has traditionally been a primary energy source for humankind. It was the dominate fuel in the United States until the advent of the Industrial Revolution (1870s) and the subsequent widespread use of fossil fuels. In the United States and many other countries, a strong dependency on fossil fuels has arisen. Oil alone accounts for 40.2% of primary energy consumption in the United States, 47.3% in Western Europe, and 59.2% in Japan (*1*). It is unsettling that a large portion of this fuel is imported, and the amount is increasing (*2*). Fossil fuels are associated with other problems. The combustion of fossil fuels has played a major role in the dramatic rise of carbon dioxide in the atmosphere (*3,4*). The atmospheric concentration of carbon dioxide has increased from a preindustrial level of 275 ppm volume in the mid1800s to around 343 by 1984 (*5*). This phenomenon is viewed as being chiefly responsible for a "greenhouse effect," which could lead to climatic warming (*4*).

Because of the political, economic, and environmental instability of fossil fuel dependency, an extensive effort has been put forth to pursue alternative energy sources. Wood has received renewed attention, in part owing to certain desirable features associated with potential woody biomass supply systems. As an illustration, the amount of carbon dioxide given off to the atmosphere through wood for energy use is offset by the CO_2 sequestered by tree growth (*6*). Faster-growing species can absorb CO_2 more rapidly, with the overall CO_2 level even decreasing until harvest. Thus, woody biomass energy systems have the potential to be at least neutral in their atmospheric impacts. Also, fuels derived from woody biomass offer varying degrees of fossil fuel replacement. This substitution, although not yet cost competitive, offers a more reliable fuel source immune to the oil price volatility experienced in the last 15 yr by such net oil importers as the United States (*7*). From an economic perspective, wood has the potential to develop new product markets, particularly in fuels and chemicals (*7*). In addition, there are the apparent advantages for an enterprise in maintaining a secure, internal energy supply.

Recently, short-rotation woody crop research has focused on growing trees for energy-related products. Most of the emphasis has been on genetic, silvicultural, and economic evaluations of plantation production strategies (*8,9*). The manufacturing techniques for converting woody biomass into energy products have also received attention (*10–16*). However, inherent to these proposed supply systems is a need to schedule and otherwise control the inventories of raw materials and final products, particularly on a commercial level (*8,17,18*). This aspect of the production system is in further need of study. Analytical procedures and inventory policies relating to specific manufacturing processes are also lacking (*19*). Furthermore, little research has been done to develop harvest and storage techniques or policies (*20*) for woody biomass material that tie into specific manufacturing processes.

Forests are a unique production function, because trees represent both the capital input and product output of an enterprise (*21,22*). As a product, they also represent a financial commitment to inventory. Moreover, trees are perishable and have a supply potential limited by the finite duration of the harvest period (*18*). The storage of harvested materials involves added capital and operating costs along with changes and losses of inventory over time (*9,23–30*). Overall, matching the cyclical and finite nature of plantation supply systems with the steady-state demands of a processing plant introduces a complex of inventory control problems and allied costs.

Increasing the consumption of woody biomass depends on a more efficient use of available and potential wood resources. Improvements in delivery systems, from the planting of cuttings through the manufacturing process, lies in the coordinated scheduling of individual requirements within the overall production function (*17*). This will establish a more integrated operation, whereby no single task hinders the productivity of another. The production function is characterized by various technical operations within the plantation, harvest, and manufacturing components of the supply system. Also, storage in some form is a common denominator throughout the system. Thus, an inventory control policy for this type of supply system was viewed as a fundamental goal of the production process.

A basic impediment in the development of biomass supply systems, beyond a lack of procedural policies, is the question of their financial competitiveness (*31*). The essential issue is supplying from standing inventories and on-site storage a high-quality, low-cost feedstock, while avoiding unacceptable shortage costs. Shortages are the result of a loss of raw materials and/or product unavailability for the market. Costs are then incurred from the dollars invested in lost materials or from a loss of profit owing to unsatisfied customer demand and no backlogging.

In summary, the inventory management problem is unique to biomass utilization, because it deals with an organic resource whose supply potential is often limited within specific time spans during the year, unless storage occurs. Conversion processes typically impose some degree of constant utilization throughout the year. Raw material storage, to prevent shortages or because of limited manufacturing process capacity (*32*), is a likely outcome of steady-state process requirements and apt to be characterized by a change of and loss of materials over time. A market environment, which includes alternative organic feedstocks, also influences the decisions of system managers. A solution to this type of inventory control problem, under the influence of both procedural and economic considerations, will have implications for commerical enterprises operating under similar circumstances.

