INTEGRATIVE INVESTMENT APPRAISAL AND DISCRETE CAPACITY OPTIMIZATION OVER TIME AND SPACE: THE CASE OF AN EMERGING RENEWABLE ENERGY INDUSTRY

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CHAPTER I

INTRODUCTION

The need to replace fossil fuels with renewable forms of energy has been expressed by several authors (Mauguiri; Hall and Scrase). Common reasons advanced for this argument include energy security, environmental concerns, and national balance of trade improvements. In many countries, most energy-related policy and research effort is being devoted towards developing a sustainable ethanol industry that uses biomass as the substrate. Biomass is a general term that embraces all organic non-fossil resources such as grain, solid waste, wood and lignocellulosics (crop residues, native grasses, improved pasture grasses and dedicated energy crops).

In general, failure to out-compete gasoline without subsidies and tax incentives is considered to be one of the greatest problems that ethanol must overcome (Vollebergh; Lynd et al.). With grain-based ethanol proving to be expensive (Kaylen et al.) and, sometimes, to result in negative net energy (Keeney and DeLuca; Pimentel), the future for the ethanol industry is generally considered to lie in the ability to use low-value feedstocks. Theoretically, it has been shown that producing ethanol with high-value co-products such as furfural and hydroxymethlfurfural in a simultaneous saccharification and fermentation (SSF) process can lower the breakeven price of ethanol substantially (Wyman; Kaylen et al.). However, market and technology to sustain large-scale production of such co-products are yet to be developed (Wyman).

Latest technological advancements involve pyrolyzing all the components of lignocellulose (including lignin) to syngas and microbially catalyzing the syngas to ethanol, inert gases, and water. This process, also referred to as gasification-bioconversion, is expected to increase yields by 20-40 gallons per ton of biomass, compared to the 80 gallons/ton obtained with the SSF process (Strawn).

While these emerging technologies are yet to be verified, their eventual adoption will also depend on their performance when subjected to comprehensive investment appraisal. Such appraisals need to recognize that lignocellulosic feedstocks are agricultural commodities and that a biomass-to-ethanol industry is essentially an agricultural processing industry. In general, it is not easy to develop a representative and effective appraisal procedure for investment in agricultural processing. Much of the challenge arises because of the amount of detail and spatial and temporal connotations that characterize the agricultural sector.

Typically, agricultural production activities tend to be unevenly distributed over wide geographical locations, whereas processing facilities can only be optimally located in a finite number of locations. This disparity between raw material production patterns and number and location of processing activities identifies the need to explicitly incorporate facility siting considerations in the investment decision processes. The size and number of such facilities that can be optimally located in any specified region (country, state, province, etc.) is determined, to a great extent, by the tradeoff between facility construction and installation costs and raw material transportation costs (Kaylen et al.). Transportation is especially important because agricultural raw materials are bulky. With respect to any single facility, the choice of type of raw material is further complicated by the interaction between their relative abundance and production and storage costs. The need to explicitly represent storage activities arises because of the disparity between short raw material harvest periods (usually a few months) and the year-round operation of the plant.

Another important aspect that demands special attention is the fact that construction and installation of the processing facilities involves large investment outlays. Regardless of the financing arrangement, the opportunity cost of these funds constitutes a significant cost component over the life of the plant. Furthermore, the unverified technologies and the usually variable and unpredictable crop growing conditions (weather, etc) render the biomass-to-ethanol industry highly risky. Social and environmental advocates would also demand incorporating the value and/or cost of any externalities arising from the operation of the plant.

Although abundant empirical literature exists on agricultural investment appraisal, few, if any, are comprehensive enough to capture all these factors and their complicated interactions. Most of the studies focus only on selected areas of the industry. Studies using the traditional project appraisal approach, for example, account for the time value of money while appropriately valuing inputs and outputs. However, because of the project focus, the challenging logistics involved in performing activities such as raw material production, storage, transportation and processing are handled only implicitly. Except in project comparison, this approach is also largely positive and does not leave room for industry optimization, which grossly under-represents the interactions and industry feedback effects. On the other hand, most studies that attempt to optimize these functions and interactions tend to assume a representative year and a cost minimization objective function (e.g. Tembo; Faminow). Such formulations ignore the time value of investment funds, while implicitly assuming that the income component of the investment does not matter. Most of these normative studies also tend to have deliberate focus on transportation, while treating all other components only implicitly. Externalities and raw material production options and storage, for example, are often completely ignored (e.g. Kaylen et al.). In general, however, an appraisal framework will only be representative if it incorporates all the concerns, interactions and feedback effects as much as possible. The additional flexibility implied by the more comprehensive and inclusive models also permits the analyst to test more scenario combinations and hypotheses.

The current research develops and demonstrates an integrative multidisciplinary approach to determining technical and economic viability of investment in agricultural processing. The proposed implementation in Oklahoma of a biomass-based ethanol industry is used as a case study. Industry net present worth is used as the investment decision criterion. In addition to biomass transportation and processing (the focus of the Kaylen et al. study), the current formulation treats several other activities more explicitly. These include biomass production (fertility choices, harvest structure options, etc.), storage and inventory management both in the field and at the processing plant site, externality handling and costing, and system net energy balance computations. The model further recognizes the pressure often exerted on biomass harvest and storage resources and incorporates the tradeoff between field losses and storage losses, a challenge commonly faced by producers in their harvest timing decisions. Because the decision to locate a plant and the choice of plant size at any prospective location are discrete variables, mixed integer mathematical programming is used to permit modeling of these integer variables alongside continuous variables.

With regard to the Oklahoma ethanol industry, this study constitutes part of the existing efforts to determine conditions under which the gasification-bioconversion process could be used to commercialize ethanol production from lignocellulosic feedstocks. At the time of the study, a multidisciplinary team of researchers from University of Oklahoma and Oklahoma State University were working on the various aspects of the process. As will become more apparent in Chapter IV, most of the parameters used in this study were obtained through a complement of secondary sources and interdisciplinary consultations with the members of that research team.

Objectives of the Study

The overall objective of this study is to develop an integrative framework for determining technical and economic viability of investment in agricultural processing, with special focus on the proposed Oklahoma biomass-to-ethanol industry. The case study approach was necessary to more explicitly demonstrate some of the pertinent investment-related questions that the model could address (see specific objectives).

Specific objectives include:

1) Determine the number, size and distribution of biomass-to-ethanol processing capacity that maximizes industry net present worth,
2) Determine the optimum quantities of biomass stocks and flows,
3) Determine the most important cost items in the Oklahoma ethanol industry,

4) Determine the ethanol threshold price that would permit non-zero ethanol production.
5) Determine the price of fossil fuel that would make ethanol competitive without subsidy or tax incentives,
6) Determine industry energy efficiency, and
7) Determine the degree of robustness of the model results to changes in selected key parameters.
8) Determine the impact of introducing a high-yielding dedicated energy crop (switchgrass) on industry net present worth and energy efficiency.

Organization of the Study

Theoretical considerations underlying the analytical approach used in the study are outlined in Chapter II. Literature review on theoretical and empirical developments in the renewable energy sector and investment appraisal and plant location studies are presented in Chapter III. The empirical model, data sources and assumptions are specified in Chapter IV. Chapter V presents the findings of the study and their analyses. The study summary, conclusions, limitations and suggestions for further research are contained in Chapter VI.

CHAPTER II

CONCEPTUAL FRAMEWORK

Locating a biomass-to-ethanol conversion facility is an investment activity, with costs and revenues extending from the present into the future. Largest costs are likely to be incurred at the beginning of the project, when the plant is constructed and equipment is installed. Other costs incurred throughout the life of the project include payments for materials and factor inputs, operating and maintenance, and item replacements. Normally, the stream of benefits begins after the initial construction and start-up period. The difference between benefits and costs constitutes the net benefit (or net profit) of the project.

Two pertinent issues that need to be addressed when considering investment proposals are i) whether the project represents an optimum use of the limited resources, and ii) whether the project under consideration is preferred to alternative investment avenues (Dinwiddy and Teal). Undoubtedly, there is hardly a single answer to these concerns. The type of information obtainable from a project appraisal exercise and the type of decisions that can be made regarding these questions will depend, in part, on the analytical framework and its underlying assumptions. In this section, an attempt is made to present an overview of different methods for formulating investment decision rules.

Although costs and benefits of investment activities extend over several years, investments can be studied and compared with static models. These models can broadly be categorized as positive or normative. Traditional project appraisal techniques presented by Gittinger are examples of the positive approach to investment analysis. With this approach, projects are evaluated and compared as they are, with their existing cost and benefit structures. Hazell and Norton propose extending these techniques into simulation models to permit policy experimentation. Normative models involve exploration of the Euclidean space of policy goals and investment projects.

Positive Investment Analysis

In traditional investment project appraisal two alternative classes of decision rules are used to determine project worth – discounted and undiscounted measures of project worth. If the projects being compared have identical sizes with similar structures of cost and benefit streams, choosing the most desired investment alternative is a trivial matter. Quite often, however, the analyst must choose among projects of different sizes and among projects with differently shaped future cost and benefit streams. These additional complications require careful consideration of the time value of money. Use of undiscounted measures of project worth in such situations is likely to lead to erroneous decisions[1].

Discounting, a technique by which future benefit and cost streams are adjusted to their present worth, is based on the premise that a sum of money deposited in a financial

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[1] For an overview of common undiscounted measures of project worth and a demonstration of their weaknesses, the reader is referred to Gittinger.

institution now will increase in value at a given interest rate. The present worth (PW_t) of a sum of money worth NB_t units t time periods in the future is computed as:

$$PV_t = NB_t(1+r)^{-t}, \tag{2.1}$$

where r and t are discount rate and time, respectively. The expression $(1+r)^{-t}$ is the discount factor that converts the price of NB_t into its present worth. In the context of benefit-cost analysis, NB_t could be project net benefit for period t. Common examples of discounted measures of project worth include net present worth, internal rate of return and benefit-cost ratio (Schreiner).

Net present worth (*NPW*), which is the present worth of the incremental net benefit or incremental cash flow, is calculated as

$$NPW = \sum_{t=1}^{T} NB_t(1+r)^{-t} \tag{2.2}$$

where T is the number of future time periods from present and $NB_t = (\text{benefit}_t - \text{cost}_t)$, $\forall t$. By this criterion, an investment is worthwhile if its *NPW* is positive. Also, one project V is preferred to another project W if $NPW_v > NPW_w$. Its invariance to the shape of the cash flow and robustness across different types of projects has made the *NPW* the most preferred basis for project appraisal (Dinwiddy and Teal).

Closely related to the *NPW*, is the concept of the internal rate of return (*IRR*), defined as the interest rate r such that $NPW = 0$. With this criterion, the rule is to proceed with the proposed project if $IRR > r$. For well-behaved projects, with initial expenditures succeeded by a stream of net benefits, it does not matter whether *NPW* or *IRR* is used, as the two are equivalent under these circumstances. If substantial net costs are anticipated at a future date, however, multiple values of the *IRR* may result and a rule based on *IRR* may prove ambiguous.

Sometimes, the ratio of the present worth of the benefit stream to the present worth of the cost stream is used in project appraisal. This ratio, commonly known as the benefit-cost (BC) ratio, is formally computed as

$$BC = \frac{\sum_{t=1}^{T} B_t (1+r)^{-t}}{\sum_{t=1}^{T} C_t (1+r)^{-t}}, \tag{2.3}$$

where B_t and C_t are benefits and costs for period t. By the BC ratio criterion, investment proposals with $BC > 1$ may be considered worthwhile. An important weakness of the BC ratio is that its value tends to vary with the netting out convention adopted for cost and benefit streams (Gittinger).

Normative Investment Analysis

The ethanol production technology proposed in this study uses crop byproducts (such as wheat straw and corn stover), native prairies (tall, mixed and short), improved pasture (bermudagrass, tall fescue, and old world bluestem), and a dedicated energy crop (switchgrass) as potential raw materials. These feedstocks are produced, or can be produced, in various locations throughout Oklahoma. Processing plants, however, can only be located in a few locations. This disparity between biomass distribution and patterns of plant locations is indicative of the fact that transportation will constitute a major component of the total cost of operating the facilities. Thus, it is imperative that the effects of space be explicitly considered in the analytical framework.

Typically, agricultural crops are harvested at certain times of the year whereas the processing facilities will need to be in operation throughout the year. One way to bridge the implied time gap between feedstock harvesting and their use in the facilities is to store them. Therefore, biomass storage and inventory management is another important aspect of the ethanol industry and needs to be explicitly considered by the chosen analytical framework.

Because of the number of variables and constraints and the need to handle complicated spatial and temporal (storage) relationships, agricultural processing plant location problems have been most successfully analyzed with mathematical programming techniques. Most recent advances are in the area of discrete optimization, which helps to adequately account for the fact that processing facilities are lumpy and need to be constructed before any production can take place. Theories of optimization and solution algorithms are discussed in this section.

Mathematical Programming and Optimization

A mathematical model of a system is a set of mathematical relationships that represent an arbitration of the real world under consideration. In general, such a model will consist of four key elements: variables, parameters, constraints and mathematical relationships. Variables, by definition, can take on different values and their specifications define different states of the system. These values can be continuous, integer or a mixed set of the two. Parameters are fixed to one or a set of specific values, and each fixation defines a different model. Equality constraints usually describe balances or equilibrium relationships whereas inequality constraints often consist of allowable operating regimes and availability or demands. The mathematical relationships can be algebraic, differential, or a mixed set of algebraic and differential constraints, and can be linear or nonlinear.

An optimization problem is a mathematical model that in addition to these elements contains one or more performance criteria, or objective function. A well-defined optimization problem features a number of variables greater than the number of equality constraints, which implies that there exist degrees of freedom upon which to optimize. If the number of variables equals the number of equality constraints, then the optimization problem reduces to a solution of nonlinear systems of equations with additional inequality constraints. A typical optimization model takes the following form:

$$\begin{aligned} &\underset{\mathbf{x},\mathbf{y}\in\Re}{\text{minimize}}\, f(\mathbf{x},\mathbf{y}) \\ &\text{s.t. } h(\mathbf{x},\mathbf{y}) = \mathbf{0}, \\ &\quad g(\mathbf{x},\mathbf{y}) \le \mathbf{0}, \\ &\qquad \mathbf{x} \in \mathbf{X} \subseteq \Re^{n}, \text{ and} \\ &\qquad \mathbf{y} \in \mathbf{Y} \text{ integer,} \end{aligned} \tag{2.4}$$

where $\mathbf{x}$ is a vector of continuous variables, $\mathbf{y}$ is a vector of integer variables, $h(\mathbf{x},\mathbf{y}) = \mathbf{0}$ are equality constraints, $g(\mathbf{x},\mathbf{y}) \le \mathbf{0}$ are p inequality constraints, and $f(\mathbf{x},\mathbf{y})$ is the objective function.

Model (2.4) contains a number of classes of optimization problems, by appropriate consideration or elimination of its elements. If the set of integer variables is empty, and the objective function and constraints are linear, then Model (2.4) becomes a linear programming (LP) problem. If the set of integer variables is empty and there exists nonlinear terms in the objective function and/or constraints, then Model (2.4) becomes a nonlinear programming (NLP) problem. If the set of integer variables is nonempty, the integer variables participate linearly and separably from the continuous ones, and the objective function and constraints are linear, then Model (2.4) becomes a mixed-integer linear programming (MIP) problem. If the set of integer variables is nonempty and there exists nonlinear terms in the objective function and constraints, then Model (2.4) is a mixed-integer nonlinear programming (MINLP) problem. Linear and nonlinear pure integer optimization problems are obtainable if the vector of continuous variables is null.

In general, optimality of any feasible point is defined by its relationship with neighboring points. In Model (2.4), for example, the point (x^*, y^*) is said to be a strong local minimum if there exists $\delta > 0$ such that

(2.4.1) $f(x^*, y^*)$ is defined on $N(x^*, y^*, \delta)$ and

(2.4.2) $f(x^*, y^*) \le f(x, y)\ \forall\ (x,y) \in N(x^*, y^*, \delta),\ (x, y) \ne (x^*, y^*)$,

where $N(x^*, y^*, \delta)$ is a set of feasible points contained in a δ-neighborhood of (x^*, y^*). If all the variables are continuous, i.e. if **y** is null in Model (2.4), it is possible to define such an optimum point with necessary and sufficient conditions. For a linearly constrained problem with equality constraints, for example, an optimum point $\mathbf{x}^*$ satisfies the following conditions:

(2.4.3)

$\hat{\mathbf{A}}\mathbf{x}^* = \hat{\mathbf{b}}$,

$\mathbf{z}'\nabla f(\mathbf{x}^*) = 0$, or $\nabla f(\mathbf{x}^*) = \hat{\mathbf{A}}'\boldsymbol{\lambda}$,

$\mathbf{z}'\nabla^2 f(\mathbf{x}^*)\mathbf{z}$ is positive semi-definite (necessary), and

$\mathbf{z}'\nabla^2 f(\mathbf{x}^*)\mathbf{z}$ is positive definite (sufficient),

where $\hat{\mathbf{A}}$ is the matrix of the coefficients of the constraints active at vector $\mathbf{x}^*$ and $\mathbf{z}$ is such that $\hat{\mathbf{A}}\mathbf{z} = \mathbf{0}$. Expressions $\mathbf{z}'\nabla f(\mathbf{x}^*)$ and $\mathbf{z}'\nabla^2 f(\mathbf{x}^*)\mathbf{z}$ are projected gradient and projected Hessian, respectively. Gill, Murray and Wright present optimality conditions for other types of continuous optimization problems – linear or nonlinear with equality and/or inequality constraints. Within the class of continuous models, solutions are most difficult to find when the problem is nonlinearly constrained. Numerical algorithms often used for these problems are presented in Gill, Murray and Wright. If **y** is not empty in Model (2.4), however, the limitations imposed by the nature of discrete variables imply that the standard definitions of differentiability and continuity are not applicable. In this case, numerical methods for differentiable nonlinear problems must be used indirectly (except for a certain number of special cases where the solution of the continuous problem is known to satisfy the discrete/integer constraints automatically), which makes integer problems extremely difficult to solve.

Discrete optimization and facility location

Integer or discrete programming deals with mathematical programs in which some or all of the variables are restricted to be members of a finite set, $\{0, 1, 2, ...\} \in \Re$. An integer program is said to be mixed or pure depending on whether some or all the variables are restricted to integer values. An all-or-nothing phenomenon portrayed by indivisible input elements is a special integer set with two elements, zero or everything. In the case of ethanol production, for example, the full investment costs (construction and machinery installation) must be incurred before any production activity can be initiated at any particular location.

Consider a production planning problem involving commodity x in J plant locations. If the object is to minimize total costs of production TC over all locations, the planner's problem can be expressed as:

(2.5) $$\underset{x \in \Re}{\text{Minimize}}\, TC = \sum_{j=1}^{J} c_j(x_j)$$

subject to

$$x_j \geq 0,$$

where $c_j(x_j)$ is the cost of producing commodity x in location j. Suppose $c_j(x_j)$ consists of a fixed component (charge) fc_j and a linear variable cost component, a_j per unit. Then the total cost of producing x at each of the J locations, $c_j(x_j)$, may be defined as

(2.6) $$c_j(x_j) = \begin{cases} fc_j + a_j x_j, & \text{if } x_j > 0 \\ 0, & \text{otherwise.} \end{cases}$$

Notice that Equation (2.6) has a discontinuity at the origin. The nonlinearity imposed by this condition renders TC in Model (2.5) untractable from the analytical standpoint. The usual approach to dealing with this problem is to rescale by introducing auxiliary binary variables β_j, such that:

(2.7) $$\beta_j = \begin{cases} 0, & \text{if } x_j = 0 \\ 1, & \text{if } x_j > 0. \end{cases}$$

These new variables can then be used to replace Equation (2.6) with switching constraints. Switching constraints model the requirement that continuous variables x_k can only be produced if the corresponding binary variable is equal to one:

(2.8) $$x_j \leq CAP_j \beta_j,$$

where CAP_j are derived upper bounds (capacities) on the continuous variables in any feasible solution, and $CAP_j > 0$ is sufficiently large to render $x_j \leq CAP_j$ redundant with respect to any active constraint of the problem. Thus, the above problem (Model 2.5) can be reformulated as

$$
\begin{aligned}
&\underset{\mathbf{x},\mathbf{y}\in\Re}{\text{Minimize}}\, TC = \sum_{j=1}^{J}\left(a_j x_j + fc_j \beta_j\right), \\
&\text{subject to:} \\
&\qquad x_j - CAP_j \beta_j \le 0, \\
&\qquad x_j \ge 0, \\
&\qquad \beta_j \in \{0,\ 1\},
\end{aligned}
\tag{2.9}
$$

where all the variables are as defined above. Notice that if $x_j > 0$, $\beta_j = 1$ and the fixed charge fc_j is added in the objective function and a plant is located at j. If $x_j = 0$, β_j is either zero or one, but since $fc_j > 0$ and TC is minimized, β_j must be equal to zero.

While the original problem (Model 2.5) has almost nothing to do with integer programming, the "transformed" problem (Model 2.9) becomes a zero-one mixed integer problem. The transformation is introduced only for analytic convenience. The added binary variables are "extraneous" in the sense that they do not reveal any new information about the solution. For example, $\beta_j = 1$ in the optimal solution is already implied by $x_j > 0$.

Solution Algorithms for Mixed Integer Programming

A major problem with MIP problems of the zero-one type emanates from the combinatorial nature of the domain of $\boldsymbol{\beta}$ variables. Any choice of zero or one for the elements of the vector $\boldsymbol{\beta}$ results in a linear programming problem on the $\mathbf{x}$ variables, which can be solved for its best solution. The brute-force approach involves enumerating fully all possible combinations of 0-1 variables for the elements of the $\boldsymbol{\beta}$ vector.

However, such an approach grows exponentially in time with respect to its computational effort. One hundred 0-1 variables, for example, would have 2^{100} possible combinations, which implies solving a prohibitive 2^{100} LP solutions. The computational difficulty with available IP algorithms has led users to find alternative methods. One such approach is to solve the model as a continuous linear programming (LP) and then round the optimum solution to the closest feasible integer values. The problem with this approach is that there is no guarantee that the resulting rounded solution will satisfy the constraints. Furthermore, although the infeasibility created by rounding may be tolerated when integer variables are thought of as representing a discrete number of objects, it is nonsensical to deal with fractional values of variables that represent quantification of some codes (i.e. if the variable is categorical).

Several algorithmic approaches have been proposed and applied successfully to medium and large size application problems. Floudas lists four major algorithmic approaches proposed in the literature: branch-and-bound methods, decomposition methods, logic-based methods, and cutting plane methods. In the branch and bound algorithms, a binary tree is employed for the presentation of the 0-1 combinations, the feasible region is partitioned into subdomains systematically, and valid upper and lower bounds are generated at different levels of the binary tree. In the cutting plane methods, the feasible region is not divided into subdomains but instead new constraints (cuts) are generated and added to reduce the feasible region until a 0-1 optimal solution is obtained. In the decomposition methods, the mathematical structure of the models is exploited via variable partitioning, duality, and relaxation methods. In the logic-based methods, disjunctive constraints or symbolic inference techniques are utilized that can be expressed in terms of binary variables. The branch-and-bound method is the most commonly used algorithm. In the general algebraic modeling system (GAMS), for example, CPLEX, the solver commonly used for MIP problems, uses the branch and bound algorithms. Algorithmic approaches to the nonlinear version of mixed-integer programming problems are reviewed in Floudas.

Towards a More Integrative Approach

Typically, most mathematical models are designed such that optimal plant locations and plant sizes are determined at the unique point that minimizes total transportation, processing and storage costs. An implicit assumption underlying this approach is that only internal costs are important in the investment decision-making process. Often, however, the set of economic goals tends to be much broader and will include benefits and/or external net benefits. Therefore, considering only internal investment and operating costs would grossly under-represent the real set of decision rules. Also, these models tend to ignore the opportunity cost of investment funds and use a single 'representative' period (a year, a month, etc.) as a time unit.

Traditional investment appraisal techniques, such as *NPW*, on the other hand, use discounting to more adequately account for time value of money. Also, *NPW* uses both project costs and benefits. External costs and benefits (e.g. environmental consequences) can also be considered within the framework of *NPW* by means of non-market valuation – e.g. willingness to pay - of the externalities. However, using *NPW* in its traditional form is also limited in scope. In traditional project appraisal, for example, location is often assumed predetermined. This makes its ability to explicitly handle the intricacies of spatial relationships very limited.

One way to circumvent the shortfalls of these two approaches is to combine them. Incorporating NPW as an objective function in a plant location optimization model can broaden the decision criterion in the model while also increasing the ability to handle intricate relationships/constraints. The implied normative formulation also presents more flexibility and ability to optimize the industry.

CHAPTER III

LITERATURE REVIEW

Energy in its various forms is an integral part of our society. Most of this energy is derived from fossil fuels. In the United States, 97 percent of transportation energy is derived from petroleum (Wyman). Most of the world's fossil fuel deposits are concentrated in a few places of the globe. As was demonstrated by the energy crisis of the 1970s (Farhar; Van Dyne, Kaylen and Blase), the non-petroleum supplying countries are subject to sudden energy supply disruptions and balance of trade deficits. The United States satisfies 50 percent of its 410 gigaliter (110 billion gallon) annual gasoline market through imports (Wyman). These petroleum imports cost about U.S. $68 billion and constitute about 41 percent of the national trade deficit (Choi).

Considerable debate exists in the literature about the long-term effects of over-reliance on fossil fuels. Being a finite nonrenewable resource, the possibility of its depletion seems to present the ultimate threat on the world's energy security. It is argued that fossil fuel deposits may not last beyond the first half of the twenty-first century (Amann; Mauguiri). Another highly debated issue in the literature concerns the impact of fossil fuel utilization on the environment.

In general, scientific literature on the problems associated with fossil fuel utilization and what could constitute the set of substitutes is vast and cannot all be presented in a single review. The remainder of this chapter, though by no means comprehensive, attempts to highlight some of this debate and important developments in the energy industry. The next section gives some of the major highlights of the debate on environmental consequences of fossil fuels. Next, literature on prospects and challenges associated with alternative energy sources is reviewed. Because the innovations required to effectively and economically use these new energy forms are still undergoing development, their adoption demands intensive investment appraisal. The last section of the review presents major highlights in the literature with respect to appraisal techniques for such projects.

Fossil Fuels and the Environment

Global warming due to the "greenhouse effect" has been one of the greatest environmental concerns since the first Earth Day in 1970. Shedenhelm divides this concern into three distinct theses: that the earth is warming, that man's activities significantly contribute to the warming, and that such warming will have, on the whole, a negative effect on human and animal well-being. The United Nations Environment Program (UNEP) presents some of the major environmental trends, required key actions and the resultant impacts (Figure 1).