This study views the plantation, harvest, and manufacturing components of a woody biomass supply system within the context of inventory control. The overall goal is to examine the efficiency and financial performance of such an investment under the associated constraints of the system. The attainment of this central goal involves two allied objectives relating to the model development and interpretation of results.

The first objective was to develop a model and analytical procedure to aid the decision-making process of a manager concerned with inventory control of a natural-resource-based production system. Specifically, this involved the use of dynamic programming in the analysis of the inventory control model.

A second objective was to utilize the model to determine a least-cost solution for producing ethanol from a biomass/processing scheme. Evaluations were made on the supply potential for ethanol of a particular plantation, harvest, and manufacturing system under varying rotation lengths. The harvesting decision was used as the key decision variable in the model. These results determined the optimum ordering (harvest) policy for a given rotation length while minimizing the total cost of the overall system. The analysis sought the advantages of balancing various inventories, in order to cut costs (e.g., raw material storage losses), and by having inventories delivered, as needed, in order to minimize potential shortages of feedstocks and end products.

METHODS

The development of the model is illustrated through a detailing of background information relevant to the inventory control problem. A description of the general model will clarify the relationships within the inventory control problem. The model in turn supported the decision on the use of this particular mathematical programming technique to derive an optimal solution.

Model Description

An inventory control model can be an integral part of an organization's planning process. In general, the model was intended to fulfill the short- and long-term operational planning objectives and needs of an enterprise. The inventory model described a system of feedstock development and/or procurement programs used to create an end product for its market.

The specific form of the model used in this study consisted of three components:

1. A woody biomass plantation;
2. Woody biomass harvesting and transport; and
3. End product manufacturing.

All components were characterized by the initiation of specific tasks, various types of inventories, and the associated costs. The plantation component described the availability of the raw material resource as standing trees. The harvest component was characterized by the harvest method, and the transport and storage options for raw materials. The manufacturing component detailed the process for converting raw materials into a final product, and their subsequent storage or sale. Although each component was the impetus for a particular inventory, there was a considerable overlap of inventories within each component. For example, standing trees, harvested raw materials, and liquid fuel inventories could all coexist within the same time period.

Certain assumptions and parameters were associated with the general inventory control model for the supply process. The model was capable of handling up to three different raw material or feedstock types (e.g., woody biomass, agricultural crops, fossil fuels) within a system subject to a multiechelon demand pattern throughout the year. The first demand echelon described the raw material requirements, which are a direct result of the processing capacity of the manufacturing facility expressed in Mg(OD) equivalents. This parameter can be constrained to any amount for a given time frame. Processing of on-hand raw material inventories was on a first-in, first-out (FIFO) basis. All inventories were subject to a periodic review whereby the order quantities varied, but the interval between reviews remained constant. When raw material replenishments were required, there was an immediate entry (no lead-time) into the system at the beginning of a time period. However, the replenishment opportunities were seasonal within the annual cycle because of harvesting contraints. The second demand echelon reflected the market demand for the end product identified as liters. This parameter could also be set at any level for a given period of time. Eventually, the final product leaves the system from one period to another according to a variable market demand pattern. All demands were uniform or constant within a given time period. The time periods in the model were set up as months of the year, although they could be set to any length.

Another set of parameters was characterized by the inventory replenishing capabilities of the model. This included the uncut quantity of available trees at any time after completion of a growing season (standing inventory), and the net quantity harvested and delivered at the beginning of a time period within the year. Replenishments from storage were the cumulated raw material inventories at the beginning of a current period minus the loss of raw materials during the period and inventoried final product after processing and sales transactions.

The last group of properties consisted of the costs associated with the plantation, harvest, and manufacturing component tasks. These model costs were structured under an accounting format that identified all investment and operating expenses (33). Machinery operations were based on time and motion studies in order to evaluate their variable and fixed costs features. Variable costs were based on assigned levels of operation, and included repairs, maintenance, fuel materials, and labor. The fixed costs represented the depreciation of equipment, interest charges, insurance, and shelter. Each expense, viewed as an average annual capitalized cost for a unit of output, was recorded in the year that harvesting and manufacturing of associated yields took place. For example, standing trees were considered an asset to the system until harvested, at which point they became a cost. At this juncture, the establishment and maintenance costs were added to the harvest and transport costs. Whenever rotation lengths were considered in the model, costs and plantation yields were subject to change, and this in turn could adjust the unit costs of each task. All costs were developed in US dollars (1990) per metric ton, ovendry (Mg^{-1}[OD]), or per liter (L^{-1}).