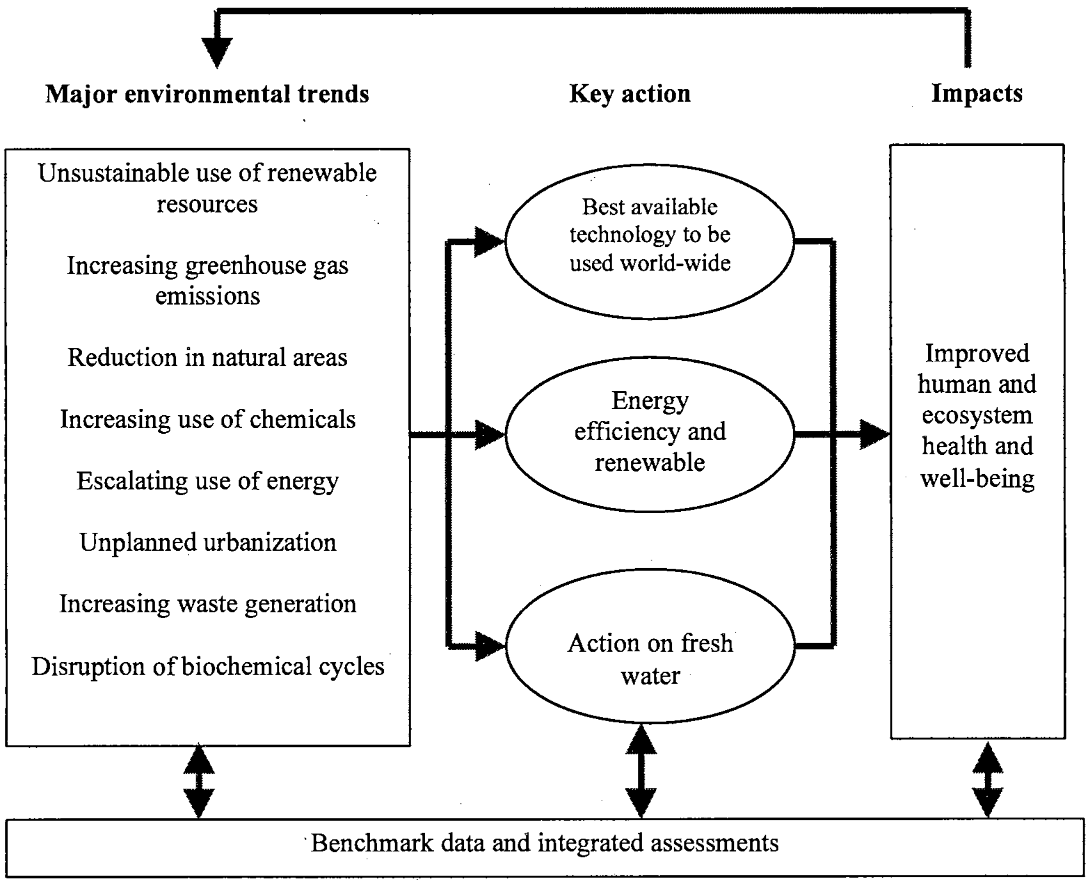

Figure 1. The action cycle

Source: Global Environmental Outlook-1 (UNEP, 1997).

The extent to which man's activities are responsible for the accumulation of greenhouse gases in the atmosphere is one of the most debated issues in the literature. Critics, mainly from the private sector, argue that the observed changes in atmospheric temperatures and the associated climatic changes are merely natural variations in the weather and have little to do with economic activities. Several theories are advanced by this category of scientists, including the effects of the earth's recovery from the "Little Ice Age" (Eminger) and effects of the lunar phase (Balling and Cerveny). Eminger contends that most of the twentieth century's warming (about one degree Celsius) occurred prior to the industrial revolution.

Environmental scientists, governments and the international community, however, share an opposite view that increased emissions and accumulation of greenhouse gases is responsible for most of recent climatic changes. It is estimated that 85 percent of the anthropogenic greenhouse gases is carbon dioxide (UNEP) of which 98 percent is from the combustion of fossil fuels in transportation, manufacturing, heating, cooling, electricity generation and other applications (H. John Heinz III Center for Science, Economics and Environment). Often the upward trend in energy consumption is blamed on economic growth (Hashimoto et al.) and the pattern of production and consumption. An estimated 400 percent increase in the number of vehicles was observed in the United States between 1950 and 1990 (UNEP).

For electricity generation, coal is considered to be one of the most viable alternatives to oil. Tyner argues that the cost of coal-generated electricity is much lower than that of oil-generated power. However, the environmental costs associated with coal are numerous, including land reclamation, CO_2 and other emissions, acid rain, water pollution, and scenic beauty destruction (Tyner). Nienow et al. determined the conditions under which a power plant would optimally co-fire coal with woody biomass, taking into account the environmental and community benefits of biomass.

Alternative Energy, Prospects and Challenges

The view that man plays a key role in environmental degradation has forced governments and international environmental organizations to seek and enforce mechanisms to reverse the trend. Sayigh contends that, unless drastic measures are taken, global warming will change the climate and terrain of many countries. The need to limit CO_2 emissions is also evident in the resolutions of the December 1997 Kyoto Protocol. The United States, for example, is expected to reduce its emissions of greenhouse gases to 1,300 million metric tons of carbon, an amount seven percent below the 1990 level (The H. John Heinz III Center for Science, Economics and Environment). One of the great challenges faced by governments is to identify and implement measures that would be effective in meeting such environmental targets, with minimal effects on economic activity. Emissions trading systems have been tried on pollutants such as sulfur dioxide (SO_2) and chloroflourocarbons (CFCs). The H. John Heinz III Center for Science, Economics and Environment argues that such conventional measures are not practical with pollutants that are emitted in large quantities, such as CO_2. The authors also argue that there are no effective procedures to directly trap and sequester CO_2 emissions or to make them harmless.

The need to foster national energy security and pollution reduction has sometimes forced scientists to recommend crude oil taxes as a means to internalize the energy security and pollution externalities (Tyner). Eventually, this is expected to have the effect of dampening crude oil demand while promoting the search for alternative fuels. Another option presented in the literature is to replace fossil fuels with renewable forms of energy. Isenberg contends that environmental well being requires a modified mix of energy sources to emit less CO_2. Ackerman evaluated various renewable energy sources as alternative technical means for reducing CO_2 emissions in electricity generation. According to Hall and Scrase, there is a growing consensus that renewable energy must progressively displace fossil fuels. Basosi, Maltagliati and Vannuccini contend that these renewable energy resources are recognized by the international community as important elements of a sustainable energy policy vector. It is sometimes argued that renewable energy will meet 10-15 percent of the world's prime energy by the year 2020 (Sayigh). Schulte-Bisping, Bredemeier and Beese argue that the transition to sustainably produced renewable energy sources might be the only option for countries in which fuelwood depletion and deforestation are rampant.

Use of renewable energy is believed to facilitate balanced regional development from decentralized energy production and use, independence from imported fuel, reduced environmental impacts, low operating costs, and use of rather simple technology (Goumas, Lygerou and Papayannakis). Chwieduk discusses the technical and financial aspects of renewable energy and argues that "… it is important to identify the energy sectors that can use renewable energy to effectively improve energy efficiency and the environment". Sustainable renewable energy forms considered to have potential economic and environmental viability include solar (Amann; Belessiotis and Delyannis; Bowen; Carmody and Sarkar), wind (Akash, Mamlook and Mohsen; Ackermann; Bowen;

Kilkis; Lucarelli), rivers and oceans (Akash, Mamlook and Mohsen; Bowen), nuclear (Amann; Boczar et al.), geothermal (Bowen), and biomass (Bowen; Hall and Scrase; Lucarelli; Skog and Rosen).

Of these renewable energy sources, biomass is expected to play a key role in sustaining future global energy supply (Hall and Scrase; Maniatis and Beenackers). Many influential organizations foresee biomass as an energy source for the future (Hall and Scrase). Biomass is a general term that embraces all organic non-fossil resources. Renewable energy biomass includes wood, forage, crops, crop residues, grains and municipal wastes (Tyner; Choi). One of the unique features of biomass is its ability to provide storable and transportable fuel in solid, liquid and gaseous forms. Because of the diversity in form and worldwide availability, biomass can also be used by a wide spectrum of countries. Specifically, biomass is believed to have greatest potential in forest-rich nations, richer countries with excess agricultural land and many low latitude countries with high biomass yields (Hall and Scrase). By stimulating new markets for the agricultural sector, production of energy from indigenous lignocellulosic biomass is also expected to increase domestic employment and reduce balance of payment deficits.

Within the biomass category, it is argued that wood possesses the highest potential followed by forage crops, and that ethanol is the biomass-based energy form with immediate potential (Tyner). With an oxygen content of 3.5 percent, ethanol is considered to be the most effective fuel additive in reducing carbon monoxide emissions. Keeney and DeLuca summarize the benefits of blending fuel with alcohol as: i) reduction in gasoline use, thereby lowering imported oil requirements, ii) increase in gasoline octane content, which in turn improves the performance of the ethanol-gasoline blend, and iii) provision of oxygen for the fuel resulting in more complete combustion. The common ethanol-gasoline blend levels include (Choi): low (petroleum-ethanol mixture with less than 22 percent ethanol), high (petroleum-ethanol mixture with at least 85 percent ethanol), neat (ethanol-water mixture with at most 20 percent water), and ethyl tertiary butyl ether (ETBE). ETBE, a compound of ethanol and isobutylene, has an additional effect of reducing vapor pressure, which further improves the suitability of gasoline for meeting Clean Air Act Amendment requirements (Wyman). As an oxygenate, ETBE competes with MTBE, the latter of which is produced from petrochemical materials. For dedicated ethanol vehicles, ethanol can be used as a pure fuel.

While MTBE contains highly toxic elements (such as benzene, toluene and xylene), ethanol reduces exhaust emission of ozone-forming volatile organic compounds (VOCs) and carbon monoxide by adding oxygen. Because the biomass feedstocks used to produce ethanol use CO_2 to grow (through photosynthesis), the CO_2 produced from combusting ethanol gets recycled, leaving a zero carbon balance (Lynd et al.). When compared to reformulated gasoline, ethanol made from biomass is also believed to generate 90 percent and 70 percent less CO_2 and sulfur dioxide, SO_2, respectively (Choi). Further, engines designed specifically for ethanol can be optimized to capture efficiency, emissions and performance benefits (California Energy Commission). Ethanol also relates to the policy of agricultural income stabilization by expanding the domestic market for the agricultural materials used to produce it.

In the United States, recognition of the importance of clean air, which brought about the 1990 Clean Air Act Amendment (CAAA) and the 1992 Energy Policy Act, has encouraged use of ethanol as a motor fuel. With dependence on imported crude oil more than doubling from 1.2×10^9 barrels in 1973 to 2.5×10^9 barrels in 1993 (Epplin), it is hoped that this will also improve the national energy security situation. Approximately 510 GL (140 billion gallons) of ethanol is needed each year to completely replace the 410 GL (110 billion gallons) annual gasoline demand (Wyman). Given its huge waste material and energy crop endowment, potential exists for the United States to produce more than enough ethanol to meet this demand. According to Wyman, as much as 618-1,320 GL (163-349 billion gallons) of ethanol can potentially be produced from the biomass materials available in the United States.

However, actual ethanol production totals only about 1.6 billion gallons per year (Choi). This supplies roughly one percent of the highway motor vehicle fuel market, mostly in a ten percent blend with gasoline (California Energy Commission). The slow expansion of the ethanol industry is attributable to high production costs. Several causes are cited in the literature for the high costs of ethanol production, including high production and opportunity cost of biomass, high biomass transportation costs, and inefficiencies in the biomass-to-ethanol conversion processes. When combined with declining prices of fossil energy, these factors, broadly categorized as economic factors and conversion process characteristics (Ballerini, Desmarquest and Pourquie), have made it impossible for ethanol to compete with fossil-based energy without some form of tax and/or subsidy incentives (Kaylen et al.).

For most of the last three decades, the United States ethanol industry has relied on corn grain as a substrate (California Energy Commission; Wyman; Keeney and DeLuca). However, the capacity of such an industry to significantly impact the energy sector is very limited. Keeney and DeLuca argue that at most 15 percent of total annual gasoline consumption can be replaced by corn-derived ethanol, even if all the corn produced in the country were converted to ethanol. Other restraints faced by the corn grain-based ethanol industry relate to inefficiencies in conversion technologies and cost of grain. In addition to a low transformation rate of about 80 gallons ethanol per ton of biomass (Kaylen et al.), the conflict with food and feed has made grain too expensive for this kind of use (Hohmann and Rendleman; Wyman). Producing grain for ethanol production also implies displacing other farm enterprises from high quality land. It is also argued that, if corn is grown under conventional input-intensive practices, the net energy balance could be negative. Keeney and DeLuca estimate this net energy deficit to be about 2,350 kJ per liter of ethanol. One reason corn grain-based conversion processes are inefficient is that only the carbohydrate part of the grain (starch) is used (Keeney and DeLuca; Hohmann and Rendleman), with little effort or ability to tap the value stored in the other constituents of the crop. Only about 15 percent of the total energy used to produce a corn crop is stored in grain (Keeney and DeLuca).

In an effort to improve the sustainability of the ethanol industry, several suggestions have been presented in the literature, including use of less input-intensive corn production practices (Keeney and DeLuca), alternative crops and crop residues. As a renewable energy source, biomass offers a number of potential energy, environmental and economic benefits. Creating a viable ethanol industry to capture these benefits, however, has posed major challenges. Unlike corn, which is composed mainly of starch, the sugars in lignocellulosic biomass are more tightly bound in long chains. More specifically, such biomass consists of 30 to 50 percent cellulose, 25 to 35 percent hemicellulose, and 10 to 30 percent lignin (Hohmann and Rendleman). The various types of feedstocks are distinguished by their exact composition of these compounds.

Over time, several technologies have been developed, and significant improvements in ethanol production costs have been realized but these economic gains have not been adequate to make ethanol competitive with gasoline. The economic performance of a biomass-to-ethanol conversion technology depends, in part, on how much of the biomass constituents are used. Most existing processes use simultaneous saccharification and fermentation (SSF) to convert the biomass into cellulose, hemicellulose and lignin. In these processes, while cellulose and hemicellulose can be potentially hydrolyzed into six- and five-carbon sugars and then fermented into ethanol, lignin is only good as a heat source (Kaylen et al.; Lynd et al.). The hydrolysis is performed either enzymatically or chemically, the latter using dilute or concentrated acid (Wyman). Typically, due to low yields and high input costs, ethanol produced by SSF is uneconomical without tax and subsidy support. Furthermore, failure to use the lignin renders that component of biomass a by-product in most of these fermentation-based processes, requiring high disposal costs.

Kaylen et al. showed that ethanol production with dilute acid hydrolysis could be economically viable but only if it is co-produced with furfural (a much higher-value co-product). Typically, in this process, ethanol and furfural are produced from cellulose and hemicellulose, respectively. Wyman also recognizes the potential of co-product hydroxymethylfurfural (HMF). However, because technology and market to foster large-scale production of furfural and HMF are not yet developed, the processes whose economic performance relies on such co-products cannot be sustained. Lately, alternative technologies involving gasification and bioconversion of biomass have been shown to yield substantial efficiency gains (Barfield et al.). These technical gains have only been demonstrated at laboratory level and remain to be examined on a larger scale.

The Decision to Invest: Is Commercialization Viable?

The development of new technologies seems to present hope for the biomass-based ethanol industry. Like any other new innovation, however, the uncertainties surrounding these technologies present additional challenges that must be overcome to foster and nurture a commercial ethanol industry. To provide an effective and representative assessment, the appraisal process needs to capture these challenging areas as much as possible. For the biomass-to-ethanol industry, the entire chain of activities from biomass production to biomass transportation and biomass-to-ethanol conversion need to be considered.

Knowledge of alternative implementation strategies for each of these stages is important in determining the most optimal combination of activities. Because all these stages are interconnected, interaction effects also need to be considered. It is argued that evaluation criteria should embrace socioeconomic and environmental effects of producing and consuming ethanol (Giampietro, Ulgiati and Pimentel). The rest of this section summarizes some of the important literature on modeling approaches with respect to the spatial and temporal decisions that need to be made as part of the appraisal process. Note that these interrelated facets require simultaneous consideration.

Spatial Considerations: Facility Location

Because agricultural biomass is unevenly concentrated and has to be collected from widely distributed geographical locations, location of biomass-to-ethanol processing activities form an important part of the investment decision process. Research dealing with efficiency of marketing areas or marketing sub-industry organization has focused mainly on the determination of the optimum (or least-cost) number, size, and location of marketing facilities. French classifies this problem into two major model classes: one which treats space as continuous for purposes of defining optimal marketing areas for individual firms, and the other which specifies a finite number of markets, locations, and raw material sources.

In the continuous space formulation, the density of raw material supplies and/or spatial density of demand are assumed to be uniform. The number of processing facilities is approximated by dividing the total regional supply by the optimum plant capacity. The optimal plant volume is determined at the point at which the decision rule is optimized. Common objective functions involve minimization of the sum of long run average cost and average assembly and/or distribution costs (French).

Olson was the first to use this approach to determine optimum size and number of agricultural marketing plants. Williamson later elaborated the model into a more general spatial equilibrium framework for plant location, including both competitive and monopsonistic cases. He also showed how, under certain assumptions, the model can be applied to cross-section data to obtain statistical estimates of the relation of optimum plant size to supply density.

One major problem with the continuous space approach is that supply density typically is not uniform and supply areas are not regular and continuous in shape. This is especially true for biomass production activities. Moreover, there often is a limited number of realistic choices of prospective plant locations, and the plant cost functions may not be independent of these locations. More details and important studies that have used and critiqued the continuous space formulation are summarized in Tembo.

The discrete space formulation, on the other hand, groups supply sources and market territories into a finite number of point locations and considers some predetermined set of feasible potential plant locations. As in the continuous case, the discrete approach also requires knowledge of transportation cost functions (or all point-to-point rates) and the long run processing or hauling cost function. One of the first models for solving this type of problem was developed by Stollsteimer, commonly referred to as the Stollsteimer model. In its original form, the Stollsteimer model used a strategic assumption that the long-run total cost function could be approximated by a linear equation with a positive intercept. Its subsequent modifications include extension to multiple product plants by Polopolous and to discontinuous plant cost functions by Chern and Polopolous.

Although the Stollsteimer model may be used to determine optimum plant locations, sizes, and number with respect to either assembly or distribution systems, it is unable to consider both (French). This led to the development of the transshipment model, which is a variant of the basic linear programming transportation model (King). The transshipment model classifies each production or consumption area as a possible shipment or transshipment point. In its first application to agricultural marketing, King and Logan used a "heuristic" technique to handle the problem of economies of scale in the study of livestock slaughter plant location.

Hurt and Tramel further developed the transshipment model to handle more than one level of processing, more than one plant at each level, and more than one final product. Leath and Martin extended the model to include inequality constraints, and Toft, Cassidy, and McCarthy developed a procedure for testing the sensitivity of the model to changes in the cost elements of the model. Miller and King further extended and compared several classes of programming models and computational procedures and applied the models to a peanut plant location study.

One limitation of the transshipment and Stollsteimer models is that they ignore fixed charges associated with plant establishment and operation. The opening of a plant, however, will typically involve a considerable initial plant investment plus other fixed costs that are amortized over the life of the plant. Faminow argues that failure to consider these fixed costs may lead to research results that are of limited use to policy makers and/or industry. In recent years, the need to incorporate these fixed charges has led to the emergence of fixed-charge facilities location models (Thompson and Thore). This formulation also permits modeling the decision to locate a plant and plant sizes as discrete variables. Because the rest of the variables often are continuous, solutions for this class of models are determined by using mixed integer programming. In agriculture, examples of facility location studies that have used this approach include Fuller, Randolph and Klingman, Cleveland and Blakley, Sweeney and Tatham, Faminow, and Tembo.

While theoretically appealing, the fixed charge problem was for a long time constrained by computational difficulties. With improvement in computational ability and development of advanced solution algorithms, most of these problems have been dispensed. Some of the most widely used algorithms employ the branch-and-bound technique for locating solutions that satisfy the integer specifications. Tembo et al. employed this procedure using the GAMS/CPLEX solver.

Temporal Considerations: Time Value of Investment Funds

Traditionally, the models discussed above are specified to determine cost minimizing solutions with a representative planning period in mind, often one year. The implied assumptions are that i) only costs matter, and ii) investment funds have a zero opportunity cost. In reality, however, investors are also interested in the return to their capital. This is especially true for venture capital owners. Because the cost and benefit streams occur unevenly throughout the useful life of the plant, discounted measures of project worth are more appropriate than the undiscounted ones. Kaylen et al. used the net present worth (NPW) as the objective function in their plant location nonlinear optimization problem.

One of the challenges in using discounted measures of project worth is to choose a discount rate. Discounting generally portrays bias against future generations. A low discount rate will tend to favor capital intensive projects with long term returns, compared to high rates. According to Pearce and Turner, positive discount rates arise because of time preference or impatience created by people's tendency to prefer benefits now to later, and the productivity or opportunity cost of capital. Much of the controversy surrounding selection of the discount rate concerns the extent to which the discount rates should reflect the rate of return on capital or rates of time preference (Toman).

Gittinger identifies four types of discount factors, one (the marginal cost of money) for financial analysis and the rest (the opportunity cost of capital, the borrowing rate, and the social time preference rate) for economic analysis. Usually, discount rates that weight time preference more heavily tend to be lower, with the effect of favoring capital intensive projects whose returns accrue in the future (Van Kooten). Toman states, "… to the extent that the marginal costs of reducing future risks rise over time, the implications for evaluating policies are similar to the use of lower discount rates."

The idea that future environmental degradation should be discounted at a rate lower than the market rate is old. Numerous justifications are given but most revolve around intergenerational equity and the desire to lessen any adverse effects of current choices on future generations (Horowitz). Many proponents of the 'shadow price of capital' approach to discounting have argued that the social rate of time preference is the appropriate rate at which to discount the benefits and costs of public projects (Toman). Such social discount rates often are of the magnitude in the range of 5-12 percent (Pearce and Turner). In reference to environmental concerns, Nordhaus suggests emission or concentration limitations, climate targeting, differential discounting, raising savings and lowering the overall discount rate as alternative ways to redesign policies to suit social goals. Some authors have suggested performing sensitivity analysis using a range of discount rates (Van Kooten; Kolb and Scheraga).

Although social discount rates are often used in projects with nonmarket impacts, they have been shown to have major shortfalls. In expressing preference for market discount rates, Weitzman contends, "... there is no reason we should not keep on discounting the deep future at today's best estimates of the rate of return of capital..." It has also been shown that a non-market discount rate is time-inconsistent. Following rigorous mathematical proofs, Horowitz contends, "... if the argument behind the social rate is that it is needed in order for present decision-makers to adequately account for future costs and benefits, then time inconsistency is troublesome because it leads to a disregard for the choices made by future regulators." (Horowitz, p. 78). Horowitz argues that a combination of market discount rates and some valuation of future "price" (or value) of the environment is a much more realistic framework. Kaylen et al. used a risk-adjusted discount rate of 15 percent.

CHAPTER IV

PROCEDURES AND DATA SOURCES

One of the central objectives of this paper is to determine and quantify Oklahoma's potential to produce ethanol from crop residues and energy grasses (biomass). If we assume that the decision-maker's preferences can be adequately represented by the net present worth (NPW) of investment in the processing facilities, then the NPW can be used as a decision rule. The fact that biomass production activities are widely distributed throughout the state identifies the need to adequately represent biomass transportation and facility location considerations. In this study, a multi-region, multi-period mixed integer mathematical programming model is developed and used to determine the optimum number, size and location of the plants. Other variables being optimized include type and quantity of biomass produced, location of biomass production, fertility regime(s), harvest structure and month(s), biomass storage, and biomass shipment networks. The object is to maximize industry net present worth over all plants. For the current application, the strength of mixed integer programming lies in its ability to model the decision to locate or not to locate a facility of a particular size as a discrete variable.

In this chapter, a full description of the model and data sources and assumptions are presented. Descriptions of all the indices, parameters and variables used in the model are also summarized in Appendix A, tables 15 through 17. The integrative investment appraisal-plant location, biomass production, storage and transportation optimization model as specified here is:

$$(4.1)\quad \underset{\substack{q,x,xt,\\ xs,\mathrm{A}}}{\mathrm{Max}}\ \mathrm{NPW} = \left\{ \sum_{m=1}^{12} \left(\sum_{j=1}^{11}\sum_{s=1}^{3}\sum_{g=1}^{4} \rho_g q_{jsgm} - \sum_{i=1}^{77}\sum_{k=1}^{10}\sum_{f=1}^{5}\sum_{h=1}^{2} \alpha_{kh} A_{ikfhm} - \sum_{i=1}^{77}\sum_{k=1}^{10} \gamma_k xs_{ikm} - \sum_{i=1}^{77}\sum_{j=1}^{11}\sum_{s=1}^{3}\sum_{k=1}^{10} \tau_{ij} xt_{ijskm} \right) - \sum_{j=1}^{11}\sum_{s=1}^{3}\sum_{ft=1}^{2} TAFC_{s,ft}\beta_{js} \right\} * PVAF,$$

Subject to:

$$(4.2)\quad \sum_{f=1}^{5}\sum_{h=1}^{2}\sum_{m=1}^{12} A_{ikfhm} - LAND_{ik} \le 0$$

(Land constraints)

$$(4.3)\quad \sum_{f=1}^{5} x_{ikfhm} - YAD_{km} * \sum_{f=1}^{5} A_{ikfhm} BYLD_{ikf} = 0$$

(Computing biomass from harvested acres)

$$(4.4)\quad \sum_{f=1}^{5} A_{ikfhm} \Big|_{YAD_{km} = 0} = 0$$

(No acres harvested in months with zero adjusted yield)

$$(4.5)\quad \sum_{j=1}^{11}\sum_{s=1}^{3} xt_{ijskm} + xs_{ikm} - \theta_k xs_{ikm-1} - \sum_{f=1}^{5}\sum_{h=1}^{2} x_{ikfhm} \le 0$$

(Biomass supply at the source)

$$(4.6)\quad \sum_{f=1}^{5}\sum_{h=1}^{2}\sum_{m=1}^{12} x_{ikfhm} - \sum_{j=1}^{11}\sum_{s=1}^{3}\sum_{m=1}^{12} xt_{ijskm} - (1-\theta_k) * \sum_{m=1}^{12} xs_{ikm} = 0$$

(Biomass balance at the source)

$$(4.7)\quad q_{jsem} - CAPP_s\beta_{js} \le 0$$

(Processing plant capacity in terms of ethanol)

$$(4.8)\quad \sum_{k=1}^{10} xs_{jkm} - CAPS_s\beta_{js} \le 0$$

(On-site biomass storage capacity)

$$(4.9)\quad \sum_{i=1}^{77} xt_{ijskm} + \phi_k xs_{jkm-1} - xs_{jkm} - xp_{jskm} \ge 0$$

(Biomass supply at the plant)

(4.10) $\sum_{i=1}^{77}\sum_{m=1}^{12} xt_{ijskm} - (1-\phi_k) * \sum_{m=1}^{12} xs_{jskm} - \sum_{m=1}^{12} xp_{jskm} = 0$ (Biomass balance at the plant)

(4.11) $\sum_{k=1}^{10} xs_{jkm} - MBINV_s \geq 0$ (Satisfy biomass minimum inventory at the plant)

(4.12) $q_{jsgm} - \sum_{k=1}^{10} \lambda_{kg} xp_{jskm} \leq 0$ (Output supply constraints)

(4.13) $q_{jsem}\lambda_{kg} - q_{jsgm}\lambda_{ke} = 0$ (Leontief ethanol-byproduct production possibilities frontier)

(4.14) $\sum_{s=1}^{3} \beta_{js} \leq 1$ (Locate at most 1 plant per location)

(4.15) $A_{ikfhm},\ x_{ikhm},\ xs_{ikm},\ xs_{jkm},\ xt_{ijskm},\ xp_{jskm},\ q_{jsgm} \geq 0$ (Non-negativity conditions)

(4.16) $\beta_{js} \in \{0,1\}$ (Binary variables)

where NPW is biomass-to-ethanol industry net present worth over the life of the processing facilities, q is a vector of commodities produced in a single planning period (one month) by the gasification-bioconversion process, and A is the number of acres of biomass harvested in the same planning period. The parameter *LAND* in Equation (4.2) represents the land upper bound in acres. The quantity of biomass corresponding to the harvested area is denoted by x and *BYLD* and *YAD* are the potential yield and yield adjustment factor used in the computation of x (Equation 4.3). The yield adjustment factor, *YAD,* varies from zero to one, depending on the month the biomass is harvested (Table 4).

The variable xt represents quantities of biomass transported from the supplying counties to the plants, xs_{ikm} is the quantity of biomass stored in the field, xs_{jkm} is the quantity of biomass stored at the plant, and xp is quantity of biomass processed at the plant. For each prospective plant location and size, $\beta = \{0,1\}$ is a binary variable, equal to one if a processing plant of size s is optimal at location j and zero otherwise. Each optimal plant is subject to monthly processing, $CAPP$, and storage, $CAPS$, capacities. Choice of optimum plant size from among three options, $s = \{\text{small}, \text{medium}, \text{large}\}$, is influenced, to a great extent, by size economies.

The parameter ρ represents a vector of output unit prices. These prices are positive for products (ethanol) and zero or negative for by-products, depending on whether or not we want to ignore the environmental consequences of the resultant externalities. The parameter α is the unit cost of producing and procuring biomass, τ is the round-trip transportation cost per ton of biomass, and γ is the cost of storing a ton of biomass in the field. The parameter λ in the output supply constraint (Equation 4.12) is a vector of process input-output coefficients, in units of output (ethanol) or byproduct (CO_2, N_2 or Ash) per ton of biomass. The model recognizes the possibility of storage losses through parameters $\{\theta, \phi\} \leq 1$, where θ and ϕ represent proportions of biomass that is usable following one month in-field and on-site storage, respectively. $MBINV$ is the minimum biomass inventory that has to be satisfied at the plant. $TAFC$, or total annual fixed costs, is the sum of the amortized fixed charges and annual operating and maintenance costs. $PVAF$ is the present value of an annuity factor (see Equation 4.19).

Indices $i, j \subset \{\text{all counties}\}$ are sets of biomass supplying counties and prospective plant locations, respectively. Oklahoma has ten major categories of herbaceous biomass, represented in this model by the index k. Specifically, the biomass types considered in this model include crop residues (corn stover and wheat straw), native prairies (tall, mixed and short), improved pasture (old world bluestem, bermudagrass, tall fescue), and a dedicated energy crop (switchgrass). For each biomass type, *k*, the index $f = \{0, 50, 100, 150, 200\}$ is used to define the alternative fertility levels (lbs. of nitrogen) that can be used to grow it. The model considers vertically integrated and atomistic structures as alternative specifications for the biomass harvesting activities, indexed here by *h*. The symbol *bc* indexes categories of costs incurred in producing and procuring biomass, which include establishment costs, maintenance costs, land rent and opportunity cost of the feedstock.

The eleven (11) prospective facility locations (counties) used in the model were selected on the basis mainly of concentration of biomass production and availability of road infrastructure. At each of these locations, the model can potentially locate any of the plant sizes, indexed by *s*. If a particular location is optimal, both processing and on-site biomass storage facilities need to be constructed. Facility type is indexed by $ft = \{\text{storage, process}\}$. At the processing plant, outputs of the gasification-bioconversion process are represented by index $g = \{\text{Ethanol, } CO_2, N_2, \text{Ash}\}$, which can be subdivided into two mutually exclusive subsets of product(s), $e = \{\text{Ethanol}\}$, and by-products, $b = \{CO_2, N_2, \text{Ash}\}$. Ash here represents all process byproducts other than CO_2 and N_2. To facilitate modeling of monthly variations in biomass availability, this model is setup to use the month as the planning period, indexed by the letter *m*.

To help trace fuel and energy balances, all machinery-intensive activities in the system were identified. The set of these specific activities is indexed by *ami* and is defined as $ami = \{\text{Tillage, Planting, Cutting, Raking, Baling, Transport, Grinding}\}$.

With the exception of Transport and Grinding, all the other members of set *ami* are generally referred to as field activities.

Technical Description of the Model

The above model maximizes aggregate industry net present worth, subject to land constraints, biomass production by species, plant capacity, biomass flows and balances, and process input-output relationships. This sub-section provides a complete technical description of the model as formulated here.

The objective function, Equation (4.1), reflects the industry net present worth with ethanol sales constituting the only benefit. Costs are incurred at the facility - fixed costs, and operating and maintenance (O and M) costs - and in biomass production, harvesting, storage and transportation. Environmental costs of by-products can be accounted for by specifying appropriately valued non-zero prices for the externalities through the vector ρ. The biomass unit cost, α, is defined as

$$(4.17) \qquad \alpha_{kh} = HC_{kh} + \sum_{bc=1}^{4} POC_{k,bc} + NCOST_k$$

where HC_{kh} is the cost of harvesting a unit of biomass *k* using structure *h*, $NCOST_k$ is the cost of nitrogen fertilizer used in the production of biomass *k*, and $POC_{k,bc}$ is the cost associated with establishment, maintenance and procurement (opportunity cost) of biomass of species *k*. The subscript *bc* indexes these cost categories (see Table 2). That is, *bc* = {Establishment costs, Maintenance costs, Land rent, Opportunity cost of biomass}. For each plant location and size, total fixed costs, *TAFC*, are charged to the objective function only if the corresponding binary variable attains a value of one. *TAFC* is defined as

$$TFAC_{s,ft} = AFC_{s,ft} + OMA_{s,ft}, \tag{4.18}$$

where $AFC_{s,ft}$ is annual fixed charge amortized over the life of the plant and $OMA_{s,ft}$ is annual operating and maintenance cost, assumed to be a fixed proportion of $AFC_{s,ft}$. In this study, $OMA_{s,ft}$ is assumed to be equal to two percent and five percent of $AFC_{s,ft}$ for *ft* = "storage" and *ft* = "process", respectively.

With an expected useful plant life of fifteen years, this multi-period, multi-plant model is optimized over 15 x 12 months. If we assume that all the years are identical, the annual net benefits can be treated as an annuity. The above model uses this assumption and defines the *NPW* with the present value of an annuity factor (PVAF), defined as:

$$PVAF = \frac{(1+r)^t - 1}{r(1+r)^t}, \tag{4.19}$$

where *r* is the discount rate and *t* is useful plant life in years. Because the model includes a lot of detail, the simplification implied by assuming that the years are identical is necessary as a check on dimensionality, without much loss of generality.

Equation (4.2) imposes land constraints at each county. It tells the model that, in each year and at each county, the acres of biomass *k* harvested cannot exceed the land upper bound, *LAND*. The land upper bound depends on assumptions about land availability. Two versions of the above model can be derived by alternative definitions of *LAND*. That is,

$$(4.20)\quad LAND_{ikl} = \begin{cases} BIPROP * CURACRE_{ik}, & \text{if existing biomass acreage is used} \\ BIPROP * POTACRE_{il}, & \text{if model permits displacement of} \\ & \text{other activities,} \end{cases}$$

where *CURACRE* and *POTACRE* are existing biomass acreage and potential acreage, respectively. The parameter *BIPROP* defines the proportion of land allocated to the feedstocks that is potentially available for the biomass-to-ethanol industry. This is particularly important to avoid exerting too much pressure on the activities currently using the land. Following, Kaylen et al. a conservative 10 percent is used for *BIPROP.* Most of the runs performed in this study assume that $LAND = BIPROP * CURACRE_{ik}$. The alternative specification of the land upper bound (Equation 4.20) is used only in one model scenario, where switchgrass is permitted to displace some of the existing cropping activities. The GAMS/CPLEX code for these alternative specifications and the rest of the model is presented in Appendix C.

Equation (4.3) imposes the condition that the quantity of biomass actually produced cannot exceed the product of the number of acres harvested and yield, adjusted for the month in which the biomass is harvested. The yield adjustment factor, *YAD*, is based on the assumption that biomass yields are highest if harvested at certain times of the year and decline thereafter. Inclusion of this adjustment factor enables the industry to tradeoff between in-field losses and in-storage losses, as may be required in the quest to maximize the objective function. The model is constructed to permit limiting the proportion of potential acres in a county that may be used for production of biomass. The base model assumes that this proportion is 10 percent, following Kaylen et al.'s conservative specification. Equation (4.4) imposes the constraint that no acres should be harvested during the months in which adjusted yield is equal to zero.

Equation (4.5) imposes biomass supply constraints at each source. It tells the model that, in each month and at each source, the sum of quantity shipped to plants and quantity put in storage of each biomass type, *k*, cannot exceed the sum of current production and usable portion of stored biomass. Usable biomass in this case is the quantity of biomass after accounting for deterioration while in storage. Equation (4.6), defined on an annual basis for each supplying county, ensures that quantity of biomass shipped out plus that lost in in-field storage balance with total biomass produced.

Processing and biomass storage volumes at the plant, and their respective capacities are linked to the binary variable through the capacity constraints represented by equations (4.7) and (4.8). If $\beta_{js}=1$, $CAPP_s\beta_{js}=CAPP_s$, the processing capacity upper bound in gallons of ethanol, and the total ethanol production at each plant in that month will be bounded by $0\le q_{jsem}\le CAPP_s$ (Equation 4.7). Similarly, total biomass storage at that plant will be bounded by $0\le\sum_{k=1}^{10}xs_{ikm}\le CAPS_s$ (Equation 4.8). Optimal levels of ethanol produced and biomass stored at the plant will be determined in the solution. If $\beta_{js}=0$, expressions $CAPP_s\beta_{js}$ and $CAPS_s\beta_{js}$ will also be equal to zero, by definition. Because neither q_{jsem} nor xs_{jkm} can assume negative values, they both must also be equal to zero. No storage upper bounds are assumed for in-field storage.

For each planning period (month), the sum of the quantity of biomass transported to the plant and the usable portion of stored biomass constitute total biomass supply at the plant. Equation (4.9) imposes the constraint that total biomass processed or stored at the plant should not exceed the total biomass supply. Furthermore, total biomass delivered to the plant is balanced, in each year, with the sum of processed biomass and on-site storage losses for that year (Equation 4.10). To avoid biomass supply disruptions, the model permits imposition of minimum biomass inventory through Equation (4.11). In all the runs made for this study, minimum inventory is equal to zero, by assumption.

If we assume a Leontief production function at the processing facility (fixed input-output coefficients), the quantity of each output produced should be directly equal to the product of the corresponding transformation coefficient, λ, and quantity of biomass used, *xp* (summed over all biomass types). These relationships are represented by Equation (4.12), where the inequality gives allowance for production losses. Equation (4.13) imposes a Leontief production possibilities frontier between ethanol and each of the by-products. This condition is necessary to ensure that any production of ethanol results in a corresponding amount of the by-products (externalities). For the runs in this study, λ is assumed to be zero for all byproducts.[2]

Equation (4.14) represents upper bounds on the number of plants that can be built at each location, assumed here to be equal to one. Because the model is provided with three possible plant sizes, the upper bound is one plant per location. If a particular plant size is too small, then a larger plant should be built as opposed to constructing several small plants at the same location. Considering the inconvenience of constructing several plants in the same location and the probable loss of scale economies, this constraint seems to be reasonable.

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[2] Due to the zero carbon balance argument for the process (CO_2) and lack of information (N_2, Ash).

The non-negativity conditions, equation (4.15), constrain the model from negative quantities of land, biomass and process outputs. Finally, Equation (4.16) restricts values of the binary variable to the set of zero and one.

Data Sources and Assumptions

For practical purposes, the dispersed distribution of biomass is assumed to be separated into a finite number of regions in space (counties). A city approximately at the center of the county is used to represent the county as a single point. The eleven (11) prospective plant locations were selected on the basis of biomass relative density, proximity to the biomass producing centers, and availability of road infrastructure. The distance between any biomass supplying county and any plant location was estimated by the distance from the county's representative point to the plant location. The city-to-city distances reported in the official Oklahoma State road map were used for this purpose. To avoid assuming zero intracounty distances, a conservative one-half of the longest straight-line distance in each county (radius) was added to the intercounty distance estimates. This adjustment is particularly important considering that biomass is transported from all over the county. Also, if the processing plant is located in a county that is also identified as a biomass supply point, this specification provided a much more realistic estimate of the distance than zero, which would otherwise be assumed.

Total cost of transporting biomass was computed using the herbaceous biomass transportation cost regression equation developed by Bhat, English and Ojo (Equation 3 in their paper). In its original form their equation was expressed as

$$TRC_{ij} = 34.08 + 0.62d_{ij} \tag{4.21}$$

where d_{ij} is the round-trip distance, in kilometers, from biomass supplying county *i* to plant location *j*, and *TRC* is the transportation cost in U.S. dollars per 15.42 dry metric tons (17 dry tons) truck. Equation (4.21) was estimated based on weekly trucking rates charged by agricultural produce transporters across different U. S. regions and assumes that the herbaceous crops are harvested, baled and transported in form of bales (Bhat, English and Ojo). After converting the distance from kilometers to miles, Equation (4.21) becomes

$$TRC_{ij} = 34.08 + 1.00\delta_{ij}, \tag{4.22}$$

where $\delta_{ij} = \frac{d_{ij}}{1.609}$ is the round-trip distance in miles. The average per dry ton transportation cost, τ_{ij}, was determined by dividing Equation (4.22) by the assumed truck capacity (17 tons).

This specification permits the transportation rates ($/ton/mile) to vary by round-trip distance. As expected, these rates decline nonlinearly with increase in round-trip distance. Figure 2 shows that, if this relationship holds, the $0.15 per dry ton per mile transportation rate assumed by Kaylen et al. corresponds to a round-trip distance of about 22 miles.

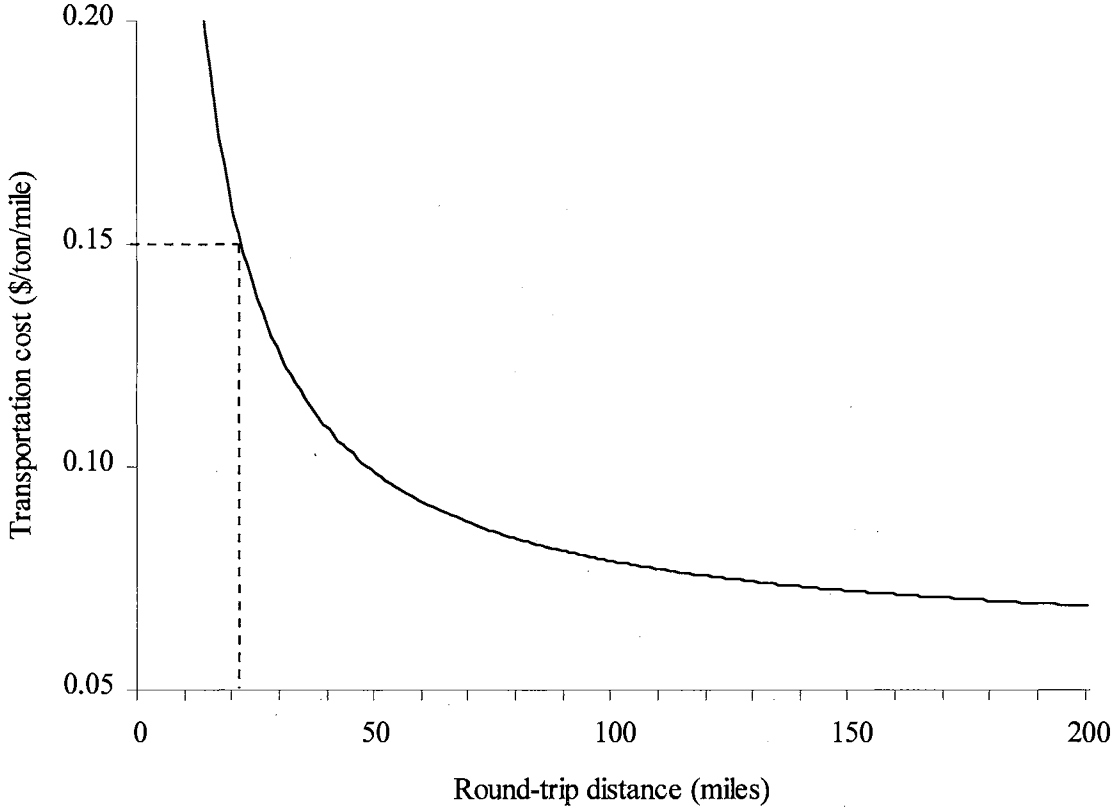

Figure 2. Relationship between round-trip distance and biomass transportation cost

Biomass Production Data

This study is concerned with converting herbaceous biomass into ethanol. In Oklahoma, the major herbaceous feedstocks include crop residues (mainly wheat straw and corn stover), native prairies (tall, mixed and short) and improved pasture (tall fescue, old world bluestem and bermudagrass). Due to its high-yielding nature, switchgrass establishment has been considered in one of the scenarios.

Five-year data (1993-1997) from the Oklahoma Agricultural Statistics (Oklahoma Department of Agriculture) were used to estimate the average number of acres and yields of corn and wheat for each of the Oklahoma counties. The reported yields pertain to corn and wheat grain, not their residues. To compute corresponding yields of crop residues, regression equations applied to data reported by Steiner, Schomberg and Morrison were used. For corn, the estimated equation relating grain yield to stover yield is

$$CSY = 3308.2 + 0.5086CGY, \tag{4.23}$$

where CSY and CGY are corn grain and corn stover yields, respectively. Similarly, the equation relating wheat grain yield to wheat straw yield is given as

$$WSY = 329.99 + 1.5573WGY, \tag{4.24}$$

where *WSY and WGY* are wheat grain yield and wheat straw yield, respectively. In both equations (4.23) and (4.24), both grain and residue yield estimates are in pounds per acre. In terms of the notation of the above model, crop residue yields can be defined as

$$BYLD_{i,cr,f} = \begin{cases} CSY_{if}, & \text{if } cr = \text{corn stover} \\ WSY_{if}, & \text{if } cr = \text{wheat straw,} \end{cases} \tag{4.25}$$

where $cr \subset k$ is a set of crop residues considered and i and f are as defined above.

Table 1. Land area (in '000 acres) and proportion of land area under each of Oklahoma's forage species by land-use classification

	CRP[a]		Native prairies			Improved pasture			
Region/Acres/ Proportion	OWB[b]	Other	Tall grass	Mixed grass	Short grass	Bermudagrass	OWB[b]	Tall fescue	Other
PANHANDLE									
Acres	359	120	xxx	xxx	1,617	0	209	22	64
Proportion	0.75	0.25	0.00	0.00	1.00	0.00	0.71	0.07	0.22
NORTHWEST									
Acres	252	84	419	3,141	628	388	353	16	307
Proportion	0.75	0.25	0.10	0.75	0.15	0.36	0.33	0.01	0.29
NORTHEAST									
Acres	2	28	3,254	171	xxx	548	11	455	79
Proportion	0.05	0.95	0.95	0.05	0.00	0.50	0.01	0.42	0.07
SOUTHWEST									
Acres	247	82	1,208	1,510	302	474	260	15	347
Proportion	0.75	0.25	0.40	0.50	0.10	0.43	0.24	0.01	0.32
SOUTHEAST									
Acres	1	19	2,386	265	xxx	804	12	222	82
Proportion	0.05	0.95	0.90	0.10	0.00	0.72	0.01	0.20	0.07

[a] Conservation reserve program (CRP)

[b] Old world bluestem (OWBS)

Sources: Proportions from Taliaferro (1998)
Total acres per land category from 1992 Census of Agriculture (Bureau of Census)

Oklahoma agricultural land can be categorized into cropland, improved pasture land, native pasture land and rangeland, and conservation reserve program (CRP) land. Estimates of land area under each of these categories were obtained from the 1992 Census of Agriculture (Bureau of the Census). In general, while native prairies grow on native pastureland and rangeland, improved pasture can only be grown on improved pasture land. Because no secondary information was available to facilitate allocation of these land aggregate figures to the various grasses (native prairies, improved pasture), expert opinion from the Oklahoma State University Department of Plant and Soil Sciences (Taliaferro) was used to derive approximate land proportions for each of the regions of the state. These estimates were crosschecked with a map of grassland vegetation of Oklahoma.[3] Table 1 presents these proportions and the corresponding land area under each of the grasses by region. These regional level proportions were applied to each of the counties in the corresponding regions.

Switchgrass, the only dedicated energy crop considered in this study, is not reflected in Table 1. This is because Table 1 presents only what is already in existence. Switchgrass came into play only if the model is allowed to reallocate some of the existing cropland to switchgrass. In terms of the above model description, Table 1 combined with the wheat and corn acres in cropland constitute the current acreage upper bound. If all the various land categories can be reallocated, then potential acreage becomes the land upper bound. The upper bounds are adjusted so that only a fixed proportion of the biomass land area can be allocated to ethanol production (Equations 4.2 and 4.20).

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[3] From an unpublished manuscript entitled 'Grasslands of Oklahoma' by the late J. K. McPherson, Professor, Botany Department, Oklahoma State University, Stillwater, Oklahoma, undated.

Table 2. Biomass production and opportunity costs in U.S. $/acre/year

Feedstock species	Establishment Costs	Maintenance costs	Land rent	Biomass opportunity cost
Wheat straw	0.00	0.00	0.00	10.00
Corn stover	0.00	0.00	0.00	20.00
Old world bluestem	0.00	3.00	30.00	0.00
Native tall	0.00	0.00	10.00	0.00
Native mixed	0.00	0.00	10.00	0.00
Native short	0.00	0.00	10.00	0.00
Bermudagrass	0.00	3.00	30.00	0.00
Tall fescue	0.00	3.00	30.00	0.00
Switchgrass	11.22	3.00	45.00[a]	0.00

[a] Because no land was allocated to switchgrass production in the state at the time of the study, any acre of switchgrass that came into the basis would need to displace some existing cropping activity. Hence the high land rent on switchgrass.

Sources: Epplin (1996)
Epplin (2000)

Various types of costs go into biomass production. In this study, these costs are categorized as establishment costs, maintenance costs, land rent and opportunity cost of biomass. The exact combination and levels of these costs depend on the type of feedstock. For example, while all grasses (native prairies and improved pasture) require land rent, procuring crop residues incurs only the value of their next best alternative (opportunity cost). Because switchgrass acreage is currently assumed to be zero, the switchgrass activity can become a possibility only if establishment costs are incurred. Estimates of these cost categories were obtained from budgets prepared by Epplin (1996, 2000) and are presented in Table 2 below. As is evident from the low land rental cost, the land in which native prairies grow is of lowest quality.[4]

For the improved pasture and dedicated energy crops, another cost category concerns fertilizer application. In this study, four levels of fertilization are considered for bermudagrass, tall fescue and old world bluestem. These are 50, 100, 150 and 200 pounds of nitrogen per acre. Estimates of yields corresponding to these fertility levels were obtained through personal consultations with the Oklahoma State University Department of Plant and Soil Sciences (Taliaferro). Because no switchgrass yield estimates are available for such multiple fertility regimes, only one fertility level (25 lb./acre) was used for switchgrass. Potential yield estimates corresponding to this level of nitrogen were obtained from the Oak Ridge Energy Crop County Level Database, authored by Graham, Allison and Becker. For the native grasses, yield estimates were obtained through a survey of field staff in the respective regions. A zero fertility level is assumed for native prairies and crop residues.

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[4] In Table 2, $10/acre is the lowest land rent. Zero rent is charged to wheat straw and corn stover because they are crop residues and the true land rent is already accounted for in the grain production activities.

Table 3. Dry biomass yield estimates by region and fertility regime

Species	Nitrogen level (lb.)	Yield by region (tons/acre/year)				
		Panhandle	North-west	South-west	South-east	North-east
Bermudagrass	50	1.75	1.75	1.75	2.25	1.75
	100	2.50	2.50	3.00	3.50	2.50
	150	3.00	3.00	3.75	4.50	3.00
	200	4.50	4.50	4.25	5.50	4.25
Tall fescue	50	xxx	xxx	xxx	1.75	2.00
	100	xxx	xxx	xxx	2.25	3.00
	150	xxx	xxx	xxx	3.00	3.75
	200	xxx	xxx	xxx	3.75	4.75
Old world bluestem	50	1.50	1.50	1.50	1.50	1.25
	100	2.00	2.00	2.25	2.36	2.31
	150	2.50	2.50	3.00	2.75	2.75
	200	3.00	3.00	3.75	3.50	3.25
Switchgrass	25	0.00	5.00	5.00	6.50	6.00
Native tall prairies	0	xxx	1.57	1.40	2.09	3.00
Native mixed prairies	0	xxx	1.27	1.25	1.68	1.90
Native short prairies	0	0.67	0.95	0.85	xxx	xxx
*Wheat straw	0	0.72	0.71	0.68	0.80	0.81
*Corn stover	0	3.01	2.14	2.08	2.14	2.05

xxx the feedstock is not grown in that region.
* The values in the table are averages over all counties in each region.