The costs for each task were calculated and entered into the model program. While generating a solution from the program, these task costs were summed both for each time period and then incrementally over the annual cycle. Alongside these cost calculations was a coinciding end product unit cost and the respective contributions by each task to the total. Costs were also realigned within the model program to describe the feedstock and manufacturing costs and the basic inventory cost categories, as they exist throughout the model components. Feedstock costs consider all costs up to the point of raw material processing.

The major inventory cost categories were subsequently described to reflect the specific tasks encompassed. These cost breakdowns are typically classified as:

1. Replenishment, ordering, or manufacturing;
2. Carrying or holding; and
3. Shortage (*34,35*).

Ordering or replenishment costs describe expenses attributed to the initiation of inventories. They can be further described to include setup and processing or manufacturing costs (*35*). Establishment costs were incurred to setup the standing tree inventories. Plantation costs included all operations based on the equipment's total principal cost, operating lifetime, and a 5% real interest charge. Material and labor costs for the operations used the current market value of these inputs. Similarly, harvest and transport tasks represented the costs to bring raw materials to the manufacturing site. The processing of raw materials leads to the creation of the final product (e.g., ethanol), and the cost may vary depending on the feedstock.

Carrying costs for inventories pertain to any expenses that relate to the holding of inventories for any time period. Plantation maintenance costs included those associated with carrying standing trees after plantation establishment. Storage and handling of raw materials were the costs for holding harvested woody biomass and any purchased feedstocks before processing. Storage and handling were also considered for the final product before it was sold. The opportunity cost of capital, considered a carrying cost, was recorded for all inventories during every year of operation.

Shortage costs traditionally relate to shortfalls or "lost sales" resulting from the final product and market demand. Penalty costs have been used to represent a loss of sales and goodwill for any time that a product was out of stock (*36*). Using "lost sales" to represent a system cost is a technique often used in economic inventory models (*34,35,37,38*). However, shortages can be incurred during the input or production phase of an operation. "Lost sales" associated with feedstock inputs were unique to this study and were used to gage the efficiency of operations associated with raw material procurement. The model was constructed so a penalty cost to the system could be incorporated for each missed opportunity attributed to the input and/or the output. In the former instance, for shortages resulting from harvesting inefficiencies and storage deterioration, it included a penalty cost, expressed as the selling price per liter minus the processing cost. For shortages related to the output, it included the loss of final product sales, excluding harvest and deterioration losses, expressed as the selling price per liter minus the total cost of production. Since demands in the system were not backlogged, the model sustained a penalty cost for "lost sales" known as the unsatisfied demand cost.

The general cost model has the capability of including all of the above costs as they occur during the predetermined time periods of an annual cycle. The cost of any operational policy alternative at a given point in time is the summation of all the costs up to and including any period. The model solution for an annual cycle determined:

1. The optimum cost of a specific plantation, harvest, and manufacturing system within a rotation;
2. The harvesting schedule within a year;
3. A recommended inventory policy for standing trees, harvested raw materials, and the final product; and
4. How well the existing supplies met demand for specific manufacturing processes.

Technical Inputs to the Model

An application of the general model described an ethanol production facility with a self-owned woody biomass plantation supply system. Table 1 includes the parameters associated with this system. All data were entered into the model whereby a dynamic programming (DP) framework was used to arrive at specific optimal prescriptions under the given sets of assumptions.

Table 1
Parameter Inputs of the Model

Components	Units	Parameters
Plantation		
Establishment		
Land area	ha	Variable[c]
Rotation	yr	4–8
Harvest		
Harvester		
Window	mo	6.00
Capacity	h ha^{-1}	[d]
Utilization	%	100.00
Transport		
Van capacity	Mg (green)	24.50
Round trip	km	80.00
Storage		
Raw material	Wood chips	Hardwood
Method	Conical piles	Uncovered, outdoor
Area	ha	Unlimited
Decay rate[a]	% mo^{-1}	1.00
Manufacturing		
Equipment capability[b]		
Wood chips	Mg(OD) mo^{-1}	10,000
Conversion rate		
Ethanol	L Mg^{-1}(OD)	346.00
Ethanol storage		
Area	L mo^{-1}	Unlimited
Demand	Megaliters yr^{-1}	37.85

[a]Percent of an inventory per month in storage.
[b]Capability if only one material is used as a feedstock.
[c]Based on 9020 ha and the rotation length.
[d]Mg (green) ha^{-1}/Mg (green) h^{-1} = h ha^{-1}.