Sources: Taliaferro (2000) for bermudagrass, tall fescue and old world bluestem
Survey of county field staff (1998) for the native prairies
Graham, Allison and Becker (1996) for switchgrass
Regression estimates, *E*(forage yield)=*f*(grain yield), for crop residues using data from Steiner, Schomberg and Morrison

Table 3 summarizes the yield estimates for all the feedstocks by region and fertility level, where applicable. Except for wheat straw and corn stover whose county level yield estimates are available, the yields for all other types of feedstocks are regional estimates. Because the model uses the county as the smallest regional unit, in this case the same regional estimates are applied to each of the counties in the respective regions.

In general, biomass yield will be highest if the biomass is harvested in the most appropriate month(s). The estimates in Table 3 are potential yield levels assuming that the harvesting is carried out in the months that yield the most for each feedstock. However, harvesting all the biomass in a short period will exert additional pressure on in-field storage and other resources. Since loss in biomass quantity and quality is also eminent in storage, the decision-maker may wish to tradeoff storage losses with field losses by harvesting later than is appropriate for maximum yield.

To allow the model the option of harvesting over a wide range of months, the potential yield (Table 3) is penalized by the yield loss factor corresponding to the month the biomass is actually harvested (Equation 4.3). Table 4 presents the proportions of Table 3 yields that would be attainable in each of the twelve months of the year. The contents of Table 4 were obtained through agronomic expert opinion (Taliaferro, 2000).

Other biomass production data include those associated with harvest and postharvest activities. The model permits two harvest structures, individual farm (or atomistic) and vertically integrated. In an atomistic structure, the individual farmer uses his/her own machinery to produce and harvest the biomass he/she produces and sells the biomass to the ethanol industry. In a vertically integrated structure, the biomass-to-

Table 4. Yield adjustment factor by month of harvest

	Proportion of potential yield by month of harvest											
Species	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wheat straw	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00
Corn stover	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.00	0.00
Old world bluestem	0.80	0.75	0.00	0.00	0.00	0.00	1.00	1.00	1.00	0.95	0.90	0.85
Native tall prairies	0.80	0.75	0.00	0.00	0.00	0.00	1.00	1.00	1.00	0.95	0.90	0.85
Native mixed prairies	0.80	0.75	0.00	0.00	0.00	0.00	1.00	1.00	1.00	0.95	0.90	0.85
Native short prairies	0.80	0.75	0.00	0.00	0.00	0.00	1.00	1.00	1.00	0.95	0.90	0.85
Bermudagrass	0.80	0.75	0.00	0.00	0.00	0.00	1.00	1.00	1.00	0.95	0.90	0.85
Tall fescue	0.00	0.00	0.00	0.00	0.00	1.00	0.90	0.80	0.75	0.00	0.00	0.00
Switchgrass	0.80	0.75	0.00	0.00	0.00	0.00	1.00	1.00	1.00	0.95	0.90	0.85

Source: Taliaferro (2000).

ethanol industry rents the land away from the farmers and uses its own machinery to harvest the feedstocks. The costs associated with these harvest structures were computed using Huhnke's (1999) agricultural field machinery cost estimation software (AGMACH$).

At the biomass supply point, storage is the only postharvest activity considered in the model. Strictly speaking the various feedstock types will deteriorate at different rates. However, because of lack of data, this model uses a single deterioration rate for all biomass types. Specifically, it is assumed that a 0.5 percent loss in quantity and quality will be incurred every month the biomass stays in storage (Huhnke, 2000). Unlike at the plant, very cheap storage structures are assumed at the biomass source. It is assumed that such in-field storage structures would cost about $2.00 per ton per month (Huhnke, 2000).

Table 5 summarizes the biomass harvest and post-harvest data and assumptions used in this study. Details of the machine specifications and assumptions used to arrive at the harvest cost estimates for all forage grasses, wheat straw and switchgrass are presented in tables 17, 18 and 19, respectively. Biomass storage and processing activities at the plant are discussed in the next section.

Facility-Related Estimates

With the biomass production relationships and costs established, the next question is: which locations should be considered for locating the plant(s) and what sizes should the plant(s) be? In this model, proximity to high biomass production centers and

Table 5. Biomass harvest and in-field postharvest data

Feedstock Species	Harvest costs by harvest structure ($/acre)[a]		In-field storage cost ($/ton/month)	In-field storage losses (% /month)
	Individual farm	Vertically integrated		
Wheat straw	11.60	7.30	2.00	0.50
Corn stover	16.30	12.30	2.00	0.50
Old world bluestem	16.30	12.30	2.00	0.50
Native tall	16.30	12.30	2.00	0.50
Native mixed	16.30	12.30	2.00	0.50
Native short	16.30	12.30	2.00	0.50
Bermudagrass	16.30	12.30	2.00	0.50
Tall fescue	16.30	12.30	2.00	0.50
Switchgrass	29.33	24.29	2.00	0.50

[a] Refer to tables 18 through 20 for computational details and machine assumptions.

Sources: Agricultural Field Machinery Cost Estimation Software (Huhnke, 1999).
Personal communication with Huhnke (2000).

availability of road infrastructure are the major criteria used to identify prospective plant locations. A total of eleven prospective plant locations (counties) were identified for Oklahoma. These include counties Canadian, Comanche, Custer, Garfield, Jackson, Okmulgee, Payne, Texas, Pontotoc, Washington and Woodward. Each of these locations, if in the basis, will involve construction and installation of a processing facility and a biomass storage facility. The costs associated with these facilities will vary by plant size.

In this study, a processing plant with a 50 million gallons per year ethanol capacity is assumed to be medium in size. If we assume that three week's storage capacity is enough as contingency for most biomass supply disruptions and an ethanol yield of 100 gallons per ton of biomass, a plant of this capacity will need to be equipped with a 28,846 ton biomass storage facility (Table 6). Therefore, construction and installation costs of a 50 million-gallon plant will involve both facilities. In this study, \$100 million (Johannes, 2000) and \$1,528,846 (Huhnke, 2000) were assumed for the processing and storage facilities, respectively.

A factor of 0.5 was used to scale the facilities up or down. For the processing facilities, with an annual capacity of 50 million gallons regarded as "medium", 50 x 0.5 = 25 million gallons and 50 ÷ 0.5 = 100 million gallons would be regrarded as "small" and "large", respectively. Similarly, storage capacities of 28,846 tons, 28,846 x 0.5 = 14,423 tons, and 28,846 ÷ 0.5 = 57,692 tons correspond to "medium", "small" and "large" plant sizes, respectively.

For both processing and storage facilities, the usual engineering assumption that doubling capacity increases construction costs by 70 percent (Johannes, 2000) was used

Table 6. Construction and Equipment Cost for an On-Site Biomass Storage Facility for a 50 Million Gallon per Year Plant

Item description	Unit	Quantity
1. Land	ft^2 / ton	9
2. Storage period	week	3
3. Construction costs		
3.1 Land cost	\$ / ft^2	3
3.2 Land cost	$/ton	27
3.3 Processing facility capacity		
3.3.1 Ethanol	Gallon	50,000,000
3.3.2 Biomass	ton	500,000
3.4 Biomass storage capacity	ton	28,846
Subtotal construction costs	ton	778,846
4. Equipment		
4.1 Payloaders (2 x $250,000)	dollar	500,000
4.2 Grinding equipment	dollar	250,000
Subtotal equipment costs	dollar	750,000
Total fixed costs for biomass storage facility	dollar	1,528,846
Annual operating and maintenance cost (2% of total fixed costs)	dollar	30,577

Source: Personal Communication with Huhnke (2000) to adjust the medium plant costs to large and small plants. Table 7 summarizes these facility capacity and cost data. Annual operating and maintenance costs are computed as a fixed proportion of total investment. In this study, these proportions are assumed to be two percent (Huhnke, 2000) and five percent (Johannes, 2000) for storage and processing facilities, respectively.

For all the facilities, a fifteen-year useful life and zero salvage value were assumed. In storage, minimum biomass inventory and storage losses are assumed to be equal to zero and 0.1 percent, respectively. Following Horowitz's argument about policy inconsistency of non-market interest rates, this study uses a market discount rate of 15 percent (Kaylen et al.) and incorporates the external costs of emissions by putting a price on those externalities. However, since the emissions (CO_2, N_2) are non-market goods, there is no cash value associated with them. This study uses Bernow and Marron's revealed preference based estimates to represent the external costs implied by emission of these gases. Because no estimates were available for byproduct (ash) disposal costs at the time of the study, a value of zero was assumed.

Furthermore, the above model assumes that all the ethanol produced by the facilities will be bought at the plant at some price. Wyman argues that, if a barrel of crude oil costs at least $25, ethanol should have a breakeven price of $0.67 per gallon to be competitive. However, if production is optimally zero at that price, the difference between the threshold price (the price at which the first plant enters the basis) and $0.67 provides a measure of the required subsidy to keep that plant in operation. A grid search procedure was used to determine the threshold (or break-even) price of ethanol.

Table 7. Facility capacities and construction and installation costs by plant size

Plant size	Facility monthly capacity		Facility fixed costs ('000$)		Total plant costs ('000$)
	Processing (gal of ethanol)	Biomass Storage (tons)	Processing	Storage	
Small	2,083,333	14,423	58,824	899	59,723
Medium	4,166,667	28,846	100,000	1,529	101,529
Large	8,333,333	57,692	170,000	2,599	172,599

Another important piece of information needed by the above model is the quantity of each of the products (ethanol) and by-products (CO_2, N_2, and Ash) that will be produced from a unit of biomass. Based on preliminary materials balance computations, it was estimated that a ton of biomass would produce 100 gallons of ethanol. However, similar information was not available for the by-products at the time of the study. The Solar Energy Information Data Bank argues that for every one gallon of ethanol produced in a fermentation process, 6.33 pounds of CO_2 are formed. It is argued, however, that any such CO_2 emissions would be completely used up by the growing biomass plants, through photosynthesis, in turn leaving a zero net carbon balance.

Using this argument, a zero biomass-to-CO_2 transformation rate is assumed in this study. Because of lack of information, transformation rates for all other by-products are also set to zero. Table 8 summarizes the information on the input-output coefficients, and output prices and costs assumed for this study.

Energy Balance Computations and Related Assumptions

One of the sustainability-related issues raised about a biomass-based ethanol industry is whether or not the industry could actually yield positive net energy gains. To a great extent, the results of an energy assessment exercise will depend on assumptions that it embodies. For the corn-to-ethanol industry, for example, while some authors have shown that positive net energy gains are possible (Marland and Turhollow; Morris and Ahmed; Shapouri, Duffield and Graboski), others have concluded otherwise (Pimentel; Keeney and DeLuca; Ho). Shapouri, Duffield and Graboski showed that these divergent conclusions arise mainly because of differences in "… assumptions about corn yields,

Table 8. Input-output coefficients, subsidized price of ethanol, and external cost of byproducts.

Commodity	Unit	Quantity produced per ton of biomass	Subsidized price/external cost per unit ($)
Ethanol	Gallon	100	0.67 + sub[a]
CO2	Ton	0	-24.70
N2	Ton	0	-246.40
Ash	Ton	0	0

[a] Subsidy (sub) is the difference between $0.67 and the subsidized price of ethanol.

ethanol conversion technologies, fertilizer application rates, coproduct evaluation, and number of energy inputs included in the calculations…" (Shapouri, Duffield and Graboski, p. 4).

In general, determining the net energy of ethanol requires adding up all the energy required to produce, transport and process the substrate (in this case biomass) into ethanol. Elements of the vector of energy spending activities include both primary and secondary inputs. Because secondary inputs, such as those imbedded in the equipment, are difficult to quantify, most studies ignore them. Shapouri, Duffield and Graboski argue that even if secondary inputs were included, their contribution to total energy value of a gallon of ethanol would be negligible.

In this study, primary inputs were used to estimate total energy spent and net energy per gallon of ethanol. The energy consuming activities considered include tillage, planting, fertilizer application (for improved pasture and dedicated energy crops), cutting, raking, baling, transportation, and grinding of biomass. This vector of machinery-intensive activities is indexed in the model by *ami*. On assumption that the gasification-bioconversion process would be able to use its own energy (heat from biomass combustion plus some of the ethanol) to run (Johannes, 2000), the energy computations here include only activities prior to processing. Implicit in this premise is the assumption that the biomass-to-ethanol transformation rate(s) already accounts for the ethanol used to run the process.

Except for the fertilizer activity (with the fertilizer, nitrogen, itself representing most of the energy spent), all the other energy-consuming activities use fuel (diesel) as the major primary input. Thus, for these activities, the challenge rested in estimating the amount of diesel used. The specific computations depended also on the nature of the energy consuming activity in question. For biomass transportation, for example, the quantity of diesel consumed per mile for a 17-ton truck was computed from the average number of miles the truck can travel per gallon of diesel. That is

$$gpm = \frac{1}{mpg}, \tag{4.26}$$

where *gpm* is gallons of diesel per mile and *mpg* is miles per gallon of diesel. The average *mpg* was computed from the California Department of Transportation 1993 forecasts. Averaged over the period 1992-2000, the value used here is 5.43 miles per gallon (*mpg*).

For all the other fuel consuming activities, the quantity of diesel consumed was computed by using the horsepower of the machinery, time required to perform a unit of the task and the standard diesel engine fuel multiplier. That is,

$$du = hp * time * fm, \tag{4.27}$$

where *du* is diesel used in gallons per unit, *hp* is the horsepower of the machinery used to perform the activity, *time* is the number of hours used per unit of the activity, and *fm* is the fuel multiplier in gallons per horsepower hour. The unit of analysis is acre for field activities (tillage, planting, cutting, raking, and baling) and ton of biomass for grinding. The value of the fuel multiplier used, *fm* = 0.044, was obtained through personal communication with Huhnke (2000). For field activities, estimates of *hp* and *time* were obtained from Huhnke's AGMACH$ software (Huhnke, 1999) and personal communication with Huhnke (2000). Table 9 reports these values. For the grinding activity, it was assumed, based on a telephone conversation with the manufacturer (Huhnke, 2000), that $hp * time = 15$ horsepower hour per ton of biomass.

Table 9. Machinery horsepower and time required to perform each of the field activities per acre

Activity	Machinery horsepower (*hp*)	Hours per acre (*time*)
Tillage	150	0.13
Planting	75	0.11
Cutting	75	0.15
Raking	75	0.10
Baling	150	0.05

Sources: AGMACH$ Software (Huhnke, 1999)
Personal communication with Huhnke (2000).

Once the quantity of diesel was determined, it was converted to British thermal units (Btu) of energy by multiplying by a fixed energy content per unit. Similarly, the quantity of fertilizer used to produce biomass, if applicable, was converted to Btu by multiplying by the fertilizer energy content estimate. In general, diesel and gasoline contain 137,202 Btu and 125,073 Btu per gallon, respectively (Shapouri, Duffield and Graboski). The authors also estimate that about 22,159 Btu are expended to produce a pound of nitrogen fertilizer. An estimate of the energy contained in a gallon of ethanol (78,000 Btu) was obtained from Hohmann and Rendleman.

Modeling Ethanol's Competitiveness with Diesel

Wyman argues that if a barrel of crude oil costs at least $25, ethanol should have a breakeven price of $0.67 to be competitive. In this study, we do not try to re-derive these conditions of competitiveness. Rather, we assume that the price ratio implied by this relationship, $\frac{25}{0.67} = 37.31$, defines the threshold that must be attained to make ethanol competitive.

To re-express this ratio in terms of diesel-to-ethanol, a relationship is established between the price of diesel and that of crude oil. Historical price data (1992-1997) published in the June 2000 Petroleum Marketing Monthly (U.S. Department of Energy, Energy Information Administration) were used to regress the price of diesel on the price of crude oil, assuming a univariate relationship. That is,

$$diepri = \psi_0 + \psi_1 crudpri + \varepsilon, \tag{4.28}$$

where ψ_0 and ψ_1 are intercept and slope, respectively, and ε is the random error term. The variables *diepri* and *crudpri* are diesel (\$/gallon) and crude oil (\$/barrel) pretax prices, respectively.

Because autocorrelation was suspected, the SAS MIXED procedure was used with the covariance structure initially specified as AR(1). However, following rejection of this covariance structure, the model was re-specified with a spherical random error term. The regression results obtained are summarized in Table 10 below. In general the data produced a very good fit with $R^2 = 0.97$. Also, both parameter estimates are significant at 0.95 level of significance (*p-value* < 0.0001). In Table 10, the values in the parentheses are the standard errors for the respective estimates.

Given equation (4.28) and the parameter estimates in Table 10, the diesel-ethanol price ratio that makes ethanol competitive, *cdepr*, was computed as

$$cdepr = \frac{0.1526 + 0.0242crudpric}{ethpric}, \tag{4.29}$$

where *crudpric* (= \$25 per barrel) and *ethpric* (= \$0.67 per gallon) are crude oil and ethanol prices used by Wyman to define competitiveness. Notice that the numerator is equal to the price of diesel that corresponds to *crudpric*, or *diepric*.[5] Substituting *crudpric* = 25 and *ethpric* = 0.67 into equation (4.29) yields a price ratio of *cdepr* = 1.13. If we assume that this ratio defines the locus of all those points in the diesel-ethanol price space where ethanol is competitive, then the price of diesel that would make ethanol competitive at any given price of ethanol can be calculated as

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[5] The *c* is added to *diepri* and *crudpri* (i.e. the two are defined as *diepric* and *crudpric*) to denote the specific (competitive) prices quoted by Wyman.

Table 10. **Regression results for the relationship between the price of crude oil ($/barrel) and price of diesel ($/gallon), based on 1978-1997 historical data**

Variable	Parameter symbol	Parameter estimate	p-value
Intercept	ψ_0	0.1526 (0.0247)	< 0.0001
Price of crude oil	ψ_1	0.0242 (0.0011)	< 0.0001

$$diepri = cdepr * ethpri. \tag{4.30}$$

Thus, the model could be run with current price of diesel (estimated to be about $0.80 at the time of this study, Huhnke 1999) or with the price of diesel as defined in Equation (4.30).

If the current price of diesel is used (i.e. if $diepri = diepri0$, where $diepri0$ is current price of diesel) and ethanol production is optimally nonzero at any chosen price of ethanol, then the difference between that price of ethanol and $\frac{diepri0}{cdepr}$ is the amount of subsidy required to keep the biomass-to-ethanol plant(s) in operation. Condition (4.30) is imposed whenever the model is required to run with a price of diesel that would make ethanol competitive without subsidies or tax incentives. Thus, for any given price of ethanol,

$$diepri = \begin{cases} diepri0, & \text{if subsidies are acceptable,} \\ cdepr * ethpri, & \text{otherwise.} \end{cases} \tag{4.31}$$

The corresponding price of crude oil could then be computed from Equation (4.28).

Note that these alternative definitions of the price of diesel and crude oil will be reflected in the cost of all the diesel-consuming activities (field activities, biomass transportation, and grinding). The resultant cost adjustments will be transmitted throughout the model during the optimization process. In the model, this was modeled by defining the portion of these costs that is attributable to diesel as the product of quantity and price of diesel.

Determining the Breakeven Price of Ethanol

In this study, the base model is based on, among other things, the assumption that the price of ethanol is \$1.25 per gallon. This is the price that prevails in the ethanol market following heavy tax and subsidy incentives (Kaylen et al.). It is argued that, for most existing technologies such as the SSF, ethanol will continue to rely on some form of fiscal support unless it can be produced for not more than \$0.67 per gallon (Wyman).

After determining that no plant would be located in the state when the price of ethanol is \$0.67 per gallon, a grid search procedure was used to approximate the breakeven price. A loop was setup that adds \$0.01 to the price of ethanol every time it updates.[6] Starting at \$0.67 per gallon, the model was left to run until the price of ethanol was high enough for the first plant to come into the basis. The GAMS code used to perform this is presented in Appendix C (starting with the statement "SCALAR IT…" towards the end of the program).

Model Experiments: Sensitivity Analyses

Robustness of the results obtained in the base scenario was tested with respect to several key parameters and assumptions. While an almost infinite number of alternative scenarios can be constructed from a complicated model like this one, only a few selected experiments were performed here, for practical purposes.

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[6] Alternatively, if the starting point is higher than the breakeven price of ethanol (where production is nonzero), the loop could be setup to subtruct \$0.01 from that price with each update.

The experiments considered include i) increasing the proportion of biomass (land) that can be allocated to ethanol production, ii) imposing the competitiveness condition (that is, defining the price of diesel as in Equation 4.30), iii) imposing the breakeven price of ethanol (see previous section), iv) reducing the yield of ethanol to 80 and 60 gallons per ton of biomass, v) increasing the opportunity cost of land and crop residues by 100 percent, vi) increasing plant construction and operating costs by 100 percent, and vii) increasing transportation costs per mile by 100 percent. For each of these experiments, the corresponding condition constitutes the only departure from the base model, *ceteris paribus*.

CHAPTER V

RESULTS

In this study, a comprehensive and multidisciplinary mixed integer mathematical programming model has been developed for appraising investment in agricultural processing, with specific emphasis on a biomass-to-ethanol industry. The model determines an optimum combination of plant sizes, number and location while simultaneously optimizing several other spatial and temporal aspects of the industry. Recognizing the fact that difficult logistics constitute a major problem for most agriculture-based industries, the present formulation has been deliberately developed to include most of the associated challenges throughout the chain of activities, from biomass production to storage, transportation and processing. This model was implemented with GAMS/CPLEX software (see code in Appendix C). The base model included about 400,000 activities and 56,000 equations.

The rest of this chapter discusses the specific results obtained from the Oklahoma biomass-to-ethanol industry case study. As specified, the model could be used to represent several different analytical scenarios. The results of several of these are discussed here in line with the study specific objectives, starting with the base scenario.

Table 11. Optimal plant size(s), number and capacity usage for the base model scenario

Plant size	Annual capacity (gallons ethanol)	Number of plants	Capacity usage (%)	Plant Location(s)
Large	100,000,000	3	100%	Custer, Pontotoc, and Washington Counties
Medium	50,000,000	0	n/a	n/a
Small	25,000,000	0	n/a	n/a

n/a = not applicable

The Base Scenario

This section summarizes the results obtained when the subsidized market price of ethanol ($1.25 per gallon) was assumed while holding all other parameters at their original levels. Some of the important parameters held constant include price of energy ($0.80 per gallon of diesel), proportion of land that can be harvested for ethanol production (10 percent), plant costs (Table 7), transportation costs (Equation 4.22), land and biomass opportunity cost (Table 2), and ethanol transformation rate (100 gallons per ton of biomass).

Under these conditions, three large plants were located in the state, all operating at full capacity. Thus, 3 x 100 million = 300 million gallons would be produced annually. Together, the three plants would produce a net present worth of US $553,614,554 over the 15-year useful plant life. The optimal plant locations include Custer County in the Northwest region, Pontotoc County in the Southeast region, and Washington County in the Northeast region. Table 11 summarizes the plant location and capacity usage results obtained for the base model.

With the biomass-to-ethanol transformation rate set at 100 gallons per ton of biomass, the three plants would need to process a total of 3,000,000 tons of biomass annually. The results show that a total of 1,760,193 acres of land would be harvested to satisfy this demand. Because of the restriction on the proportion of land that can be harvested in each county (10 percent), the feedstocks would be fetched from several counties in the state. Figure 3 presents the number of acres that would be optimally harvested in each of the state's five regions as a proportion of total harvested land area.

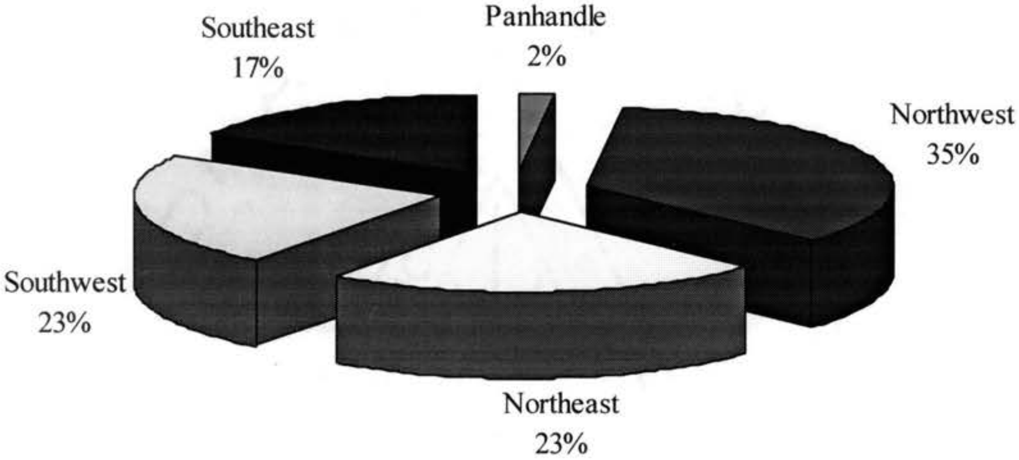

Figure 3. Acres harvested in each region as a proportion of a total of 1,760,193 acres harvested in the state annually

The Northwest region supplies the largest proportion of feedstocks, accounting for about 35 percent of total harvested land area in the state (Figure 3). About 51 percent and 38 percent of the area harvested in this region is under mixed native prairies and wheat straw, respectively; the bulk of which is delivered to the Custer County plant. Counties in each of Northeast and Southwest regions contribute 23 percent of the total harvested land area. In the Northeast region, about 80 percent of this is under tall native prairies. Most of the feedstocks harvested in that region are delivered to the Washington County plant. Osage County alone supplies about 23 percent of the total land area harvested in the Northeast region.

Unlike the Northeast region, the Southwest region supplies a variety of feedstocks, including mixed native prairies (38 percent), tall native prairies (33 percent) and wheat straw (27 percent). The Southeast region contributes about 17 percent of total land area harvested in the state, supplying mainly to the Pontotoc County plant. Most (76 percent) of that land area is under tall native prairies.[7] Panhandle contributes a very small proportion (two-percent) of harvested land area of which 73 percent is under wheat straw.

As is evident from the above discussion, tall native prairies account for a major proportion of the total harvested land area in three of the four major biomass-supplying regions (with the exception of the Northwest region). Its dominance is more apparent in Figure 4, which presents the harvested land area under each of the supplied feedstocks as proportions of total harvested land area.

Figure 4 shows that, on aggregate, tall native prairies account for most (41 percent) of the harvested land area in the state. Mixed native prairies and wheat straw

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[7] Tall native prairies account for 80 percent, 76 percent and 33 percent of total land area harvested in Northeast, Southeast and Southwest regions, respectively

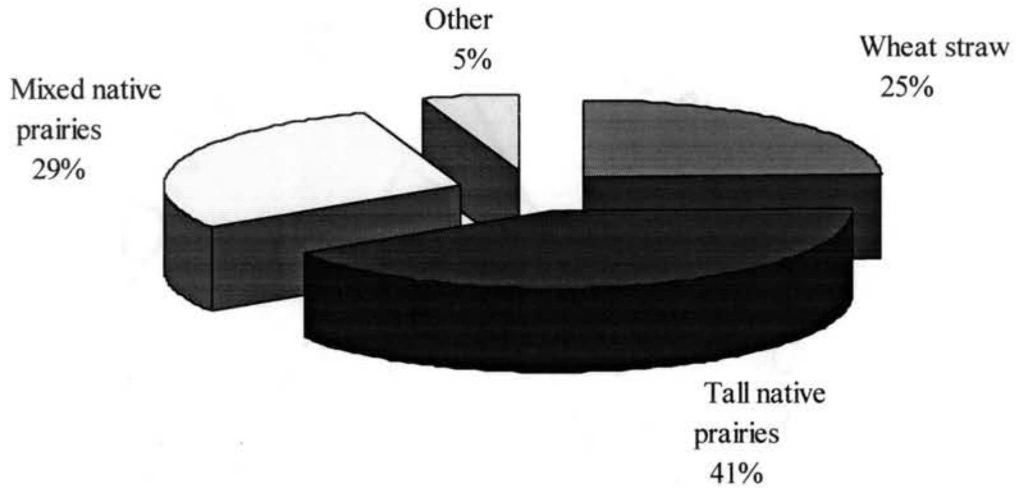

Figure 4. Acres harvested under each of the optimal feedstocks as a proportion of a total of 1,760,193 acres harvested in the state annually

account for 29 percent and 25 percent of total harvested acres, respectively. The remaining 5 percent is attributable to bermudagrass (2.5 percent), short native prairies (1.6 percent), corn stover (0.9 percent) and tall fescue (0.2 percent). These minor biomass sources are represented in Figure 4 by the category “other”.

Post-Harvest Activities: Biomass Balances

Figure 5 presents an overall picture of the biomass post-harvest activities in the state in a typical year. The results indicate that feedstocks would be harvested from June through October, with most (60 percent) of the harvesting performed in September. This is consistent with the highest levels of the yield adjustment factor ($YAD = 1.00$) for most of the feedstocks, including tall native prairies (see Table 4). The YAD remains high (i.e. $YAD \geq 0.95$) during most of the harvest period for native prairies, improved pasture grasses and switchgrass. Crop residues, however, can only be harvested during the months the main crop is being harvested. This is why wheat straw and corn stover have high yield adjustment factors ($YAD = 1.00$) only in periods June-July and September-October, respectively. For all other months, $YAD = 0$ for these crop residues. From November until June, all the shipments are drawn from in-field storage. Shipment to the processing plants is done throughout the year. The quantity shipped in any particular month depends, to a great extent, on the feedstock balances at the plant(s).

With each plant operating at full capacity (100 million gallons per year), a constant amount of feedstocks will be processed in each month. Thus, each of the three plants will convert about 83,333 tons of biomass per month. In any particular month, this may be harvested and delivered straight to the plant or may be obtained from in-field

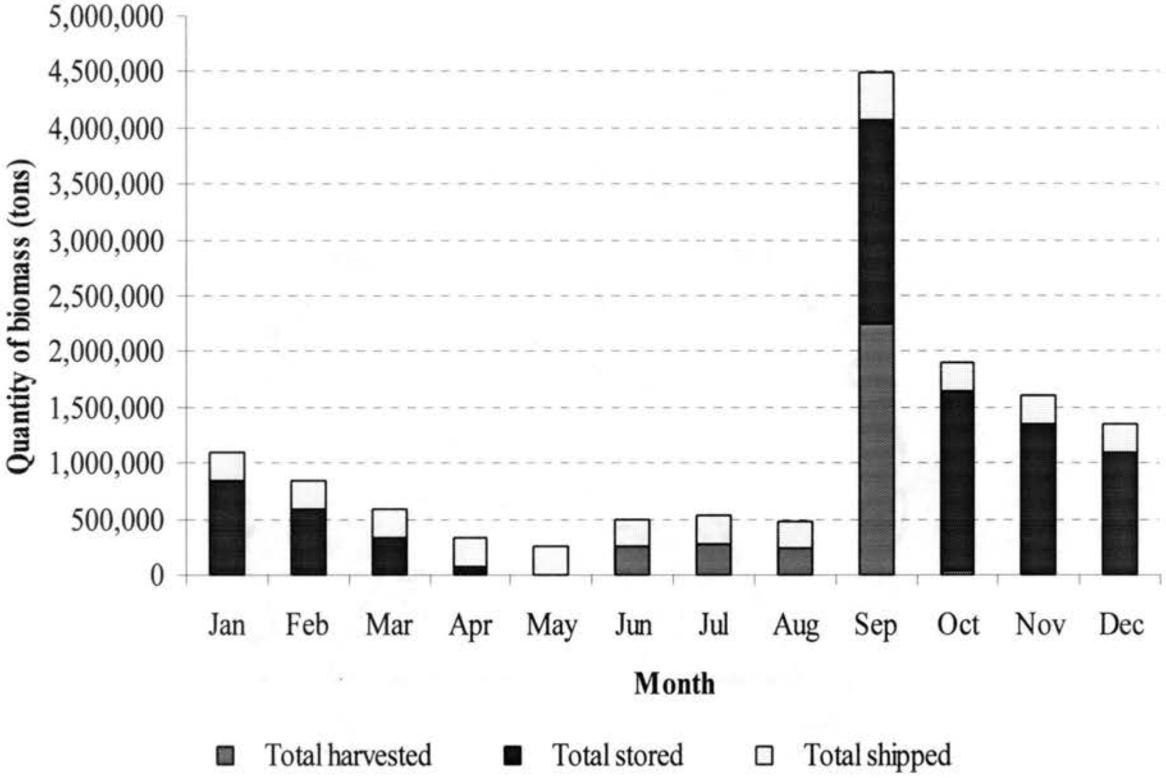

Figure 5. Total dry tons of biomass harvested, stored and shipped from all supplying counties, assuming a base scenario

and/or on-site storage. If from storage, feedstock deterioration while in storage needs to be taken into account, estimated here to be about 0.5 percent and 0.1 percent per month for in-field and on-site storage, respectively. The model uses the biomass balance relationships at the supplying counties and at the plants and interactions between them to determine the optimal shipment and storage patterns.

Figure 6 shows that each plant will use full storage capacity (57,692 tons) in eight of the twelve months. On-site storage is optimally zero in May, June, and August and almost zero (an average of 5,675tons per plant) in July. By assumption, the model is set up to permit zero inventory (*MBINV* = 0 in Equation 4.11). In each of the months September through April, the on-site storage facilities will pass on to the proceeding month an amount of biomass equal to the full storage capacity less storage losses. For the three large plants, a total of 3 x 0.999 x 57,692 = 172,903 tons of biomass will be available from on-site storage in each of the months following full on-site storage capacity usage.

With the plants using 100 percent processing capacity, 3 x 83,333 = 250,000 tons of biomass will be processed each month. If storage is optimally zero in month m but was at full capacity in month $m - 1$, then about 250,000 – 172,903 = 77,097 tons of biomass would need to be shipped in from the supplying counties. In terms of Figure 6, this is true for May. If storage was optimally at full capacity in month $m-1$ and has to be fully replenished in month m while satisfying the processing needs, then a total of 77,097 + (3 x 57,692) = 250,173 tons of biomass would need to be delivered to the three plants in month m. This is the case for months October through April. In June, because storage was zero in the preceding month (May), all the processing needs (250,000 tons of

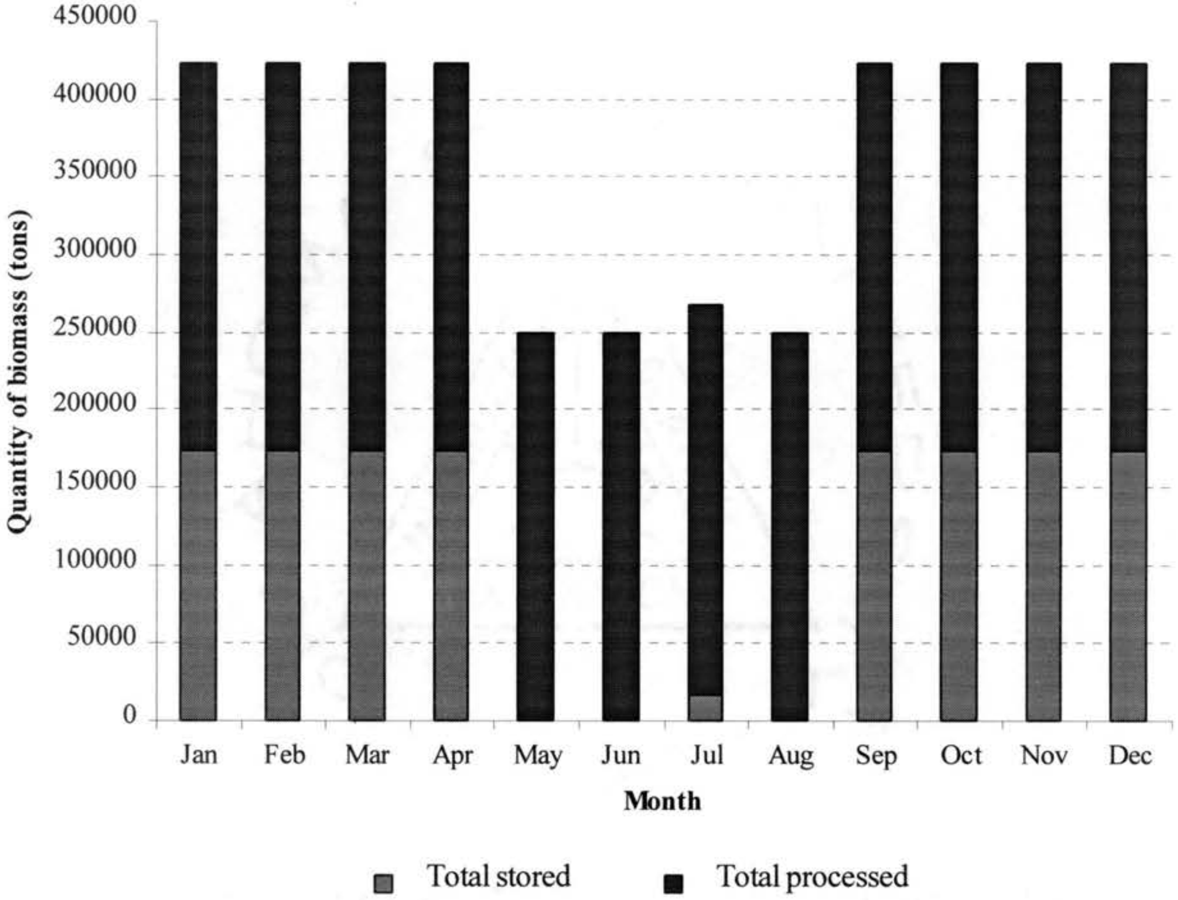

Figure 6. **Total dry tons of biomass stored and processed at the plant sites, assuming a base model scenario**

biomass) would be satisfied by direct delivery from the supplying counties. In July, 250,000 + 17,026 = 267,026 tons would need to be shipped to the plants, where the additional 17,026 tons is put to storage.

To satisfy the biomass demand by processing facilities in August, about 0.999 * 17,026 = 17,009 tons would be obtained from July's on-site storage and the remaining 250,000 – 17,009 = 232,991 tons would be shipped directly from the field. In September, both storage and processing activities have to be at full capacity, starting with zero biomass inventory from August. This requires a direct delivery of 250,000 + 173,076 = 423,076 tons of biomass.

The shipment patterns implied by the above discussion are fully consistent with Figure 5 (see "Total shipped"). In general, to understand the patterns realized at the processing sites, it is helpful to refer to both figures 5 and 6. Notice, for example, that the plants were forced to run down their biomass inventories in May (Figure 6) following depletion of in-field inventories when the biomass harvesting activity was optimally equal to zero (Figure 5).

Net Energy and Energy Efficiency

Given the energy assumptions described in Chapter IV, an estimated 5,513 Btu of energy would need to be spent to produce a gallon of ethanol, of which 54 percent is due to biomass transportation. With biomass available for ethanol production fixed at a maximum of 10 percent of total land area under each feedstock type per county, biomass would need to be fetched from relatively long distances. Therefore, it is not surprising that transportation accounts for most (54 percent) of the total primary energy consumed

Table 12. Primary energy input, energy yield and energy efficiency for the base scenario

Activity/item	Total energy[a] (million Btu)	Energy per gallon of ethanol (Btu)	As a proportion of total energy input (%)
Energy input			
Nitrogen fertilizer	214,634	715	13
Field activities	274,248	914	17
Transportation	893,438	2,978	54
Biomass grinding	271,660	906	16
Subtotal energy input	1,653,980	5,513	100
Energy yield		78,000[b]	1400[c]

[a] Based on the three large plants, each producing 100 million gallons of ethanol per year.

[b] Ethanol energy content estimate (Btu/gallon) adopted from Hohmann and Rendleman.

[c] System energy efficiency (output/input) ratio.

in the system. Field activities, grinding, and nitrogen fertilizer account for 17 percent, 16 percent and 13 percent of total energy spent per gallon, respectively. Nitrogen fertilizer is used in the production of bermudagrass and tall fescue, the only improved pasture grasses that came into the basis, each using 200 lbs. of nitrogen per acre. The energy results obtained in the base case scenario are summarized in Table 12.

Compared to an energy yield of 78,000 Btu per gallon of ethanol (Hohmann and Rendleman), these results show that the ethanol industry using the gasification-bioconversion technology would have a positive net energy balance of 78,000 – 5,513 = 72,487 Btu and an energy output-input ratio equal to 14, or 1400 percent. In this study, it is assumed that the conversion process will be able to operate without external energy input. The high energy efficiency indicated by the empirical results is based on the premise that this is true. If this assumption is relaxed, system energy efficiency could be much lower.

The Break-Even Price of Ethanol and Associated Results

By a grid search process, the threshold price of ethanol was found to be US $0.78 per gallon. It was determined that no plant(s) would be constructed if the price was less than $0.78 per gallon. At $0.78 per gallon, one large plant would be optimally located in Washington County in the Northeast region of the state. The industry net present worth at that price would be US $2,311,473, a 99.6 percent decrease from that obtained with the base model scenario.

With the exception of energy efficiency, all the other major variables showed significant reduction when the breakeven price of ethanol was imposed on the model

(Table 13). Reducing the price of ethanol from $1.25 to $0.78 per gallon posed additional challenges for the model whose direction of optimization is defined by a maximum (i.e., to maximize industry net present worth). The model compensated for the loss in value of output by selectively choosing the cheapest input combination possible. As the results indicate (Appendix D), only the cheap feedstock species remained in the basis. Notice, for example, that tall native prairies and wheat straw account for 83 and 13 percent of total harvested acres of biomass, respectively. It is not surprising, therefore, that the energy output-input (efficiency) ratio improved by as much as 24 percent (Table 13). Detailed results of the breakeven model scenario are summarized in Appendix D, Scenario III.

Model Experiment Results

Most of the results discussed so far pertain to a single scenario with the price of ethanol set equal to US $1.25 per gallon, while holding all the other parameters at their initial values. An implicit assumption in basing a model on point estimates of the parameters is that these parameters are known with certainty. However, this is often not true and definitely not the case here. The point estimates used were determined based only on the information available at the time of the study. This section presents results of several model scenarios in which parameters are changed.

Parameters subjected to sensitivity analysis include plant construction costs, opportunity cost of land and crop residues, transportation costs, biomass-to-ethanol transformation rate, level of subsidy, and cost of energy (diesel). The robustness of the model results to these changes was examined. Such sensitivity analysis also helped to identify the important parameters whose point estimates are critical to the validity of the results. Table 13 summarizes the results obtained with each of the counterfactual scenarios relative to the base scenario. More detailed results are presented in tables and figures of Appendix D.

Overall, the model showed some response to changes in each of the assumptions examined. The degree and direction of response varied both by scenario and variable of interest. For most variables, the largest response was recorded when the biomass availability constraint was relaxed (i.e., the proportion of produced biomass that can be allocated to ethanol production was increased from 10 to 30 percent). The net present worth, acres harvested, and number of plants, for example, increased by at least 200 percent.

The number of feedstock species used remained the same, seven. However, with more land allowed in each county, the model harvested more cheap feedstocks from counties relatively close to the plant locations. This resulted in 16 percent and 15 percent savings in nitrogen energy and transportation energy, respectively. Overall energy efficiency improved by 11 percent.

While raising the proportion of biomass available for conversion (scenario I) and permitting switchgrass establishment (scenario IX) introduce additional flexibility in the model, the other seven model scenarios impose more restrictions on the model. This is also reflected in the fact that the industry net present worth dropped in each of these latter scenarios (Table 13). The highest reduction in net present worth was recorded ($99.6 \approx 100$ percent) when the breakeven price of ethanol was used, which is consistent with the concept of breaking even. Strictly speaking, a breakeven price is expected to result in

Table 13. Summary of results for the base and counterfactual scenarios

Scenario	Net present worth ('000$)	No. of plants	Gallons ethanol ('000)	Tons of Biomass ('000)	Acres/ year ('000)	No. of biomass species	Energy efficiency ratio
Base scenario	553,615	3	300,000	3,000	1,760	7	14
Counterfactual scenarios[a]							
I. 30 % Land availability	1,752,467 (217%)	9 (200%)	900,000 (200%)	9,000 (200%)	5,411 (207%)	7 (0%)	16 (11%)
II. No ethanol subsidies[b]	495,158 (-11%)	3 (0%)	300,000 (0%)	3,000 (0%)	1,700 (-3%)	7 (0%)	14 (-1%)
III. Breakeven ethanol price	2,311 (-100%)	1 (-67%)	100,000 (-67%)	1,000 (-86%)	420 (-76%)	4 (-43%)	18 (24%)
IV. Ethanol yield is 80 gal./ton	233,887 (-58%)	2 (-33%)	200,000 (-33%)	2,500 (-17%)	1,452 (-17%)	5 (-29%)	12 (-18%)
V. Ethanol yield is 60 gal./ton	51,259 (-91%)	1 (-67%)	50,000 (-83%)	833 (-72%)	331 (-81%)	3 (-57%)	11 (-22%)
VI. Double land cost	446,293 (-19%)	3 (0%)	300,000 (0%)	3,000 (0%)	1,676 (-5%)	7 (0%)	14 (-2%)
VII. Double plant fixed costs	54,532 (-90%)	1 (-67%)	100,000 (-67%)	1,000 (-67%)	420 (-76%)	4 (-43%)	18 (24%)
VIII. Double shipping cost/mile	350,911 (-37%)	3 (0%)	300,000 (0%)	3,000 (0%)	1,728 (-2%)	7 (0%)	14 (-1%)
IX. Establish switchgrass	1,244,363 (125%)	6 (100%)	600,000 (100%)	6,000 (100%)	2,145 (22%)	8 (14%)	16 (16%)

[a] In the parentheses are percentage changes from the base values.

[b] When price of diesel is raised enough to make ethanol competitive (Equation 4.30).

zero profit. The nonzero net present worth obtained here, \$2,311,473, is, however, not surprising due to the method of computation that involved increasing the price of ethanol by a discrete quantity of \$0.01 until it was economical to construct a plant. The breakeven price of ethanol was determined to be \$0.78 per gallon by a grid search procedure.[8]

The effects of doubling plant construction and operating costs and of reducing the yield of ethanol were also very significant in reducing the level of activity and earning power of the industry. Table 13 shows that increasing plant construction and operating costs by 100 percent could reduce the number of plants by two thirds and net present worth by as much as 90 percent. The increase in cost of the processing facilities also forced the model to use only a cheap combination of feedstocks, resulting in the number of feedstocks dropping by 43 percent. All the nitrogen consuming feedstocks, such as bermudagrass and tall fescue, were dropped from the basis. This 100 percent reduction in nitrogen energy input combined with some energy savings in field activities and transportation resulted in an energy efficiency gain of 24 percent.

Industry net present worth reduced by 58 percent and 91 percent when ethanol yield was reduced to 80 and 60 gallons per ton of biomass, respectively. As expected the reduction in conversion efficiency implied by lowering the ethanol yield led to a larger reduction in ethanol production than that in biomass used. For the 80 gallons per ton yield rate, for example, ethanol production and tons of biomass processed dropped by 33 percent and 17 percent, respectively. For all the other scenarios that were examined these two variables responded by exactly the same magnitudes, which is expected since in those cases ethanol yield is fixed at 100 gallons per ton of biomass.

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[8] The results of the breakeven scenario were discussed in more detail in the previous section.

When the slope of the transportation cost function (Equation 4.22) was increased by 100 percent (Scenario VIII), the number of plants did not change but the net present worth dropped by 37 percent. By reducing distances traveled, the model economized on transportation energy, leading to a three-percent reduction in the same. However, the need to keep distances short forced the model to keep in the basis feedstocks that use a nonzero level of nitrogen (tall fescue and bermudagrass). Nitrogen energy increased by about 17 percent. Because of the high yields associated with these improved pastures when fertilized, energy required to perform field activities dropped by two percent. Overall, there was a one-percent gain in energy efficiency.

Of all the scenarios considered here, imposing Equation 4.30 (Scenario II) and doubling land and crop residue opportunity costs (Scenario VI) produced the lowest response in most of the variables. In both cases, ethanol production, number and size of plants and number of feedstock species did not change from the base scenario. Industry net present worth dropped by 11 percent in Scenario II and 19 percent in scenario VI. According to the Scenario II results, ethanol would be competitive with diesel without fiscal support if the price of crude oil increases to $52 per barrel.

Which cost components matter?

The costs incurred to produce a gallon of ethanol can be broadly categorized as i) land and crop residue opportunity costs, ii) field costs, iii) in-field storage costs, iv) biomass transportation costs and v) plant costs. The category "field costs" refers to all costs associated with establishing (for switchgrass only) and maintaining feedstock fields, including harvest costs and cost of nitrogen fertilizer. After harvesting, the feedstock is stored in the field and/or subsequently transported to the plant(s), incurring in-field storage and/or transportation costs, respectively. The last category, plant costs, refers to all costs associated with construction, operation and maintenance of on-site storage and processing facilities. Table 14 summarizes these components as levels and proportions of total cost of producing a gallon of ethanol.

In all the model scenarios considered, plant construction, operating and maintenance activities constitute the largest cost component. With the exception of scenario VII, these plant costs account for about 40 percent of total cost per gallon of ethanol. This proportion increased to 66 percent when plant costs were doubled (Scenario VII). In Scenarios I to VI, VIII and IX, field activities (from establishment to harvesting) accounted for about 30 percent of total cost per gallon of ethanol produced. This proportion reduced to 17 percent in Scenario VII. Biomass transportation is the third largest cost component, accounting for between 12 and 20 percent of total cost per gallon of ethanol. Together, land rent and in-field storage account for the remaining 6-14 percent. The exact proportions under each of the cost categories vary from scenario to scenario (Table 14).

Overall, about \$0.98 is spent to produce a gallon of ethanol under the base scenario. However, it is possible to produce a gallon of ethanol for as low as \$0.776 (Scenario III). The \$0.004 difference between this lowest level of costs possible and the breakeven price of ethanol (\$0.78) is due to the discrete nature of the search method used to determine the breakeven price of ethanol. Otherwise, the two are supposed to be exactly equal.

Table 14. Level and proportion of costs incurred to produce a gallon of ethanol under the various model scenarios

		Cost by activity/item (\$/gallon)[a]					
Scenario	No. of plants	Land rent	Field Costs[b]	In-field storage	Biomass Transport	Plant Costs[c]	Total Cost
Base scenario	3	0.06 (7%)	0.30 (32%)	0.05 (5%)	0.14 (15%)	0.38 (41%)	0.93 (100%)
Counterfactual scenarios							
I. 30 % Land availability	9	0.06 (7%)	0.30 (33%)	0.05 (6%)	0.12 (13%)	0.38 (42%)	0.92 (100%)
II. No ethanol subsidies[b]	3	0.06 (6%)	0.32 (33%)	0.05 (5%)	0.15 (15%)	0.38 (40%)	0.97 (100%)
III. Breakeven ethanol price	1	0.04 (5%)	0.20 (25%)	0.02 (3%)	0.13 (17%)	0.38 (49%)	0.776 (100%)
IV. Ethanol yield is 80 gal./ton	2	0.08 (7%)	0.32 (31%)	0.07 (6%)	0.20 (19%)	0.38 (36%)	1.05 (100%)
V. Ethanol yield is 60 gal./ton	1	0.07 (6%)	0.32 (30%)	0.02 (2%)	0.21 (20%)	0.45 (42%)	1.07 (100%)
VI. Double land cost	3	0.12 (12%)	0.31 (31%)	0.05 (5%)	0.14 (14%)	0.38 (38%)	1.00 (100%)
VII. Double plant fixed costs	1	0.04 (4%)	0.20 (17%)	0.02 (2%)	0.13 (12%)	0.76 (66%)	1.16 (100%)
VIII. Double shipping cost/mile	3	0.06 (6%)	0.31 (29%)	0.05 (5%)	0.25 (24%)	0.38 (36%)	1.05 (100%)
IX. Establish switchgrass	6	0.07 (8%)	0.27 (30%)	0.06 (6%)	0.12 (13%)	0.38 (43%)	0.90 (100%)

[a] Values in parentheses are activity/item costs as percentages of total costs.

[b] All costs associated with establishing (for switchgrass only) and maintaining feedstock fields, not including land rent or opportunity cost of crop residues.

[c] All costs associated with construction, operation and maintenance of on-site storage and processing facilities.

Compared to the base model, increasing the proportion of biomass acres that can be harvested for ethanol production (Scenario I) from 10 percent to 30 percent reduces total costs from $0.93 to $0.92 per gallon of ethanol. Introducing switchgrass as a prospective feedstock reduces total costs to $0.90. In all the other scenarios, total costs are greater than the base level. Table 14 shows that the largest total cost ($1.16 per gallon) is incurred when plant costs are doubled, which explains why the profitability of the industry is very sensitive to plant costs (Table 13).

Switchgrass as a Potential Feedstock

Up to this point, much of the discussion has focused on scenarios where the vector of potential substrates is restricted to existing feedstocks. These include the native prairies (tall, mixed and short), improved pasture (old world bluestem, bermudagrass and tall fescue), and crop residues (wheat straw and corn stover). Thus, the existing acreage under each of these feedstocks has been used as a land upper bound. Because switchgrass production was zero at the time of the study, this definition of the land upper bound precludes this high-yielding feedstock from consideration.