Plantation Component

The plantation component encompassed the silvicultural aspects and availability of the raw material resource as standing trees. The model was capable of considering different types and yields of forest biomass grown under varying rotation lengths. A fixed plantation size of about 9020 ha was used as a reasonable estimate on land availability for tree production within an area defined by a 40-km transport radius. Rotation lengths of 4 through 8 yr required 2255, 1804, 1503, 1289, and 1128 ha to be established annually. The analysis examined a tree spacing of 2988 trees ha^{-1} and used unfertilized yields for each rotation, based on estimates from previous studies (*39,40*) (Table 2).

Table 2
Yield and Cost Model Inputs for the First Rotation Analysis

	Rotation years				
	4	5	6	7	8
Yields (Mg [OD] ha^{-1})	33.71	51.58	73.80	90.42	101.45
Cost inputs ($ Mg^{-1} [OD])					
Establishment	4.82	4.11	3.06	3.44	3.20
Maintenance	20.77	17.49	14.31	13.91	13.91
Harvest/transport	24.81	23.80	23.23	22.99	22.87

Harvest Component

The main features of concern for the harvesting component involved the harvesting and transport, and raw material storage practices. Plantation harvests were influenced by feedstock and end product demand rates. The harvesting window in the model was set at 6 mo, from October to March. When a harvest occurred, the raw material was transported into storage and/or processing at the beginning of the next respective period, from November to April. In the model, the minimum harvest, in any period when one occurs, was 10%. The percentage of total biomass removed from the growing site and delivered to the point of storage or manufacture was 100%. There were no raw materials on hand at the beginning of the harvest window.

Harvesting involved a tractor-pulled cutting unit capable of a single- or double-row operation. The model used a harvest rate of 19.85 Mg (green) h^{-1}, a value derived from the capabilities of prototype machines developed for short-rotation forestry (*17,41,42*). It was assumed that a harvester would operate for an entire month and that additional machine capacity would act as a buffer in case of machinery breakdown or to compensate for inclement weather.

After harvest, the trees were chipped at the site and placed in a trailer van. Transport was by tractor-trailer units with a capacity of 24.5 Mg of green wood/trip. A weighted average haul of 80 km round trip was considered from the harvest area to storage at the manufacturing facility. On delivery, the wood was subject to unloading and transport at the storage site (*9*). The model used the outdoor storage of hardwood chips, in uncovered conical piles, with an unlimited land area for storage.

Of concern were the physical characteristics of harvested materials and the changes that occur for different storage systems over varying time intervals. Forest biomass contains high moisture contents relative to other fuels and is subsequently prone to deterioration after harvesting. Quantitative losses were attributed to variations in moisture content, wood disintegration, and physical deteriorations, such as fungi infestations and increased acidity. The model assumed an exponential loss rate whereby a fixed fraction of on-hand stock was rendered unusable in each time period (*32,36,43*). In the model, woody biomass raw materials deteriorated at an average rate of 1% mo^{-1} in storage.

Manufacturing Component

The general manufacturing process used in the model to convert wood into ethanol was hydrolysis/fermentation. The technical inputs represented a process that contributed to a higher level of biomass conversion through yeast xylose fermentation (*14,44,45*). The model required information on the delivered form and condition of stored woody biomass materials prior to conversion into a product. Variations in the feedstock may result in increased or decreased yields for a particular manufacturing system, and were capable of being reflected in the model. The conversion rate used was 346 L of ethanol for each Mg(OD) of woody biomass, in the form of hardwood chips, available from the plantation (*44*). In the model, all biomass was directed to a plant capable of processing 10,000 Mg(OD) of woody biomass equivalent/mo to meet a coinciding target demand of 37,850,000 L of ethanol/yr^{-1} (10,000,000 ga). This latter parameter was indicative of a borderline market demand for a small- to medium-size production plant (*46*).

In the analysis, the firm was only permitted to acquire raw materials that were self-owned and without any internal borrowing of feedstocks from other plantation units. After raw materials processing was completed, the final product was either stored or sold. Since the model disallowed backlogging, there could potentially be shortages of raw materials at the processing level and liters of ethanol in the open market. No inventory of finished product existed at the initiation of a harvest year.