An alternative and more flexible definition of the land upper bound is to let available suitable land be the upper bound and permit establishment of new feedstock fields (Equation 4.20). In Scenario IX, this latter definition was used to permit the possibility of displacing some of the existing cropping activities with switchgrass, *ceteris paribus*. With this in place, six large plants would be optimally located in the state, of which three are the same as those located under the base scenario and are supplied by the same (existing) feedstock species as in the base model. The other three plants would be located in counties with a lot of cropland (Canadian, Garfield and Okmulgee), supplied mainly by the newly established switchgrass.

Overall, the net present worth of the industry increased by 125 percent. Table 13 shows that, though the level of industry activity (ethanol produced, biomass processed) would double, total harvested land area would increase by only 22 percent due to the high biomass yield levels obtainable with switchgrass. Although there would be energy losses due to nitrogen fertilizer (8 percent), these would be totally overshadowed by energy savings in field activities and biomass transportation. Overall, energy efficiency would increase by 16 percent, while reducing total ethanol production costs by more than three percent per gallon. Detailed results of the model scenario with switchgrass are summarized in tables 54 through 57 and figures 23 and 24 (Appendix D).

CHAPTER VI

SUMMARY AND CONCLUSIONS

The need to replace fossil fuels with renewable energy alternatives has been expressed by both policy makers and scientists for some time. Some of the common justifications advanced for this argument include environmental degradation caused by fossil fuels, national and global long run energy security, the improvement in balance of trade. In most countries, ethanol from agricultural materials features prominently in both research and policy efforts to identify a sustainable substitute for fossil-based fuels. In Oklahoma, for example, a multidisciplinary team of researchers from Oklahoma State University and University of Oklahoma has been set up to study the possibility of establishing a biomass-to-ethanol industry based on the gasification-bioconversion technology.

Like most other agricultural processing industries, any energy industry that uses agricultural raw materials will be faced with numerous logistical and operational challenges. Usually, these industries involve intricate choices, relationships and interactions with respect to production, post-harvest handling and transportation of bulky raw materials. The success and representativeness of an appraisal exercise for investment in such industries depends, to a great extent, on the extent to which these logistics are incorporated.

In this study, a comprehensive framework has been developed that can be used to appraise investment in agricultural processing. Unlike many similar studies, this study has modeled most of the logistical intricacies more explicitly, including raw material production choices, inventory management both in the field and at the processing sites, and transportation. Included also is the ability to incorporate the impact of non-market externalities in the decision process. The model optimizes both spatial and temporal aspects of the entire system using the net present worth of the industry as the objective function.

The model is deliberately designed to accommodate a lot of flexibility and can be used to answer a number of investment and policy questions. Central issues include determination of the optimal quantity and distribution of processing capacity in a region, optimal raw material stock and flow patterns, and system economic and energy efficiency levels.

To demonstrate empirical application of this framework more clearly, a case study approach was adopted using the proposed biomass-to-ethanol industry in Oklahoma. This study constitutes part of the existing efforts to determine the conditions under which the gasification-bioconversion process could be used to commercialize ethanol production from herbaceous lignocellulosic feedstocks. Estimates for several parameters used in this study were determined through interdisciplinary consultations with the members of the multidisciplinary research team assigned to the project.

Huhnke's (1999) software and personal consultations with Huhnke (1998-2000), for example, provided most of the estimates of the parameters and assumptions with regard to farm machinery and biomass harvesting and handling. Other interdisciplinary consultations involved Taliaferro on feedstock production estimates and options, Johannes on conversion technology, plant costs and materials balance estimates, and Epplin on dedicated energy crop budgets and opportunity costs of taking the land and feedstocks away from alternative uses. Eleven prospective plant locations and three alternative plant sizes were determined through similar consultations. In terms of ethanol production per year, the three plant sizes considered in the study include 25 million gallons (small), 50 million gallons (medium) and 100 million gallons (large).

The model treats plant location and size as discrete variables. Mixed integer mathematical programming is used to handle the discrete variables alongside continuous variables. The CPLEX solver in the generalized algebraic modeling system (GAMS) software was used for this purpose (see Appendix C for the code) . Several model scenarios were run using different sets of assumptions. In the base model, important assumptions included i) a price of $1.25 per gallon of ethanol, ii) 10 percent of each feedstock species produced in each county could be used for ethanol production, iii) diesel, the major primary energy source, could be bought at $0.80 per gallon, and iii) a biomass-to-ethanol transformation rate of 100 gallons per ton of biomass. Other parameter estimates, such as opportunity cost of land and crop residues, plant construction and operating costs, and transportation costs, remained at their initial levels, as described in Chapter IV. These conditions were assumed in the base model because they constituted the "best" parameter estimates, given information available at the time of the study.

The results from the base scenario indicate that three large (100 million gallon per year) plants would be optimally located in Oklahoma, with an industry net present worth of $553,614,554 over a 15 year useful plant life. When all the costs of producing, harvesting, storing, transporting and processing biomass are taken into account, it costs $0.98 to produce a gallon of ethanol. The major cost items include plant construction, operation and maintenance (41 percent), field activities (32 percent), and biomass transportation (15 percent).

About 1,760,193 acres of land would need to be harvested annually to satisfy the implied biomass demand. Most of this land would be under tall native prairies (41 percent), mixed native prairies (29 percent) and wheat straw (25 percent). Although feedstocks are shipped from all over the state, most of them are shipped from Northeast (35 percent), Northwest (23 percent), Southwest (23 percent) and Southeast (17 percent) regions of the state. Optimal plant locations include Custer, Pontotoc and Washington counties, whose distribution is consistent with the biomass production patterns.

From the results of the grid search for a threshold price of ethanol, it was determined that the breakeven price of ethanol is $0.78 per gallon, at which one plant would be located in Washington county. Assuming, as Wyman contends, that energy market conditions are such that ethanol would be competitive without fiscal support if it can be produced at $0.67 per gallon, then the ethanol industry envisioned here would need a subsidy of $0.11 to keep one large plant in operation. Alternatively, if the price of ethanol were maintained at $1.25, then ethanol would be competitive with diesel only if the price of crude oil increases from $25 to $52 per barrel (Scenario II). Given the historical fossil fuel trends, however, such a huge jump (more than 100 percent increase) in crude oil price does not seem very likely in the short run.

Throughout this study, it has been assumed that no external energy would be needed to run the biomass-to-ethanol conversion facilities. Thus, the energy accounting exercise performed includes only the activities prior to biomass conversion, including biomass production, storage, transportation, and grinding. Furthermore, because of the complexity of the energy embedded in secondary inputs, only primary inputs were considered. Specifically, the quantity of energy spent was traced through diesel usage by the various equipment. With these assumptions in place, the energy efficiency (output/input) ratio of the system under the base scenario was found to be about 14, or 1400 percent. About 54 percent of the primary energy spent is due to biomass transportation.

In a sensitivity analysis exercise, nine additional scenarios were run. Each was implemented by changing one of the base assumptions and/or estimates, *ceteris paribus*. The responsiveness of the base results to each of these scenarios was determined. For most variables, the largest response was recorded when the biomass availability constraint was relaxed (i.e., when the proportion of produced biomass that can be allocated to ethanol production was increased from 10 to 30 percent – Scenario I). The net present worth, acres harvested, and number of plants, for example, increased by at least 200 percent.

The base results are quite robust with respect to increases in cost of external energy and opportunity cost of land and crop residues. With a vertically integrated biomass harvesting structure being favored, this result seems to indicate additional flexibility on the part of the ethanol industry decision-maker. If land is difficult to acquire, for example, the decision-maker can raise the price he/she pays to take it away from alternative uses without much effect on the industry profitability.

However, the industry will be faced with daunting challenges with respect to plant costs and transformation rate. The attractive picture obtained here assumes that plant costs will not increase significantly during implementation. If they do, industry profitability will respond very significantly. Policy makers can influence the profitability of the industry by influencing the cost of equipment. The viability of the industry will also be greatly affected by the conversion efficiency at the plant. Research to improve ethanol yield per ton of biomass will, therefore, be very crucial in sustaining the industry. Land policies are bound to be ineffective as a tool to influence the industry.

When switchgrass establishment is permitted in the model (Scenario IX), about 537,894 acres of cropping activities, mainly in the wheat belt, would be displaced by the activity. The switchgrass produced would then be used to support three additional large plants, bringing the total number of plants to six. The new plants would be located in Canadian, Garfield and Okmulgee counties. Because switchgrass can only be grown in cropland and most of the feedstocks used in the base model (native prairie grasses) grow in rangeland, there seems to be little, if any, interaction between the three new plants and the three old ones. Thus, establishment of switchgrass can only increase the level of industry activity. The results indicate that the net present worth of the industry would increase by 125 percent if switchgrass were introduced as a potential feedstock. Energy efficiency per gallon of ethanol would improve by about 16 percent (Table 13). Because of the high-yielding nature of switchgrass, the industry would gain about 38 percent in field energy savings per gallon of ethanol produced.

Limitations and Suggestions for Further Research

This study provides a comprehensive framework for evaluating quantity and distribution of agricultural processing activities, with special attention to logistics in raw material production, handling and transportation. While we believe that the general framework, as formulated here, is more realistic than most other investment models in the literature, the validity and representativeness of the results will be greatly influenced by the quality of the key parameters. With respect to the Oklahoma ethanol industry, this study has used a combination of secondary data, survey results and expert opinion for data and parameter point estimates. If any of these estimates change or are inaccurate, the results and conclusions may change.

One of the weakest parameter estimates in this study is the biomass-to-ethanol transformation rate, assumed to be 100 gallons per ton of biomass in the base model. Although the gasification-bioconversion process has theoretical yields in excess of 100 gallons per ton of biomass, this had not been empirically tested at the time of the study. The multidisciplinary team of researchers from University of Oklahoma and Oklahoma State University were still working on and testing the various components of the process, using a pilot plant. As is evident from the results of the sensitivity analysis, the level of the transformation rate can greatly influence the overall profitability of the industry. Several other assumptions will also influence the results and conclusions arrived at in this study. Studies aimed at improving the parameter point estimates and estimates of their variability could be useful in ensuring the appraisal results are representative and realistic.

Although the picture looks so attractive when switchgrass is included in the vector of feedstocks, caution needs to be exercised to ensure that the benefits are not overstated. One of the issues that may need special attention is the need to fully understand the economic and social repercussions of displacing existing crops. In this study, some of this risk has been accounted for by charging a high opportunity cost ($45) for every acre of cropland that is displaced by switchgrass. However, because this value was determined using expert opinion, it is only a tentative approximation. Further research is needed to ascertain the true value of cropland and the externalities introduced by the sudden change in cropping pattern.

If, as the results indicate, vertical coordination is preferred to an atomistic structure in biomass production, harvesting and handling, then there is need to understand the existing institutional setup as a means for developing effective implementation strategies. This issue is not a part of the current study and will need serious attention prior to implementation.

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APPENDICES

APPENDIX A

SUMMARY OF INDICES, PARAMETERS AND VARAIBLES

Table 15. Model indices and their descriptions

Index	Description and member elements
Main sets	
Bc	Biomass production cost categories: *bc* = {Establishment cost, Maintenance cost, Land rent, Biomass opportunity cost}
f	Level of nitrogen application (in lbs.): *f* = {0, 50, 100, 150, 200}.
ft	Set of facilities. In this case, *ft* = {Processing facility, Storage facility}
g	Vector of products (ethanol) and by-products (CO_2, N_2, and Ash).
h	Set of harvest structure. *h* = {Atomistic, Vertically integrated}
i	Set of biomass supply centers (or source counties): *i* = {All counties}.
j	Set of prospective plant locations: *j* = {Canadian, Comanche, Custer, Garfield, Jackson, Okmulgee, Payne, Pontotoc, Texas, Washington, Woodward}.
k	Set of feedstock species: *k* = . {Corn stover, Wheat straw, Old world bluestem, Tall fescue, Native tall, Native medium, Native short, Switchgrass}
l	Land categories: *l* = {Cropland, Improved pasture, Rangeland, CRP}
m	Month: *m* = {Mar, Apr, May, Jun, Jul, Aug, Sep, Oct, Nov, Dec, Jan, Feb}.
s	Set of plant sizes: s = {Small, Medium, Large}
Subsets	
b(*g*)	Set of process by-products or externalities: *b* = {CO_2, N_2, ash}
cr(*k*)	Set of crop residues: *cr* = {Wheat straw, Corn stover}
e(*g*)	Set of process main product(s): *e* = {Ethanol}

Table 16. Description of the model parameters

Parameter	Description
ρ_g	Price of output g
v_{ks}	Variable cost for processing biomass type *k* into a unit (one gallon) of ethanol at plant size *s*.
α_{kh}	Cost, in U.S. $, of producing and procuring a unit (ton) of biomass type *k* using harvest method *h*.
τ_{ij}	Round-trip cost, in U.S. $, of transporting a ton of biomass from source county *i* to plant location *j*.
γ_k	Cost of storing a ton of biomass *k* in the field for one month
θ_k	Proportion of biomass *k* stored in the field that is usable a month later
ϕ_k	Proportion of biomass *k* stored at the plant that is usable a month later
λ_{kg}	Quantity of output *g* produced from a ton of biomass *k* at the plant
λ_{ke}	Quantity of ethanol (e) produced from a ton of biomass *k* at the plant
$AFC_{s,ft}$	Amortized fixed costs of constructing and operating facility *ft* of plant size *s*.
$BYLD_{ikf}$	Yield (tons/acre/year) of biomass *k* if under fertility regime *f* at county *i*.
$CAPP_s$	Processing facility capacity associated with plant size *s* (gallons of ethanol per month).
$CAPS_k$	Biomass storage facility capacity associated with plant size *s* (tons of biomass).
$FSV_{s,ft}$	Salvage value of facility *ft* of plant size *s*.
$LAND_{ik}$	Land upper bound for biomass *k* at county *i* (acres).
$MBINV_s$	Minimum biomass inventory for plant size *s* (tons/month).
$PVAF$	Present value of an annuity factor, where the annuity factor is the annual net benefit for the ethanol production industry (see Equation 4.16).
r	Market discount rate, used in the computation of *PVAF*
t	Plant useful life, here assumed to be 15 years.
YAD_{km}	Yield adjustment factor for biomass *k* if harvested in month *m*.

Table 17. Description of variables

Variable	Description
NPW	Overall net present worth of the ethanol industry
q_{jsgm}	Quantity of output *g* produced in month *m* by a size *s* plant at location *j*.
q_{jsem}	Gallons of ethanol (e) produced in month *m* by a size *s* plant at location *j*.
A_{ikfhm}	Acres harvested by method *h* at source *i* in month *m* of biomass *k*, where *k* is under fertility regime *f*.
x_{ikfhm}	Tons of biomass *k* harvested in month *m* at source *i* by method *h*, where *k* is under fertility regime *f*
xt_{ijskm}	Tons of biomass *k* transported in month m from county *i* to a plant of size *s* at location *j*.
xs_{ikm}	Tons of biomass *k* stored at source county *i* in month *m*.
xs_{jkm}	Tons of biomass *k* stored at plant location *j* in month *m*.
xp_{jskm}	Tons of biomass *k* processed by a plant of size *s* at plant location *j* in month *m*.
β_{js}	The value of the plant location zero-one variable associated with plant size *s* at location *j*.

APPENDIX B

HARVEST COSTS AND HARVEST MACHINE ASSUMPTIONS

Table 18. Harvest machinery assumptions and costs ($/acre) for corn stover and all forage grasses[a]

Organization structure/ Activity	Implement used	Implement assumptions Width (feet)	Speed (mph)	Purchase price($)	Tractor assumptions Horse-power	Purchase price ($)	Activity cost ($/acre)
Vertically integrated[b]							
Cutting	Disk mower conditioner	9.8	7.0	18,500	75	30,000	5.05
Raking	Twin-wheel rake	18.0	6.0	6,000	75	30,000	2.22
Baling	Large square baler	30.0	7.0	65,000	150	61,000	5.05
Total harvest cost vertically integrated structure							12.32
Atomistic[c]							
Cutting	Rotary disk mower	9.2	7.0	6,000	75	30,000	4.66
Raking	Twin-wheel rake	18.0	6.0	6,000	75	30,000	3.22
Baling	Large round baler	30.0	5.0	18,500	150	61,000	8.41
Total harvest cost atomistic structure							16.29

[a] Forage grasses include native prairies (tall, mixed, short), bermudagrass, and tall fescue

[b] Assuming 5,000 acres are harvested annually

[c] Assuming the individual farmer harvests an average of 500 acres each year

Source: AGMACH$ Software (Huhnke, 1999); and Huhnke (2000).

Table 19. Harvest machine assumptions and costs ($/acre) for wheat straw

Organization structure/ Activity	Implement used	Implement assumptions Width (feet)	Speed (mph)	Purchase price($)	Tractor assumptions Horse-power	Purchase price ($)	Activity cost ($/acre)
Vertically integrated[a]							
Cutting[b]	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Raking	Twin-wheel rake	18.0	6.0	6,000	75	30,000	2.22
Baling	Large square baler	30.0	7.0	65,000	150	61,000	5.05
Total harvest cost vertically integrated structure							7.27
Atomistic[c]							
Cutting[b]	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Raking	Twin-wheel rake	18.0	6.0	6,000	75	30,000	3.22
Baling	Large round baler	30.0	5.0	18,500	150	61,000	8.41
Total harvest cost atomistic structure							11.63

[a] Assuming 5,000 acres are harvested annually

[b] Wheat straw is cut during wheat grain harvesting

[c] Assuming the individual farmer harvests an average of 500 acres each year

Source: AGMACH$ Software (Huhnke, 1999); and Huhnke (2000).

Table 20. Harvest machinery assumptions and costs ($/acre) for switchgrass[a]

Organization structure/ Activity	Implement used	Implement assumptions Width (feet)	Speed (mph)	Purchase price($)	Tractor assumptions Horse-power	Purchase price ($)	Activity cost ($/acre)
Vertically integrated[b]							
Cutting	Disk mower conditioner	9.8	4.0	18,500	75	30,000	7.89
Raking	Single-wheel rake	9.0	4.0	2,000	75	30,000	5.50
Baling	Large square baler	9.8	7.0	65,000	150	61,000	10.90
Total harvest cost vertically integrated structure							24.29
Atomistic[c]							
Cutting	Rotary disk mower	9.2	4.0	6,000	75	30,000	7.59
Raking	Single-wheel rake	9.0	4.0	2,000	75	30,000	5.82
Baling	Large round baler	9.8	5.0	18,500	150	61,000	15.92
Total harvest cost atomistic structure							29.33

[a] Machine specifications are adjusted to fit the high yields attained with switchgrass

[b] Assuming 5,000 acres are harvested annually

[c] Assuming the individual farmer harvests an average of 500 acres each year

Source: AGMACH$ Software (Huhnke, 1999); and Huhnke (2000).

APPENDIX C

GAMS/CPLEX CODE FOR THE MODEL

```
$OFFUPPER OFFSYMXREF OFFSYMLIST OFFUELLIST OFFUELXREF
OPTIONS LIMROW=0, LIMCOL=0;
OPTION OPTCR = 0.0000;
*OPTION SYSOUT = ON;
OPTION SOLPRINT=OFF;
OPTION RESLIM=1000000;
OPTION ITERLIM=5000000;

SETS
 C Counties
   /Adair, Alfalfa, Atoka, Beaver, Beckham, Blaine, Bryan, Caddo,
    Canadian, Carter, Cherokee, Choctaw, Cimarron, Clevelan, Coal,
    Comanche, Cotton, Craig, Creek, Custer, Delaware, Dewey, Ellis,
    Garfield, Garvin, Grady, Grant, Greer, Harmon, Harper, Haskell,
    Hughes, Jackson, Jeffers, Johnston, Kay, Kingfish, Kiowa,Latimer,
    LeFlore, Lincoln, Logan, Love, Major, Marshall, Mayes, McClain,
    McCurt, McIntosh, Murray, Muskogee, Noble, Nowata, Okfuskee,
    Oklahoma, Okmulgee, Osage, Ottawa, Pawnee, Payne, Pittsbur,
    Pontotoc, Pottawat, Pushmata, RogerMil, Rogers, Seminole,
    Sequoyah,Stephens, Texas, Tillman, Tulsa, Wagoner, Washing,
    Washita, Woods, Woodward/

 I(C)  Biomass supplying counties
   /Adair, Alfalfa, Atoka, Beaver, Beckham, Blaine, Bryan, Caddo,
    Canadian, Carter, Cherokee, Choctaw, Cimarron, Clevelan, Coal,
    Comanche, Cotton, Craig, Creek, Custer, Delaware, Dewey, Ellis,
    Garfield, Garvin, Grady, Grant, Greer, Harmon, Harper, Haskell,
    Hughes, Jackson, Jeffers, Johnston, Kay, Kingfish, Kiowa,
    LeFlore, Lincoln, Logan, Love, Major, Marshall, Mayes, McClain,
    McCurt, McIntosh, Murray, Muskogee, Noble, Nowata, Okfuskee,
    Oklahoma, Okmulgee, Osage, Ottawa, Pawnee, Payne, Pittsbur,
    Pontotoc, Pottawat, RogerMil, Rogers, Seminole, Sequoyah,
    Stephens, Texas, Tillman, Tulsa, Wagoner, Washing, Washita,
    Woods, Woodward/

 J(C)  Processing plant locations
   /Pontotoc, Jackson, Washing, Canadian, Garfield, Texas,
    Comanche, Okmulgee, Payne, Woodward, Custer/

 R Geographical Regions of Oklahoma
   /PANHAND, NWEST, NEAST, SWEST, SEAST/

 IR(I,R) Counties by geographical region
   /(Beaver, Cimarron, Texas).PANHAND, (Alfalfa, Blaine, Canadian,
     Custer, Dewey, Ellis, Garfield, Grant, Harper, Kingfish, Logan,
     Major, Oklahoma, RogerMil, Woods, Woodward).NWEST,(Adair,
     Cherokee, Craig, Creek, Delaware, Kay, Lincoln, Mayes, Muskogee,
     Noble, Nowata, Okfuskee, Okmulgee, Osage, Ottawa, Pawnee, Payne,
     Rogers, Tulsa, Wagoner, Washing). NEAST, (Beckham, Caddo, Carter,
     Clevelan, Comanche, Cotton, Garvin, Grady, Greer, Harmon, Jackson,
     Jeffers, Kiowa, Love, McClain, Stephens, Tillman, Washita).SWEST, (Atoka,
     Bryan, Choctaw, Coal, Haskell, Hughes, Johnston, LeFlore,
     Marshall, McCurt, McIntosh, Murray, Pittsbur, Pontotoc, Pottawat,
     Seminole, Sequoyah).SEAST/
```

```
 JR(J,R) Prospective plant locations by region
   /Pontotoc.SEAST, (Jackson, Comanche).SWEST, (Washing, Okmulgee, Payne).NEAST,
   (Canadian, Garfield, Woodward, Custer).NWEST, Texas.PANHAND/

 K Lignocellulosic feedstocks
   /Wheatstr, Cornstov, Cowbs, Natall, Namixed, Nashort, Iberm, Iowbs,
    Tfesc, Switchgr/

 CRS(K) "Crop residues and switchgrass"
   /Wheatstr, Cornstov, Switchgr/

 KF Lignocellulosic biomass differentiated by fertility program
   /Wheatst, Cornsto, Cowbs50, Cowbs100, Cowbs150, Cowbs200, Ntall,
    Nmixed, Nshort, Iberm50,Iberm100, Iberm150, Iberm200, Iowbs50,
    Iowbs100, Iowbs150, Iowbs200, Tfesc50, Tfesc100, Tfesc150,
    Tfesc200, Switchg/

 KKF(K,KF) Allocating fertility subactivities to biomass activities
   /Wheatstr.Wheatst, Cornstov.Cornsto, Cowbs.(Cowbs50, Cowbs100,
    Cowbs150, Cowbs200), Natall.Ntall,Namixed.Nmixed, Nashort.Nshort,
    Iberm.(Iberm50,Iberm100, Iberm150, Iberm200), Iowbs.(Iowbs50,
    Iowbs100, Iowbs150, Iowbs200), Tfesc.(Tfesc50, Tfesc100, Tfesc150,
    Tfesc200), Switchgr.Switchg/

**********************************************************************
***CR = Crop residue;     NP = Native prairies;                      *
***IP = Improved pasture; SG = Switchgrass                           *
**********************************************************************

 CA Feedstock Categories
   /CR, NP, IP, SG/

 KCA(K,CA) Mapping lignocellulosic feedstocks to feedstock categories
   /(Wheatstr, Cornstov).CR, (Natall, Namixed, Nashort).NP,
    (Cowbs, Iberm, Iowbs, Tfesc).IP, Switchgr.SG/

 L Categories of land
   /Cropland, Cropast, Pastran, CRP/

 LC(L) Crop land
   /Cropland, Cropast, CRP/

 LK(L,K) Mapping biomass types to suitable land in which they can be grown
   /(Cropland, Cropast, CRP).(Wheatstr, Cornstov, Cowbs, Iberm,
     Iowbs, Tfesc, Switchgr), Pastran.(Natall, Namixed, Nashort)/

 H Harvest structure
   /Farm, Integrate/

 BC Biomass production cost categories
   /Estcost, Maincost, Landrent, Biopcost/

 BCO(BC) Biomass opportunity cost categories
   /Landrent, Biopcost/

 G Products and by-products of the process
   /Ethanol, CO2, N2, Ash/
```

```
 E(G) Ethanol only
   /Ethanol/

 B(G) Process by-products
   /CO2, N2, Ash/

 S Plant Size
   /Small, Medium, Large/

 FT Facility type at the plant location
  /Storage, Process/

 M Months of the production year
   /Mar, Apr, May, Jun, Jul, Aug, Sep, Oct, Nov, Dec, Jan, Feb/

 M1(M) The first month of the production year
   /Mar/

 M2(M) Months after the first month
   /Apr, May, Jun, Jul, Aug, Sep, Oct, Nov, Dec, Jan, Feb/

**********************************************************************
**Energy consuming machinery-intensive activities/sets follow        *
**********************************************************************

 AMI All machinery-intensive activities
   /Tillage, Planting, Cutting, Raking, Baling, Transprt, Grinding/

 FA(AMI) Field activities
   /Tillage, Planting, Cutting, Raking, Baling/

 TF Type of field activities
   /Estab, Harvest/

 TFA(TF,FA) Mapping field activity category to the activities
   /Estab.(Tillage, Planting), Harvest.(Cutting, Raking, Baling)/

SCALAR BIPROP Proportion of biomass acres available for ethanol /0.10/;

SCALAR DR "Discount rate" /0.15/;

SCALAR T "Project life in years" /15/;

********************************************************************
**CO2 yield: For every 1 gallon of ethanol produced, 6.33 lbs      *
**of CO2 are formed (assuming fermentation process):               *
**Solar Energy Information Data Bank. "Fuel From Farms: A Guide    *
**  to Small-Scale Ethanol Production." Solar Energy Research      *
**  Institute, Operated for the U.S. Dept of Energy (Midwest       *
**  Research Institute), February 1980.                            *
**However, zero-carbon balance is assumed here (IOC = 0)           *
********************************************************************

SCALAR
  IOE Transformation rate in gallons of ethanol per ton of biomass  /100/
  IOC Transformation rate in tons of CO2 per ton of biomass  /0/
```

```
  ION Transformation rate in tons of N per ton of biomass  /0/
  IOA Trans rate in tons of ash and other byproducts per ton of biomass /0/;

PARAMETER LAMBDA(K,G) Input-output coefficients;
  LAMBDA(K,G)$(ORD(G) EQ 1) = IOE;
  LAMBDA(K,G)$(ORD(G) EQ 2) = IOC;
  LAMBDA(K,G)$(ORD(G) EQ 3) = ION;
  LAMBDA(K,G)$(ORD(G) EQ 4) = IOA;

**********************************************************************
**The following estimates of diesel energy content (DBTU), gasoline  *
**energy content (GBTU) and energy expended to produce a lb of       *
**nitrogen (NBTU) were obtained from:                                *
**Shapouri, H., J.A. Duffield and M.S. Graboski. "Estimating the     *
**    Energy Balance of Corn Ethanol." U.S. Dept. of Agriculture,    *
**    Economic Research Service, Office of Energy, Agricultural      *
**    Economic Report No. 721, Washington, DC, July 1995.            *
**********************************************************************

SCALAR DBTU "Energy (Btu) contained in a gallon of diesel" /137202/;

SCALAR GBTU "Energy (Btu) contained in a gallon of gasoline" /125073/;

SCALAR NBTU "Energy (Btu) spent to produce a lb of nitrogen" /22159/;

**********************************************************************
**The following estimate of ethanol energy content (EBTU) was        *
**obtained from:                                                     *
**Hohman, N., and C.M. Rendleman. "Emerging Technologies in Ethanol  *
**     Production."  Agriculture Information Bulletin Number 663,    *
**     Economic Research Service, U.S. Dept of Agric., January 1993. *
**********************************************************************

SCALAR EBTU "Energy (Btu) contained in a gallon of ethanol" /78000/;

**********************************************************************
**The following fuel multiplier (FUMULT) was obtained from Huhnke    *
**********************************************************************

SCALAR FUMULT Fuel multiplier in gallons per horsepower hour /0.044/;

*********************************************************************
**The following MPG estimate is an average of the forecasts 1993 for*
**the period 1992-2000                                               *
**Source:                                                            *
**California Department of Transportation, Office of Traffic        *
**   Improvement. "California Motor Vehicle Stock, Travel and Fuel  *
**   Forecast."  U.S. Department of Transportation, Federal Highway *
**   Administration, November 1993. Available at                    *
**   http://www.bts.gov/ntl/DOCS/cal.html, June 26, 2000            *
*********************************************************************

SCALAR TRKLOAD Truck capacity in tons of biomass /17/;

SCALAR MPG "Diesel consumption rate/economy by 17 ton truck" /5.43/;
```

```
PARAMETER GPM Gallons of diesel per mile traveled;
  GPM = 1/MPG;



**********************************************************************
**The following GHP estimate was obtained by personal communication *
**grinder manufacturer (Huhnke, June 2000)                           *
**********************************************************************

SCALAR GHP  Grinding machinery horsepower hours per ton of bimass  /15/;

**********************************************************************
**The following horsepower estimates for field machinery were       *
**obtained from Huhnke                                               *
**********************************************************************

PARAMETER HPOWER(FA) Horse power for field and grinding machinery
   /Tillage 150, Planting 75, Cutting 75, Raking 75, Baling 150/;

PARAMETER FLDSPEED(FA) Speed for field machinery in acres per hour
   /Tillage 7.73, Planting 9.33, Cutting 6.65, Raking 10.47, Baling 20.36/;

SCALAR
   CRUDPRIC "Price of crude oil in $/barrel" /25/
   DIEPRIO  Initial price of diesel in dollars per gallon /0.80/
   ETHPRIC  Competetive price of ethanol /0.67/;

PARAMETER CRUDPRIO Initial price of crude oil in dollars per barrel;
   CRUDPRIO = (DIEPRIO-0.1526)/0.0242;

PARAMETER CDEPR "Competitive diesel-ethanol price ratio";
   CDEPR = (0.1526 + 0.0242*CRUDPRIC)/ETHPRIC;

PARAMETER FLDIES(FA) Diesel used in field activities in gallons per acre;
   FLDIES(FA) = FUMULT*HPOWER(FA)/FLDSPEED(FA);

PARAMETER GRDIES Diesel used to grind a ton of biomass in gallons;
   GRDIES = FUMULT*GHP;

***********************************************************************
**A factor of 0.5 is used to scale both storage and processing      *
**  facility capacities up/down to other plant sizes                 *
***********************************************************************

SCALAR CAPADJ "Capacity scaling/adjustment factor" /0.5/;

***********************************************************************
**Assume that doubling plant size will increase construction         *
**  costs by 70 % (Johannès, 2000)                                    *
***********************************************************************

SCALAR COADJ  "Construction cost scaling/adjustment factor" /1.7/;

**********************************************************************
**An annual processing capacity of 50,000,000 gallons of ethanol is *
**  assumed to be the medium plant size                              *
```

```
**Storage capacities indicated below (in tons of biomass) assume an *
**  equivalent of three weeks of the processing facility's annual   *
**  capacity (Huhnke, 2000)                                         *
*********************************************************************

PARAMETER CAP50(FT) "Processing/storage capacity for 50 m gal plant"
   /STORAGE     28846
    PROCESS  50000000 /;

PARAMETER CAP(S,FT) Storage and processing capacity by plant size;
   CAP(S,FT)$(ORD(S) EQ 2) = CAP50(FT);
   CAP(S,FT)$(ORD(S) EQ 1) = CAP50(FT)*CAPADJ;
   CAP(S,FT)$(ORD(S) EQ 3) = CAP50(FT)/CAPADJ;

PARAMETER CAPP(S) "Facility monthly capacity in gallons";
   CAPP(S) = CAP(S,"PROCESS")/12;

********************************************************************
**$100 million processing facility construction costs              *
**  is assumed for the 50 million gallon plant (Johannes, 2000)    *
**Construction of a corresponding storage facility is estimated    *
**  to cost about $1,528,846 (Huhnke, 2000)                        *
********************************************************************

PARAMETER FC50(FT) "Construction costs for 50 m gallon plant in $"
   /STORAGE   1528846
    PROCESS 100000000 /;

PARAMETER FC(S,FT) Construction and facility costs by plant size;
   FC(S,FT)$(ORD(S) EQ 2) = FC50(FT);
   FC(S,FT)$(ORD(S) EQ 1) = FC50(FT)/COADJ;
   FC(S,FT)$(ORD(S) EQ 3) = FC50(FT)*COADJ;

PARAMETER OMAP(FT) "Annual O & M costs as a proportion of total investment"
   /STORAGE 0.02
    PROCESS 0.05 /;

PARAMETER OMA(S, FT) "Total annual O & M costs in $ by plant size and facility";
   OMA(S,FT) = FC(S,FT)*OMAP(FT);

TABLE FSV(S,FT) "Facility salvage value in $ by plant size"
             Storage     Process
  Small         0            0
  Medium        0            0
  Large         0            0      ;

**The following formula amortizes the total facility fixed costs    *

PARAMETER AFC(S,FT) Facility annual fixed charge by plant size;
  AFC(S,FT)=[FC(S,FT)-FSV(S,FT)]*[DR*POWER{(1+DR),T}]/[POWER{(1+DR),T}-1];

PARAMETER TAFC(S,FT) Facility annual construction and operating costs by size;
  TAFC(S,FT) = AFC(S,FT) + OMA(S,FT);

PARAMETER PVAF Present worth of an annuity factor;
  PVAF= [POWER{(1+DR),T}-1]/[DR*POWER{(1+DR),T}];
```

```
PARAMETER BINV(S) Biomass minimum inventory at the plant
    /Small        0
     Medium       0
     Large        0    /;

*******************************************************************
**CO2 and N2 cost data were obtained from:                        *
**Bernow, S. S., and D. B. Marron.  "Valuation of Environmental    *
**      Externalities for Energy Planning and Operations,          *
**      May 1990 Update."  Tellus Institute, Boston, MA, May 1990. *
**NOTE: Obtained by a revealed preference procedure.              *
********************Updated to 1992 (Ag-West Biotech Inc).*********

PARAMETER RHO(G) "Output price vector in $ per unit"
  /Ethanol    1.25
   CO2      -24.70
   N2      -246.40
   Ash        -0.02/;

PARAMETER DIEPRI Price of diesel given price of crude oil;
*   DIEPRI = CDEPR*RHO("Ethanol");
   DIEPRI = DIEPRIO;

PARAMETER CRUDPRI Price of crude oil in dollars per barrel;
   CRUDPRI = (DIEPRI-0.1526)/0.0242;

SCALAR PN "Price of nitrogen in $ per lb" /0.13/;

PARAMETER NIT(KF) Level of nitrogen by fertility program in lb per acre
   /Wheatst  0, Cornsto  0, Cowbs50   50, Cowbs100   100,
    Cowbs150  150, Cowbs200   200, Ntall  0, Nmixed   0,
    Nshort  0, Iberm50  50, Iberm100  100, Iberm150  150,
    Iberm200 200, Iowbs50 50, Iowbs100 100, Iowbs150 150,
    Iowbs200 200, Tfesc50 50, Tfesc100 100, Tfesc150 150,
    Tfesc200 200, Switchg  0 /;

PARAMETER NCOST(K) Cost of applied nitrogen in USD per acre;
   NCOST(K) = SUM(KF$KKF(K,KF), NIT(KF)*PN);

TABLE YAD(K,M) Proportion of potential yield by harvest month

          Mar  Apr  May  Jun  Jul  Aug  Sep  Oct  Nov  Dec  Jan  Feb
Wheatstr   0    0    0 1.00 1.00    0    0    0    0    0    0    0
Cornstov   0    0    0    0    0    0 1.00 1.00    0    0    0    0
Cowbs      0    0    0    0 1.00 1.00 1.00 0.95 0.90 0.85 0.80 0.75
Natall     0    0    0    0 1.00 1.00 1.00 0.95 0.90 0.85 0.80 0.75
Namixed    0    0    0    0 1.00 1.00 1.00 0.95 0.90 0.85 0.80 0.75
Nashort    0    0    0    0 1.00 1.00 1.00 0.95 0.90 0.85 0.80 0.75
Iberm      0    0    0    0 1.00 1.00 1.00 0.95 0.90 0.85 0.80 0.75
Iowbs      0    0    0    0 1.00 1.00 1.00 0.95 0.90 0.85 0.80 0.75
Tfesc      0    0    0 1.00 0.90 0.80 0.75    0    0    0    0    0
Switchgr   0    0    0    0 1.00 1.00 1.00 0.95 0.90 0.85 0.80 0.75
;
```

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PARAMETER THETAI(K) Usable proportion of stored biomass at the source
    /Wheatstr  0.995
     Cornstov  0.995
     Cowbs     0.995
     Natall    0.995
     Namixed   0.995
     Nashort   0.995
     Iberm     0.995
     Iowbs     0.995
     Tfesc     0.995
     Switchgr  0.995    /;

PARAMETER THETAJ(K) Usable proportion of stored biomass at the plant
    /Wheatstr  0.999
     Cornstov  0.999
     Cowbs     0.999
     Natall    0.999
     Namixed   0.999
     Nashort   0.999
     Iberm     0.999
     Iowbs     0.999
     Tfesc     0.999
     Switchgr  0.999    /;

PARAMETER GAMMA(K) Biomass storage cost at source in USD per ton (Huhnke)
    /Wheatstr  2.00
     Cornstov  2.00
     Cowbs     2.00
     Natall    2.00
     Namixed   2.00
     Nashort   2.00
     Iberm     2.00
     Iowbs     2.00
     Tfesc     2.00
     Switchgr  2.00    /;

TABLE HC1(K,H) "Biomass harvest cost by harvest structure in $ per acre "
              Farm    Integrate
  Wheatstr    11.6        7.3
  Cornstov    16.3       12.3
  Cowbs       16.3       12.3
  Natall      16.3       12.3
  Namixed     16.3       12.3
  Nashort     16.3       12.3
  Iberm       16.3       12.3
  Iowbs       16.3       12.3
  Tfesc       16.3       12.3
  Switchgr    29.3       24.3     ;

PARAMETER HC(K,H) Internalizing price of diesel into cost of a harvested acre;
   HC(K,H)$(ORD(K) EQ 10) = HC1(K,H) + [SUM(FA$TFA("Harvest",FA), FLDIES(FA))
                            + SUM(FA$TFA("Estab",FA), FLDIES(FA))/T]
                            *[DIEPRI-DIEPRI0];
   HC(K,H)$(ORD(K) NE 10) = HC1(K,H) + SUM(FA$TFA("Harvest",FA), FLDIES(FA))
                            *[DIEPRI-DIEPRI0];
```

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*********************************************************************
**The cost of applying fertilizer is assumed to be constant at     *
**$3/acre as long as some fertilizer is applied (Epplin, 2000).    *
**In the next table, this cost is presented as maintenance cost,   *
**"Maincost".                                                      *
*********************************************************************

TABLE POC(K,BC) "Biomass production and opportunity costs in $ per acre"
               Estcost   Maincost   Landrent   Biopcost
  Wheatstr         0          0          0         10
  Cornstov         0          0          0         20
  Cowbs            0       3.00         30          0
  Natall           0          0         10          0
  Namixed          0          0         10          0
  Nashort          0          0         10          0
  Iberm            0       3.00         30          0
  Iowbs            0       3.00         30          0
  Tfesc            0       3.00         30          0
  Switchgr     11.22       3.00         45          0          ;

TABLE CURACRE(I,K) Current  acreage for each biomass type
          Wheatstr  Cornstov   Cowbs    Natall   Namixed
Adair          820       140       0     38404      2021
Alfalfa     250400        74    9005     10969     82268
Atoka          360       180       8    182570     20286
Beaver      131800      3920   87767         0         0
Beckham      76640       175   42039    101053    126317
Blaine      200500       290   12167     18363    137721
Bryan         6700      4680     131    167998     18666
Caddo       183400      3510   12056     97286    121608
Canadian    178200      1080    3855     15712    117839
Carter        2980       500     511     85634    107043
Cherokee       440       150       0     68070      3583
Choctaw       1188      2360      37     98596     10955
Cimarron    111000     20820  110038         0         0
Clevelan      7320       590       0     22436     28046
Coal           660       180       0    135793     15088
Comanche     81720        80    5788     74639     93299
Cotton      119000        65   13975     52321     65401
Craig        15400      1260     163    240531     12660
Creek         1900        90       3    155791      8200
Custer      208000       500   10075     27773    208300
Delaware      3260       320       3     66681      3510
Dewey       102600       325   24152     36649    274870
Ellis        79200       830   40667     49983    374870
Garfield    353200        74    9281     14515    108866
Garvin       10000      3260     700     82265    102831
Grady        73400      2360    3985    104615    130769
Grant       325400       420   10013     11905     89286
Greer        74680        65   37433     58664     73330
Harmon       61400        70   35660     48121     60151
Harper      109000       430   33830     39452    295888
Haskell       2300      1100     108    106034     11782
Hughes        2020      2000      36    162496     18055
Jackson     181800        70   27009     47459     59324
Jeffers      28000       163   13853    111586    139483
Johnston      1280       750       8    192180     21353
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Kay         275200       1640        303    114304       6016
Kingfish    220300        120      10196     14334     107504
Kiowa       210800         70      14640     75477      94347
LeFlore       3080       1540          0    109258      12140
Lincoln       4900        180         89    155276       8172
Logan        74900        120       3198     13611     102080
Love          5180        375        393     53828      67285
Major       156400       1340      18346     20028     150209
Marshall      2800        840         58     88672       9852
Mayes         9500        960         15     97335       5123
McClain      13200       2120        639     49949      62437
McCurt        3100       4040          0     89518       9946
McIntosh      1920        313        133     88019       9780
Murray        2320        480          0    150676      16742
Muskogee      9800       4490         90    142055       7477
Noble       142400         84         64    140573       7399
Nowata        9300       1380         37    163293       8594
Okfuskee      2740        800         60    120886       6362
Oklahoma     22900       1640        427      6636      49772
Okmulgee      2840       1900        140    132186       6957
Osage        22500        188        179    853300      44911
Ottawa       23000       2400         61     49746       2618
Pawnee       12540        390         23    160861       8466
Payne        21000        240         65    146994       7737
Pittsbur      1320        700          2    215993      23999
Pontotoc       820        210         35    188807      20979
Pottawat      7260       1160         68    111528      12392
RogerMil     35460        120      19159     48711     365336
Rogers        7100        463         33    150205       7906
Seminole      1580        400         40     94595      10511
Sequoyah      2940       3690          0     57192       6355
Stephens     30100        220       3734     89162     111453
Texas       245800      68400     161031         0          0
Tillman     141600         70      34436     53803      67254
Tulsa         4800        363         26     53936       2839
Wagoner      18500       2600         48     69721       3670
Washing       7100        420         48    133689       7036
Washita     193800        170        325    145840      16204
Woods       210400         84      27128     43912     329343
Woodward     76600         84      20513     46205     346536

+         Nashort     Iberm     Iowbs     Tfesc     Switchgr
Adair           0     33973       662     28220            0
Alfalfa     16454     22837     20759       917            0
Atoka           0     49681       771     13711            0
Beaver     561112         0     43485      4287            0
Beckham     25263     26117     14341       849            0
Blaine      27544     22059     20052       886            0
Bryan           0     66142      1026     18253            0
Caddo       24322     53851     29570      1750            0
Canadian    23568     27504     25001      1105            0
Carter      21409     32513     17853      1056            0
Cherokee        0     28969       565     24063            0
Choctaw         0     51990       806     14348            0
Cimarron   638324         0    139642     13768            0
Clevelan     5609     17343      9523       564            0
Coal            0     32720       507      9030            0
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Comanche	18660	30069	16511	977	0
Cotton	13080	21854	12000	710	0
Craig	0	34394	670	28570	0
Creek	0	31817	620	26429	0
Custer	41660	28407	25822	1141	0
Delaware	0	31735	618	26361	0
Dewey	54974	20901	18999	840	0
Ellis	74974	31123	28291	1250	0
Garfield	21773	34143	31036	1372	0
Garvin	20566	41331	22695	1343	0
Grady	26154	44722	24557	1453	0
Grant	17857	17883	16256	718	0
Greer	14666	14572	8002	473	0
Harmon	12030	31128	17092	1011	0
Harper	59178	30643	27854	1231	0
Haskell	0	42184	654	11642	0
Hughes	0	40085	622	11063	0
Jackson	11865	19130	10505	622	0
Jeffers	27897	22419	12310	728	0
Johnston	0	35239	547	9725	0
Kay	0	20653	403	17155	0
Kingfish	21501	32541	29580	1307	0
Kiowa	18869	24613	13515	800	0
LeFlore	0	62611	971	17279	0
Lincoln	0	47291	922	39283	0
Logan	20416	22213	20192	892	0
Love	13457	21348	11722	694	0
Major	30042	22639	20579	909	0
Marshall	0	19350	300	5340	0
Mayes	0	28163	549	23394	0
McClain	12487	20836	11441	677	0
McCurt	0	50664	786	13982	0
McIntosh	0	33991	527	9381	0
Murray	0	19193	298	5297	0
Muskogee	0	29618	577	24602	0
Noble	0	24734	482	20545	0
Nowata	0	18441	359	15318	0
Okfuskee	0	26209	511	21770	0
Oklahoma	9954	8785	7986	353	0
Okmulgee	0	21875	426	18171	0
Osage	0	32223	628	26766	0
Ottawa	0	20932	408	17388	0
Pawnee	0	20068	391	16669	0
Payne	0	29815	581	24766	0
Pittsbur	0	57870	898	15971	0
Pontotoc	0	49742	771	13727	0
Pottawat	0	51031	791	14083	0
RogerMil	73067	23762	21599	955	0
Rogers	0	24718	482	20532	0
Seminole	0	42368	657	11692	0
Sequoyah	0	34324	532	9473	0
Stephens	22291	37395	20534	1215	0
Texas	417348	0	26281	2591	0
Tillman	13451	14762	8106	480	0
Tulsa	0	12523	244	10403	0
Wagoner	0	18127	353	15057	0
Washing	0	11999	234	9967	0

```
Washita        0    64701     1003    17856          0
Woods      65869    18424    16748      740          0
Woodward   69307    24119    21924      969          0
;

TABLE POTACRES(I,L) Potential acres by land category
          Cropland  Cropast     Pastran       CRP
Adair        35425    67735      40425          0
Alfalfa     300821    62584     109691      12006
Atoka        40843    69257     202856        158
Beaver      340994    61247     561112     117023
Beckham     168293    60423     252633      56051
Blaine      234718    60453     183628      16223
Bryan        85954    92203     186664       2615
Caddo       302311   124587     243215      16075
Canadian    243186    75375     157118       5140
Carter       34727    75221     214086        682
Cherokee     33651    57759      71653          0
Choctaw      52085    72476     109551        735
Cimarron    191741   196679     638324     146718
Clevelan     41825    40124      56091          0
Coal         29949    45612     150881          0
Comanche    132988    69565     186597       7717
Cotton      172021    50560     130802      18634
Craig       102629    68576     253190       3267
Creek        41673    63437     163991         50
Custer      259973    77849     277733      13434
Delaware     56319    63274      70190         61
Dewey       142209    57279     366493      32203
Ellis       109541    85292     499826      54223
Garfield    407574    93569     145154      12375
Garvin       82139    95622     205662        933
Grady       169141   103466     261538       5313
Grant       416424    49009     119048      13351
Greer       144512    33713     146660      49911
Harmon       88698    72015     120302      47547
Harper      124059    83976     394517      45106
Haskell      49074    58806     117816       2164
Hughes       45504    55880     180551        727
Jackson     296595    44259     118648      36012
Jeffers      57817    51868     278965      18471
Johnston     29749    49124     213533        162
Kay         299025    41178     120320       6067
Kingfish    268826    89178     143339      13594
Kiowa       300726    56944     188693      19519
LeFlore      75961    87281     121398          0
Lincoln      67715    94290     163448       1779
Logan       114201    60874     136107       4265
Love         38904    49389     134570        524
Major       200304    62042     200278      24462
Marshall     21925    26975      98524       1153
Mayes        79112    56152     102458        308
McClain      63690    48205     124873        852
McCurt       67085    70627      99464          0
McIntosh     54383    47385      97799       2662
Murray       23656    26755     167418          0
Muskogee    107502    59052     149532       1800
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Noble       172257    49314     147972       1286
Nowata       59520    36768     171887        743
Okfuskee     35886    52255     127248       1209
Oklahoma     42366    24076      66362        570
Okmulgee     52328    43615     139143       2800
Osage        77995    64246     898210       3586
Ottawa       92904    41735      52364       1224
Pawnee       43364    40011     169327        468
Payne        74737    59446     154731       1307
Pittsbur     55299    80672     239992         38
Pontotoc     37113    69341     209785        707
Pottawat     60917    71139     123920       1350
RogerMil     93695    65118     487114      25545
Rogers       70684    49283     158111        668
Sequoyah     49649    47849      63547          0
Seminole     35651    59062     105105        810
Stephens     76494    86515     222905       4979
Texas       584804    37016     417348     214707
Tillman     303582    34152     134507      45914
Tulsa        40472    24969      56775        515
Wagoner      88700    36142      73390        959
Washing      37084    23923     140725        953
Washita     312625    90195     162044       6508
Woods       238729    50491     439124      36170
Woodward    145865    66097     462048      27350
;

TABLE BIOYLD1(I,KF) Biomass yield in lbs per acre
            Wheatst  Cornsto  Cowbs50  Cowbs100  Cowbs150 Cowbs200
Adair          1843     3936     2500     4620      5500     6500
Alfalfa        1667     3807     2660     4040      5000     6000
Atoka          1641     4302     3000     4720      5500     7000
Beaver          932     6007     2660     4000      5000     6000
Beckham        1109     4043     3000     4620      6000     7500
Blaine         1374     4352     2660     4040      5000     6000
Bryan          1608     4224     3000     4721      5500     7000
Caddo          1575     4516     3000     4620      6000     7500
Canadian       1558     4327     2660     4040      5000     6000
Carter         1363     4426     3000     4620      6000     7500
Cherokee       1692     3936     2500     4620      5500     6500
Choctaw        1271     4591     3000     4722      5500     7000
Cimarron       1618     5867     2660     4000      5000     6000
Clevelan       1478     4069     3000     4620      6000     7500
Coal           1524     4302     3000     4723      5500     7000
Comanche       1215     3995     3000     4620      6000     7500
Cotton         1271     3995     3000     4620      6000     7500
Craig          1897     4174     2500     4620      5500     6500
Creek          1369     4133     2500     4620      5500     6500
Custer         1547     4462     2660     4040      5000     6000
Delaware       1976     4020     2500     4620      5500     6500
Dewey          1377     3781     2660     4040      5000     6000
Ellis           947     5324     2660     4040      5000     6000
Garfield       1680     3584     2660     4040      5000     6000
Garvin         1650     4489     3000     4620      6000     7500
Grady          1535     4369     3000     4620      6000     7500
Grant          1548     3926     2660     4040      5000     6000
Greer          1195     3995     3000     4620      6000     7500
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Harmon	748	3995	3000	4620	6000	7500
Harper	1070	5364	2660	4040	5000	6000
Haskell	1841	4095	3000	4724	5500	7000
Hughes	1412	4119	3000	4725	5500	7000
Jackson	1121	3995	3000	4620	6000	7500
Jeffers	1848	4302	3000	4620	6000	7500
Johnston	1872	4443	3000	4726	5500	7000
Kay	1739	3914	2500	4620	5500	6500
Kingfish	1455	4133	2660	4040	5000	6000
Kiowa	1259	3995	3000	4620	6000	7500
LeFlore	1690	4278	3000	4727	5500	7000
Lincoln	1277	4220	2500	4620	5500	6500
Logan	1400	4133	2660	4040	5000	6000
Love	1759	4171	3000	4620	6000	7500
Major	1384	4788	2660	4040	5000	6000
Marshall	1713	4146	3000	4728	5500	7000
Mayes	1659	4018	2500	4620	5500	6500
McClain	1417	4153	3000	4620	6000	7500
McCurt	1430	4230	3000	4729	5500	7000
McIntosh	1412	3988	3000	4730	5500	7000
Murray	1522	4237	3000	4731	5500	7000
Muskogee	1466	4576	2500	4620	5500	6500
Noble	1701	3807	2500	4620	5500	6500
Nowata	1336	3969	2500	4620	5500	6500
Okfuskee	1218	4153	2500	4620	5500	6500
Oklahoma	1323	4270	2660	4040	5000	6000
Okmulgee	1603	4137	2500	4620	5500	6500
Osage	1542	4141	2500	4620	5500	6500
Ottawa	2163	4558	2500	4620	5500	6500
Pawnee	1715	4036	2500	4620	5500	6500
Payne	1340	4112	2500	4620	5500	6500
Pittsbur	1867	4396	3000	4732	5500	7000
Pontotoc	1673	4302	3000	4733	5500	7000
Pottawat	1565	4165	3000	4734	5500	7000
RogerMil	1294	4043	2660	4040	5000	6000
Rogers	1739	4088	2500	4620	5500	6500
Seminole	1460	4141	3000	4735	5500	7000
Sequoyah	2002	5078	3000	4736	5500	7000
Stephens	1284	4174	3000	4620	6000	7500
Texas	1779	6172	2660	4000	5000	6000
Tillman	1317	3995	3000	4620	6000	7500
Tulsa	1851	4186	2500	4620	5500	6500
Wagoner	1604	4134	2500	4620	5500	6500
Washing	1379	3892	2500	4620	5500	6500
Washita	1435	4082	3000	4737	5500	7000
Woods	1655	3807	2660	4040	5000	6000
Woodward	0	0	2660	4040	5000	6000