In the model, the storage of ethanol was set at an unlimited capacity. Ethanol demand, although subject to a uniform rate of flow throughout a month, varied on a month-to-month basis in accordance with fuel demand. Average monthly demand rates were calculated based on historical data for gasoline over the last 10 yr (*47*). It was assumed ethanol was intended for use as a gasoline additive; therefore, the demand for ethanol in a particular month was tied to gasoline demand, an association that has been previously used (*7*). Furthermore, since gasoline demand indicates the month of use, a lag of 1 mo was employed for the ethanol required for gasoline production. For example, the month of November would have October's harvest, but December's demand rate for gasoline.

Cost Inputs to the Model

As previously described, all general inventory cost categories were derived from the tasks found within the model. These task costs will now be described for the general model.

Plantation Component

Plantation establishment expenses included the field preparation tasks of mowing, disking, spraying, and harrowing. Also included were the costs of cuttings from a self-owned nursery and the planting operation. Each plantation task was analyzed on a commercial scale involving the preset plantation size. The establishment costs were prorated at a 5% rate of interest over the plantation life and based on each rotation length. The plantation lives for the 4- through 8-yr rotations were 16, 15, 18, 14, and 16 yr, respectively. The varying rotation lengths led to changes in inventory levels, such as tree yields, which subsequently resulted in cost input changes (*48*). Inflation and the capitalized cost of invested money were also responsible for cost differences. Plantation establishment costs by rotation are listed in Table 2.

After establishment, the plantation required maintenance and administrative expenditures. These included the biennial spraying of fungicides and insecticides, land rent, and the annual costs of management. Although fungicides and insecticides may not be essential to plantation maintenance, these tasks and their associated costs were incorporated to the system as an insurance against outbreaks. Spraying was scheduled in year one, when cuttings were most vulnerable, and then every other year. In the former, application was made from the ground, and in the latter from the air. Land rent was the opportunity cost of using agricultural sites for woody biomass production and represented the net revenue available to the sites from corn production. This was based on production values from agricultrual land in central Pennsylvania. Property taxes were based on a preferential use value for agricultural land in central Pennsylvania—an assessment ratio of 20% and an average county millage rate of 0.10094 per dollar of assessed value. Managerial costs represented the employment and support costs for a management, technical, and clerical staff involved in woody biomass production and harvest on four plantation units and a satellite nursery. These costs reflected the time and task requirements for the production and harvesting functions. Salaries were consistent with values found in the eastern United States (*49*). Maintenance costs for all rotations are listed in Table 2.

Harvest Component

Harvest and transport costs included cutting, chipping, transport, and the movement of raw materials to a storage or processing site. The costs for harvest and transport for each rotation and yield are reported in Table 2.

The storage and handling costs represented the preutilization strategy for plantation yields on arrival at a manufacturing site, and were consistent with methods employed by large-scale commercial enterprises. A cost of \$2.83 Mg^{-1}(OD) mo^{-1} in storage was used to reflect an outdoor system of uncovered wood chip piles. The model included the ability to calculate a "lost sales" penalty cost associated with liter production forgone from storage deterioration. This penalty, for the loss of a potential sale, was derived from the selling price of ethanol (\$0.67 L^{-1}) (*46,50*) minus the processing cost for the final product.

Manufacturing Component

Wood-to-ethanol processing facilities have seldom gone beyond the experimental stage; however, conversion costs have been estimated in feasibility studies, particularly for medium-size plants (*14,15,45*). The hydrolysis/fermentation process cost, used in this model, was \$0.22 L^{-1} of production, exclusive of feedstock and ethanol storage costs. The costs for storing ethanol on site were rarely discussed or distinguished from the other costs of manufacturing. In this analysis, the cost of storing ethanol was closely tied to that of gasoline and estimated at \$0.01 L^{-1} mo^{-1} (*51,52*).

A "lost sales" penalty cost, attributed to unsatisfied demand for the final product, was included in the model. "Lost sales" were attributed to each missed opportunity owing to demand for the final product, over and above what occurred in storage. This value was also based on the selling price of ethanol (\$0.67 L^{-1}) minus the cost of the raw materials and processing. The penalty cost was viewed as a profit loss for a unit of unsatisfied demand.

There were no credits attributed to byproducts in the analysis. Although it is recognized that byproducts were often a part of processing, the types of products and amounts vary for each conversion process. The omission of byproducts, beyond simplifying the analysis, permitted a clearer assessment of a particular system and the cost relationships within it.

Programming Approach

Various mathematical programming techniques can be used to solve for the optimum strategy for the inventory control model. In this study, the inventory control model used deterministic dynamic programming to solve for the least-cost alternative of a plantation strategy affiliated with a specific manufacturing process by using the harvest as the key decision variable. In general, inventory models are characterized by the type of demand schedule. A deterministic DP procedure is used when the demand for an item is deterministic (known with a high degree of certainty) (*38*). In the current model, although the raw material demand is held constant, the demand for the final product is both deterministic and dynamic. The term dynamic implies a demand, although known with certainty, that is variable from one time period to another (*38*). Although this programming approach ignored the element of risk in the inventory model, it permitted a consideration of seasonal trends in demand, which for analytic and computational difficulties cannot be included in a probabilistic model (*38*). Lit-

Table 3
First Rotation Policy Analysis

Rotation years	Minimum-cost harvest policy[a]/ harvest[b], %, mo^{-1}	Minimum policy production L	Maximum policy production L	Production difference min.-max. L
4	(20,10,10,10,10,40)	26,155,998	24,219,980	1,936,018
5	(10,10,10,10,10,50)	31,890,484	24,220,170	7,670,314
6	(10,10,10,10,10,50)	37,798,012	24,220,167	13,577,845
7	(10,10,10,10, 0,60)	39,539,718	24,219,900	15,319,818
8	(10,10,10,10, 0,60)	38,837,709	24,220,172	14,617,537

[a]The maximum-cost harvest policy for all cases was (0,0,0,0,0,100).
[b]The harvest window is 6 mo.

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a set of tableaus whereby alternative solutions
set of model assumptions. For example, con-
est can lead to alternative least-cost solutions.

RESULTS

Rotation Analysis

The policy analysis of each inventory control problem for any given length rotation was achieved using dynamic programming (Table 3). The harvest schedule described the percent cut per month for the 6-mo harvest window. There were a variety of optimal harvest policies over the range of rotation lengths. Among the optimal schedules, annual ethanol production ranged from a low of 26,155,998 L, for a 4-yr-old plantation unit, to a high of 39,539,718 L, for 7-yr-old plantation.

The first rotation cost analysis reported on the range of costs for all inventory strategies within a given rotation (Table 4). The production difference between the most and the least optimal harvest policy within a rotation was also reported. The production cost among all rotations ranged from \$0.376 to \$0.613 L^{-1}, with the optimum rotation age set at 6 yr.

The cost breakdowns and distributions, by component and task from the DP solutions, were recorded in Tables 5 and 6. For all rotation lengths, end product manufacturing was the greatest economic cost of the output. This category ranged from 43 to 59% of the total cost. The second highest cost was for the harvest and transport functions, with the exception of the 4-yr rotation, where the unsatisfied demand cost prevailed. Generally, the storage costs of harvested raw materials and ethanol were among the lowest in all systems.

Table 4
First Rotation Cost Analysis

Rotation years	Cost range $ L^{-1}	Cost difference, max.-min. $ L^{-1}
4	0.514–0.592	0.078
5	0.433–0.609	0.176
6	0.376–0.609	0.233
7	0.378–0.613	0.235
8	0.377–0.611	0.234

Table 5
Cost Breakdowns by Components and Tasks
for the Least-Cost Solution for Each Rotation

	Costs[a], $ L^{-1}				
	Rotation length, yr				
Components	4	5	6	7	8
Plantation					
Establishment	0.014	0.012	0.009	0.010	0.009
Maintenance	0.062	0.053	0.044	0.042	0.042
Harvest					
Harvest/transport	0.072	0.069	0.068	0.068	0.067
Storage					
Wood chips	0.008	0012	0.016	0.020	0.020
Penalty					
Deterioration loss	0.002	0.004	0.007	0.008	0.008
Manufacturing					
Processing					
Ethanol	0.222	0.222	0.222	0.222	0.222
Storage					
Ethanol	0.006	0.006	0.009	0.008	0.009
Penalty					
Market loss	0.128	0.055	0.001	0.000	0.000
Totals	0.514	0.433	0.376	0.378	0.377

The feedstock and manufacturing cost distributions, for all rotation lengths, are located in Table 7. Feedstock costs ranged from 37 to 41% of the total, whereas manufacturing ran from 59 to 63%. The inventory cost distributions for all rotation lengths are reported in Table 8. The carrying costs ranged from 15 to 19% of the total cost of the end product. For replenishment costs, the range was 59 to 79%. Shortage costs ran from 2 to 25% of the total cost.

Table 6
Cost Distributions by Components and Tasks for Each Rotation

	Distributions, %				
	Rotation length, yr				
Components	4	5	6	7	8
Plantation					
Establishment	2.7	2.8	2.4	2.7	2.4
Maintenance	12.1	12.2	11.7	11.1	11.1
Harvest					
Harvest/transport	14.0	15.9	18.0	18.0	17.8
Storage					
Wood chips	1.6	2.8	4.3	5.3	5.3
Penalty					
Deterioration loss	0.4	0.9	1.9	2.1	2.1
Manufacturing					
Processing					
Ethanol	43.2	51.3	59.0	58.7	58.9
Storage					
Ethanol	1.2	1.4	2.4	2.1	2.4
Penalty					
Market loss	24.8	12.7	0.3	0.0	0.0
Totals	100.0	100.0	100.0	100.0	100.0

Table 7
Feedstock and Manufacturing Cost Distributions by Rotation

Rotation years	Feedstock, %	Manufacturing, %
4	40.55	59.45
5	38.84	61.16
6	37.17	62.83
7	37.88	62.12
8	37.51	62.49

DISCUSSION AND CONCLUSIONS

The benefits of managing biomass/processing systems through inventory control are illustrated in Tables 3 and 4. Using inventory control, more finished products could be produced at a lower unit cost for each rotation. In most cases, greater quantities of available raw materials in the harvest year led to an increasing cost difference between the most and the

Table 8
Inventory Cost Distributions by Rotation

	Inventory costs		
Rotation years	Carrying, %	Replenishment, %	Shortage, %
4	15.60	59.09	25.31
5	17.02	69.26	13.72
6	19.28	78.82	1.89
7	19.19	78.59	2.22
8	19.40	78.44	2.16

least optimal harvest policy within a rotation (Table 4). As higher plantation yields pushed more raw materials and products through a system, there was an increased need for the storage of raw materials and, consequently, a further rise in storage deterioration (Table 6). More of the final product had to be stored as well. Inventory control helped to reduce the occurrence of "lost sales" for both storage and market demand, over more costly policies within a rotation. For example, the optimal solution for a 6-yr rotation length, \$0.376 L^{-1}, resulted in a 38% decrease from the maximum-cost solution for the rotation.

The optimal solution among all strategies was a 6-yr rotation, which also had the lowest shortage costs among all rotations (Table 8). However, it should be noted that the least-cost solution for the 6-yr rotation was not significantly lower than for the 7- and 8-yr rotation lengths. Furthermore, greater cost differences existed between these strategies and those of the shorter rotations.

The model demonstrated that systems avoided the cutting of trees unless warranted by demand or constrained to do so (e.g., by the harvest window or machine capacity). This tendency was evident in the harvest schedules for the optimal solution of the model (Table 3). The most costly harvest options, within a rotation length, delayed and/or consolidated the cut and incurred higher inventory costs relating to the storage of raw materials. For example, in the 6-yr rotation, storage costs for the highest cost solution (9.8%) were more than double that of the optimum (4.3%). However, there is a tradeoff between raw material storage and "lost sales." Although larger harvests in month six reflected an effort to reduce "lost sales" in the nonharvesting portion of the year by storing the harvest, an occurrence of "lost sales" in the latter months of the nonharvesting portion indicated a limit on carrying excess raw materials over time.

The supply system analysis also examined the cost distribution of individual tasks on the overall cost structure of each system (Table 6). The largest cost items were end product processing, the harvest/transport tasks, ''lost sales'' resulting from market demand, and plantation maintenance. The lower-cost items for all systems were plantation establishment, raw material and final product storage, and storage deterioration. Generally, the costlier tasks were those where the greatest improvements in cost reductions could be made outside the system. However, the lower-cost items were those under control of the manager and could result in final product cost differences for any system, depending on the inventory control policy. For example, lower-cost systems indicated a willingness to leave trees uncut vs storing harvested raw materials. This was attributed to an avoidance of raw material deterioration as well as storage costs. Because of a neglect of inventory control in the maximum cost solution for a 6-yr rotation (\$0.609 L^{-1}), wood chip storage deterioration was 4.9% of total costs vs 1.9% in the optimum. Also, the lowest-cost solution in the rotation held harvested materials for an average of 2.5 mo against 4.8 mo for the maximum-cost solution.

Model solutions also reflected on the harvest/transport equipment requirements for each rotation length based on the percent cut policy. The optimum schedule assumed that additional equipment could be brought on line through self-ownership or leasing, at the same cost used in Table 1. The notion is similar to that used for employing corn harvesting equipment during a short period in the fall. If the harvest equipment guidelines are not feasible, then alternative harvest schedules that meet equipment constraints can be read from the dynamic programming tableaus. Thus, the most feasible low-cost solution will be found.

The results from the model solution also produced a storage policy for standing trees, harvested materials, and finished products along with the harvest schedule and costs for each system. These policies indicated the storage times and quantities for those inventories. Most biomass studies have assumed a set or average number of months in which harvested raw materials were or should have been stored before conversion (*26,54–56*). The model solution reported on the months in storage for raw materials from each harvest. Thus, an average storage time could be calculated for wood chips. For example, for the 6-yr rotation length, each of the monthly harvests required some wood chip storage, largely owing to a capacity constraint at the processor. The average storage time per Mg(OD) over the entire year was 2.5 mo, since some harvested materials were kept during the nonharvesting portion of the year. Overall, a monthly average of 16,415 Mg(OD) was held in storage during the first 10 mo after the end of the growing season.

Anticipated yard capacity for a system could be derived for a model solution. The storage parameters assumed in the model utilized a wood chip pile configuration capable of holding approximately 4500 green tonne/ha^{-1}. In the 6-yr system, no greater than 50,232 Mg(OD) was ever held in storage at any one time for the optimum. Based on the solution for this spacing and rotation length, an upper limit on areal yard storage capacity was set at approx 23 ha.

The costs developed for the storage tasks of harvested trees were based on the parameters summarized in Table 1. These parameters and costs were based on configuration assumptions that included a provision for roading. However, storage costs may also vary according to changes in pile heights, widths, and the use of wood chip treatments, such as shelters or chip rotations.

Model solutions provide information on end product storage before final sale. The results indicated that the storage of the final product was less costly than the storage of harvested raw materials (Table 6). The ethanol inventories were influenced by monthly manufacturing, final product demand, and the inventory policy. In the 6-yr rotation, the average storage time of a liter was only 1 mo owing to a high market demand. Liters of end product were stored in the first 11 mo after the end of the growing season. The average number of liters in storage per month was 1,952,521. Also, there were never more than 3,059,317 L in storage at any one time. This upper limit could be used to approximate the minimum storage capacity requirements for a given system. The upper limit for the maximum cost solution, within the spacing and rotation, would provide the range for potential storage capacity.

Plantation systems with rotation lengths greater than 5 yr brought enough land into production to meet the demand of a small- to medium-size ethanol market. The 6-yr rotation, with 1503 ha and a yield of 73.8 Mg(OD), met the demand most adequately. Seven- and 8-yr rotation lengths incurred higher unit costs, because the supplies exceeded demands. Although "lost sales" owing to market demand were minimized, the costs of storage deterioration, and raw material and final product storage increased over rotation length six (Table 6). For shorter rotations, shortages may require bringing more land into production or necessitate the purchase of feedstocks from outside the system. Demand shortfalls, in number of liters for each system below the annual demand, for rotations four, five, and six were 11,694,002, 5,959,517, and 51,988, respectively. The shortfall in the 6-yr rotation supports the contention that an optimal solution may require shortages to occur (34). The additional hectares required annually for these systems to meet a small- to medium-size market for ethanol were susbsequently 1,003, 334, and 2, respectively. This additional land requirement was based on the corresponding plantation unit yield for each rotation length and the conversion rate at processing. In general, the yields of the longer rotations allowed for land acquisition reductions for these systems owing to increased quantities of available raw materials in the harvest year.

In conclusion, inventory policies that coordinate the volume of wood committed to plantation inventories, wood chip quantities in storage, and allied feedstock requirements of particular manufacturing processes influence harvest schedules and lower final product costs. Additionally, there are a number of parameters and tasks within the biomass/processing system that influence harvest and storage schedules. Some examples include the plantation yields or the size of the processing facility. Future research, utilizing the model and sensitivity analysis, can separate out those factors with the greatest impact. Additionally, the model will permit efficiency and cost comparisons of alternative production schemes, particularly for proposed systems.

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