+	Ntall	Nmixed	Nshort	Iberm50	Iberm100	Iberm150
Adair	6000	3800	0	3500	4660	6000
Alfalfa	3140	2540	1900	3480	5000	6000
Atoka	4180	3360	0	4080	7000	9000
Beaver	0	0	1340	0	0	0
Beckham	2800	2500	1700	4540	6000	7500
Blaine	3140	2540	1900	3480	5000	6000
Bryan	4180	3360	0	4080	7000	9000
Caddo	2800	2500	1700	4540	6000	7500

Canadian	3140	2540	1900	3480	5000	6000
Carter	2800	2500	1700	4540	6000	7500
Cherokee	6000	3800	0	3500	4660	6000
Choctaw	4180	3360	0	4080	7000	9000
Cimarron	0	0	1340	0	0	0
Clevelan	2800	2500	1700	4540	6000	7500
Coal	4180	3360	0	4080	7000	9000
Comanche	2800	2500	1700	4540	6000	7500
Cotton	2800	2500	1700	4540	6000	7500
Craig	6000	3800	0	3500	4660	6000
Creek	6000	3800	0	3500	4660	6000
Custer	3140	2540	1900	3480	5000	6000
Delaware	6000	3800	0	3500	4660	6000
Dewey	3140	2540	1900	3480	5000	6000
Ellis	3140	2540	1900	3480	5000	6000
Garfield	3140	2540	1900	3480	5000	6000
Garvin	2800	2500	1700	4540	6000	7500
Grady	2800	2500	1700	4540	6000	7500
Grant	3140	2540	1900	3480	5000	6000
Greer	2800	2500	1700	4540	6000	7500
Harmon	2800	2500	1700	4540	6000	7500
Harper	3140	2540	1900	3480	5000	6000
Haskell	4180	3360	0	4080	7000	9000
Hughes	4180	3360	0	4080	7000	9000
Jackson	2800	2500	1700	4540	6000	7500
Jeffers	2800	2500	1700	4540	6000	7500
Johnston	4180	3360	0	4080	7000	9000
Kay	6000	3800	0	3500	4660	6000
Kingfish	3140	2540	1900	3480	5000	6000
Kiowa	2800	2500	1700	4540	6000	7500
LeFlore	4180	3360	0	4080	7000	9000
Lincoln	6000	3800	0	3500	4660	6000
Logan	3140	2540	1900	3480	5000	6000
Love	2800	2500	1700	4540	6000	7500
Major	3140	2540	1900	3480	5000	6000
Marshall	4180	3360	0	4080	7000	9000
Mayes	6000	3800	0	3500	4660	6000
McClain	2800	2500	1700	4540	6000	7500
McCurt	4180	3360	0	4080	7000	9000
McIntosh	4180	3360	0	4080	7000	9000
Murray	4180	3360	0	4080	7000	9000
Muskogee	6000	3800	0	3500	4660	6000
Noble	6000	3800	0	3500	4660	6000
Nowata	6000	3800	0	3500	4660	6000
Okfuskee	6000	3800	0	3500	4660	6000
Oklahoma	3140	2540	1900	3480	5000	6000
Okmulgee	6000	3800	0	3500	4660	6000
Osage	6000	3800	0	3500	4660	6000
Ottawa	6000	3800	0	3500	4660	6000
Pawnee	6000	3800	0	3500	4660	6000
Payne	6000	3800	0	3500	4660	6000
Pittsbur	4180	3360	0	4080	7000	9000
Pontotoc	4180	3360	0	4080	7000	9000
Pottawat	4180	3360	0	4080	7000	9000
RogerMil	3140	2540	1900	3480	5000	6000
Rogers	6000	3800	0	3500	4660	6000
Seminole	4180	3360	0	4080	7000	9000

Sequoyah	4180	3360	0	4080	7000	9000
Stephens	2800	2500	1700	4540	6000	7500
Texas	0	0	1340	0	0	0
Tillman	2800	2500	1700	4540	6000	7500
Tulsa	6000	3800	0	3500	4660	6000
Wagoner	6000	3800	0	3500	4660	6000
Washing	6000	3800	0	3500	4660	6000
Washita	4180	3360	0	4080	7000	9000
Woods	3140	2540	1900	3480	5000	6000
Woodward	3140	2540	1900	3480	5000	6000

+	Iberm200	Iowbs50	Iowbs100	Iowbs150	Iowbs200
Adair	8500	2500	4620	5500	6500
Alfalfa	9000	2660	4040	5000	6000
Atoka	11000	3000	4720	5500	7000
Beaver	0	2660	4000	5000	6000
Beckham	8500	3000	4620	6000	7500
Blaine	9000	2660	4040	5000	6000
Bryan	11000	3000	4721	5500	7000
Caddo	8500	3000	4620	6000	7500
Canadian	9000	2660	4040	5000	6000
Carter	8500	3000	4620	6000	7500
Cherokee	8500	2500	4620	5500	6500
Choctaw	11000	3000	4722	5500	7000
Cimarron	0	2660	4000	5000	6000
Clevelan	8500	3000	4620	6000	7500
Coal	11000	3000	4723	5500	7000
Comanche	8500	3000	4620	6000	7500
Cotton	8500	3000	4620	6000	7500
Craig	8500	2500	4620	5500	6500
Creek	8500	2500	4620	5500	6500
Custer	9000	2660	4040	5000	6000
Delaware	8500	2500	4620	5500	6500
Dewey	9000	2660	4040	5000	6000
Ellis	9000	2660	4040	5000	6000
Garfield	9000	2660	4040	5000	6000
Garvin	8500	3000	4620	6000	7500
Grady	8500	3000	4620	6000	7500
Grant	9000	2660	4040	5000	6000
Greer	8500	3000	4620	6000	7500
Harmon	8500	3000	4620	6000	7500
Harper	9000	2660	4040	5000	6000
Haskell	11000	3000	4724	5500	7000
Hughes	11000	3000	4725	5500	7000
Jackson	8500	3000	4620	6000	7500
Jeffers	8500	3000	4620	6000	7500
Johnston	11000	3000	4726	5500	7000
Kay	8500	2500	4620	5500	6500
Kingfish	9000	2660	4040	5000	6000
Kiowa	8500	3000	4620	6000	7500
LeFlore	11000	3000	4727	5500	7000
Lincoln	8500	2500	4620	5500	6500
Logan	9000	2660	4040	5000	6000
Love	8500	3000	4620	6000	7500
Major	9000	2660	4040	5000	6000
Marshall	11000	3000	4728	5500	7000
Mayes	8500	2500	4620	5500	6500

McClain	8500	3000	4620	6000	7500
McCurt	11000	3000	4729	5500	7000
McIntosh	11000	3000	4730	5500	7000
Murray	11000	3000	4731	5500	7000
Muskogee	8500	2500	4620	5500	6500
Noble	8500	2500	4620	5500	6500
Nowata	8500	2500	4620	5500	6500
Okfuskee	8500	2500	4620	5500	6500
Oklahoma	9000	2660	4040	5000	6000
Okmulgee	8500	2500	4620	5500	6500
Osage	8500	2500	4620	5500	6500
Ottawa	8500	2500	4620	5500	6500
Pawnee	8500	2500	4620	5500	6500
Payne	8500	2500	4620	5500	6500
Pittsbur	11000	3000	4732	5500	7000
Pontotoc	11000	3000	4733	5500	7000
Pottawat	11000	3000	4734	5500	7000
RogerMil	9000	2660	4040	5000	6000
Rogers	8500	2500	4620	5500	6500
Seminole	11000	3000	4735	5500	7000
Sequoyah	11000	3000	4736	5500	7000
Stephens	8500	3000	4620	6000	7500
Texas	0	2660	4000	5000	6000
Tillman	8500	3000	4620	6000	7500
Tulsa	8500	2500	4620	5500	6500
Wagoner	8500	2500	4620	5500	6500
Washing	8500	2500	4620	5500	6500
Washita	11000	3000	4737	5500	7000
Woods	9000	2660	4040	5000	6000
Woodward	9000	2660	4040	5000	6000

+	Tfesc50	Tfesc100	Tfesc150	Tfesc200	Switchg
Adair	4080	6000	7500	9500	13000
Alfalfa	0	0	0	0	10000
Atoka	3780	4500	6000	7500	13000
Beaver	0	0	0	0	0
Beckham	0	0	0	0	0
Blaine	0	0	0	0	10000
Bryan	3780	4500	6000	7500	12000
Caddo	0	0	0	0	12000
Canadian	0	0	0	0	10000
Carter	0	0	0	0	12000
Cherokee	4080	6000	7500	9500	13000
Choctaw	3780	4500	6000	7500	12000
Cimarron	0	0	0	0	0
Clevelan	0	0	0	0	10000
Coal	3780	4500	6000	7500	12000
Comanche	0	0	0	0	0
Cotton	0	0	0	0	0
Craig	4080	6000	7500	9500	12000
Creek	4080	6000	7500	9500	12000
Custer	0	0	0	0	0
Delaware	4080	6000	7500	9500	13000
Dewey	0	0	0	0	0
Ellis	0	0	0	0	0
Garfield	0	0	0	0	10000
Garvin	0	0	0	0	10000

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Grady          0       0       0       0   10000
Grant          0       0       0       0   10000
Greer          0       0       0       0       0
Harmon         0       0       0       0       0
Harper         0       0       0       0       0
Haskell     3780    4500    6000    7500   13000
Hughes      3780    4500    6000    7500   13000
Jackson        0       0       0       0       0
Jeffers        0       0       0       0   10000
Johnston    3780    4500    6000    7500   12000
Kay         4080    6000    7500    9500   10000
Kingfish       0       0       0       0   10000
Kiowa          0       0       0       0       0
LeFlore     3780    4500    6000    7500   13000
Lincoln     4080    6000    7500    9500   12000
Logan          0       0       0       0   10000
Love           0       0       0       0   12000
Major          0       0       0       0       0
Marshall    3780    4500    6000    7500   12000
Mayes       4080    6000    7500    9500   12000
McClain        0       0       0       0   10000
McCurt      3780    4500    6000    7500   13000
McIntosh    3780    4500    6000    7500   13000
Murray      3780    4500    6000    7500   12000
Muskogee    4080    6000    7500    9500   12000
Noble       4080    6000    7500    9500   10000
Nowata      4080    6000    7500    9500   12000
Okfuskee    4080    6000    7500    9500   12000
Oklahoma       0       0       0       0   12000
Okmulgee    4080    6000    7500    9500   12000
Osage       4080    6000    7500    9500   12000
Ottawa      4080    6000    7500    9500   12000
Pawnee      4080    6000    7500    9500   10000
Payne       4080    6000    7500    9500   10000
Pittsbur    3780    4500    6000    7500   13000
Pontotoc    3780    4500    6000    7500   12000
Pottawat    3780    4500    6000    7500   10000
RogerMil       0       0       0       0       0
Rogers      4080    6000    7500    9500   12000
Seminole    3780    4500    6000    7500   12000
Sequoyah    3780    4500    6000    7500   13000
Stephens       0       0       0       0   12000
Texas          0       0       0       0       0
Tillman        0       0       0       0       0
Tulsa       4080    6000    7500    9500   12000
Wagoner     4080    6000    7500    9500   12000
Washing     4080    6000    7500    9500   12000
Washita     3780    4500    6000    7500       0
Woods          0       0       0       0       0
Woodward       0       0       0       0       0
;

*******************************************************************
**10 percent of each herbaceous biomass type is available for     *
**ethanol production in each biomass supplying county             *
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TABLE DELTA(I,J) Miles from biomass source i to facility location j
         Pontotoc  Jackson  Washing Canadian Garfield   Texas
Adair       199       346       161       240       239       450
Alfalfa     248       210       177       143        83       221
Atoka        80       314       210       189       245       427
Beaver      352       253       323       243       216       113
Beckham     230        93       310       138       190       227
Blaine      185       152       221        76        98       230
Bryan        96       237       262       205       261       443
Caddo       142       134       251        91       153       300
Canadian    144       163       206        33        95       273
Carter       95       188       256       157       213       394
Cherokee    180       327       136       215       213       425
Choctaw     132       294       241       241       297       479
Cimarron    460       361       444       351       324       111
Clevelan     93       161       195        74       130       311
Coal         58       229       198        99       223       405
Comanche    148        91       271       115       177       327
Cotton      143       103       282       127       189       341
Craig       209       334        79       218       208       412
Creek       118       244       109       127       146       354
Custer      208       113       265        99       142       234
Delaware    230       356       116       239       229       441
Dewey       232       142       244       123       115       198
Ellis       278       159       290       169       160       171
Garfield    200       215       165        95        33       245
Garvin       66       169       221       116       171       353
Grady       121       136       230        74       135       311
Grant       223       247       145       128        66       255
Greer       218        53       323       154       206       253
Harmon      236        64       352       186       238       276
Harper      293       203       254       184       156       148
Haskell      74       296       161       201       235       439
Hughes       66       225       162       131       186       369
Jackson     205        32       321       162       214       281
Jeffers     137       133       283       128       190       365
Johnston     66       208       230       169       225       406
Kay         200       274       122       155        94       282
Kingfish    158       176       190        54        68       254
Kiowa       195       71        301       132       184       276
LeFlore     179       351       216       262       290       500
Lincoln     106       215       139        98       134       327
Logan       141       202       161        84        93       285
Love        103       194       264       165       221       403
Major       223       180       208       114        78       222
Marshall     75       201       239       169       225       407
Mayes       183       308        90       192       181       393
McClain      77       158       212        91       147       328
McCurt      184       346       293       294       349       531
McIntosh    135       281       141       176       213       414
Murray       63       183       224       144       200       382
Muskogee    156       303       125       191       199       410
Noble       162       232       133       116        72       283
Nowata      193       318        45       202       177       379
Okfuskee     95       235       141       130       178       367
Oklahoma    113       168       180        56       112       294
Okmulgee    114       260       108       155       174       383
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Osage       196     321      75     205     155     357
Ottawa      227     352      98     236     226     432
Pawnee      153     265     110     149     101     312
Payne       137     234     129     117     97      299
Pittsbur    100     272     176     187     241     425
Pontotoc     29     202     193     140     196     378
Pottawat     81     200     168      96     152     334
RogerMil    256     118     309     151     185     207
Rogers      174     300      80     183     173     385
Seminole     70     222     162     128     183     365
Sequoyah    178     325     172     219     246     457
Stephens    120     121     262     106     168     344
Texas       398     298     383     289     261      49
Tillman     188      65     311     155     217     313
Tulsa       146     272      76     155     146     357
Wagoner     165     308     111     191     184     396
Washing     193     318      29     202     161     363
Washita     194      92     279     110     162     254
Woods       284     224     212     175     119     218
Woodward    256     166     246     147     120     157

+         Comanche Okmulgee   Payne  Woodward  Custer
Adair       294     125     185     326     283
Alfalfa     202     232     148     111     127
Atoka       185     127     185     302     231
Beaver      297     362     271     128     217
Beckham     150     267     217     128      94
Blaine      135     197     124     105      69
Bryan       180     157     201     318     247
Caddo        83     198     165     175      98
Canadian    115     164     119     148      77
Carter      132     183     180     270     198
Cherokee    275     100     160     300     258
Choctaw     236     158     236     354     283
Cimarron    406     470     380     236     325
Clevelan    109     138     109     187     116
Coal        172     115     163     280     209
Comanche     33     218     184     203     114
Cotton       48     229     196     216     128
Craig       283     128     155     292     261
Creek       192      67      86     229     170
Custer      134     228     169     109      55
Delaware    304     150     176     316     282
Dewey       163     243     152      74      84
Ellis       215     288     197      77     138
Garfield    177     183      99     121     133
Garvin      111     155     143     229     157
Grady        84     177     144     186     113
Grant       210     202     118     148     165
Greer       111     274     234     146     110
Harmon      120     299     265     177     142
Harper      238     303     212      69     158
Haskell     244      94     181     314     243
Hughes      174      88     126     244     173
Jackson      90     268     235     166     118
Jeffers      79     225     197     241     159
Johnston    150     156     171     282     210
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Kay         223      179       95      176      192
Kingfish    135      166       94      130       94
Kiowa       102      251      211      151       88
LeFlore     294      154      237      375      304
Lincoln     163       98       70      203      141
Logan       150      137       65      160      124
Love        139      192      189      278      207
Major       172      220      130       97       98
Marshall    144      165      176      282      210
Mayes       256      102      128      268      234
McClain     106      147      126      204      133
McCurt      289      211      289      407      336
McIntosh    230       66      155      289      218
Murray      126      151      148      257      185
Muskogee    251       76      145      286      233
Noble       181      144       56      159      157
Nowata      266      112      137      259      244
Okfuskee    183       65      117      243      172
Oklahoma    116      133       94      169       98
Okmulgee    209       24      115      258      197
Osage       269      143      125      237      247
Ottawa      300      146      172      312      278
Pawnee      214      124       64      188      190
Payne       182      122       31      175      158
Pittsbur    214       93      182      300      229
Pontotoc    144      119      135      253      182
Pottawat    149      105       91      209      138
RogerMil    175      280      213      113      107
Rogers      248       93      120      260      226
Seminole    171       91      123      241      170
Sequoyah    273      112      192      332      261
Stephens     63      209      175      219      142
Texas       343      408      317      174      263
Tillman      75      258      224      189      122
Tulsa       220       67       93      233      198
Wagoner     256       84      131      271      234
Washing     267      113      127      243      245
Washita     115      232      189      129       66
Woods       233      268      184      112      159
Woodward    202      266      176       32      121        ;

PARAMETER BYLD(I,KF) Biomass yield in tons per acre;
  BYLD(I,KF) = BIOYLD1(I,KF)/2000;

PARAMETER CURACRES(I,K) Available biomass in tons per acre;
  CURACRES(I,K) = BIPROP*CURACRE(I,K);

PARAMETER TRCA(I,J)  "Biomass transportation cost in $ per 17 dry ton truck";
  TRCA(I,J) = 34.08 + [0.62*1.609+GPM*(DIEPRI-DIEPRIO)]*2*DELTA(I,J);

PARAMETER TAU(I,J)  "Biomass transportation cost in $ per ton";
  TAU(I,J) = TRCA(I,J)/TRKLOAD;

VARIABLES
  NPW                Net present value for the ethanol production activity
  Q(J,S,G,M)         Commodity g produced at j by facility s in month m
  A(I,KF,H, M)       Acres of kf harvested by method h in month m in county i
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  X(I,KF,H,M)      Harvested biomass kf by method h in county i month m
  XT(I,J,S,K,M)    Biomass k from i to facility size s at j in month m
  XP(J,S,K,M)      Biomass k processed by facility size s at j in month m
  XSI(I,K,M)       Biomass k stored at source i in month m
  XSJ(J,S,K,M)     Biomass k stored at facility location j in month m
  BETA(J,S)        Zero-one variable for plant size s at j;
POSITIVE VARIABLES Q, A, X, XT, XP, XSI, XSJ;
BINARY VARIABLE BETA;

EQUATIONS
  OBJ              Objective function
  LANDCON(I,K)     Land constraint for native prairies at county i

****The following two constraints are mutually exclusive***********************
  LANDCON2(I,K)    Switchgrass land constraint, imposed only if no switchgrass
                   estabilishment is permitted (Base scenario and scenarios I to VIII)
  LANDCON3(I)      Constraint for cropland, imposed only if switchgrass estabilishment is
                   permitted (Scenario IX)
****End of the mutually exclusive constraints**********************************

  XCOMP(I,K,H,M)   Compute harvested biomass from harvested land
  ACRESO(I,K,H,M)  "Acres harvested when YAD(K,M)=0"
  BIOSUP1(I,K,M)   First month biomass supply balance at county i
  BIOSUP2(I,K,M)   "Other months' biomass supply balance at county i"
  BIOBALI(I,K)     Biomass balance at the supplying county
  PLTCAP(J,S,E,M)  Plant capacity constraints in gallons of ethanol
  STOCAPJ(J,S,M)   Biomass storage capacity constraint at the plant
  BIOXPJ1(J,S,K,M) First month biomass supply at plant location j
  BIOXPJ2(J,S,K,M) "Other months' biomass supply at location j"
  BIOBALJ(J,S,K)   Biomass balance at the plant
  MBINVJ(J,S,M)    Minimum biomass inventory at the plant
  OUTSUP(J,S,G,M)  Output supply constraint
  LEONT(J,S,G,K,M) Leontief ppf for ethanol and by-products
  PLTLOC(J)        At most one plant per location;

OBJ..  NPW =E= {SUM[M,(SUM((J,S,G), RHO(G)*Q(J,S,G,M))
               -SUM((J,S), Q(J,S,"Ethanol",M)/IOE)*GRDIES*(DIEPRI-DIEPRIO)
               -SUM((I,K,H,BC), (HC(K,H)+POC(K,BC)+NCOST(K))*
                SUM(KF$KKF(K,KF), A(I,KF,H,M)))
               -SUM((I,J,S,K), TAU(I,J)*XT(I,J,S,K,M))
               -SUM((I,K), GAMMA(K)*XSI(I,K,M)))]
               -SUM((J,S,FT), TAFC(S,FT)*BETA(J,S))}*PVAF;

LANDCON(I,K)$(ORD(K) NE 10)..      SUM(KF$KKF(K,KF), SUM((H,M),
                                   A(I,KF,H,M)))-CURACRES(I,K)=L=0;

LANDCON2(I,K)$(ORD(K) EQ 10)..     SUM(KF$KKF(K,KF), SUM((H,M),
                                   A(I,KF,H,M)))-CURACRES(I,K)=L=0;

*LANDCON3(I)..          SUM([H,M], SUM(K$CRS(K), SUM(KF$KKF(K,KF),A(I,KF,H,M))))
*                       -BIPROP*POTACRES(I,"Cropland") =L= 0;

XCOMP(I,K,H,M)..                   SUM(KF$KKF(K,KF), X(I,KF,H,M))-
                                   SUM(KF$KKF(K,KF), A(I,KF,H,M)*
                                   BYLD(I,KF))*YAD(K,M)=E=0;

ACRESO(I,K,H,M)$(YAD(K,M) EQ 0)..  SUM(KF$KKF(K,KF), A(I,KF,H,M))=E=0;
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BIOSUP1(I,K,M)$M1(M)..           SUM(KF$KKF(K,KF),SUM(H, X(I,KF,H,M)))
                                 +THETAI(K)*XSI(I,K,"Feb")
                                 -SUM((J,S), XT(I,J,S,K,M))-XSI(I,K,M)=E= 0;

BIOSUP2(I,K,M)$M2(M)..           SUM(KF$KKF(K,KF),SUM(H, X(I,KF,H,M)))
                                 +THETAI(K)*XSI(I,K,M-1)
                                 -SUM((J,S), XT(I,J,S,K,M))-XSI(I,K,M) =E= 0;

BIOBALI(I,K)..                   SUM(KF$KKF(K,KF), SUM([H,M], X(I,KF,H,M)))
                                 -SUM([J,S,M], XT(I,J,S,K,M))
                                 -(1-THETAI(K))*SUM(M, XSI(I,K,M)) =E=0;


PLTCAP(J,S,E,M)..                Q(J,S,E,M)-CAPP(S)*BETA(J,S)=L=0;

STOCAPJ(J,S,M)..                 SUM(K, XSJ(J,S,K,M))
                                 -CAP(S,"STORAGE")*BETA(J,S)=L=0;

BIOXPJ1(J,S,K,M)$M1(M)..         SUM(I, XT(I,J,S,K,M))
                                 +THETAJ(K)*XSJ(J,S,K,"Feb")
                                 -XSJ(J,S,K,M)-XP(J,S,K,M) =E= 0;

BIOXPJ2(J,S,K,M)$M2(M)..         SUM(I, XT(I,J,S,K,M))
                                 +THETAJ(K)*XSJ(J,S,K,M-1)
                                 -XSJ(J,S,K,M)-XP(J,S,K,M) =E= 0;

BIOBALJ(J,S,K)..                 SUM([I,M], XT(I,J,S,K,M))
                                 -(1-THETAJ(K))*SUM(M, XSJ(J,S,K,M))
                                 -SUM(M, XP(J,S,K,M))=E=0;

MBINVJ(J,S,M)..                  SUM(K, XSJ(J,S,K,M))-BINV(S)*BETA(J,S)=G=0;

OUTSUP(J,S,G,M)..                Q(J,S,G,M)
                                 -SUM(K, LAMBDA(K,G)*XP(J,S,K,M))=L= 0;

LEONT(J,S,G,K,M)..               Q(J,S,"Ethanol",M)*LAMBDA(K,G) -
                                 Q(J,S,G,M)*LAMBDA(K,"Ethanol") =E= 0;

PLTLOC(J)..                      SUM(S, BETA(J,S)) =L= 1;

MODEL Ethanol /ALL/;

SOLVE Ethanol MAXIMIZING NPW USING MIP;

DISPLAY RHO, BETA.L, Q.L, XP.L, XSJ.L, XT.L, X.L, XSI.L, A.L, CRUDPRI;

***RESULTS SUMMARY***

PARAMETER TOTLAND Total land producing biomass;
  TOTLAND(K,M) = SUM(KF$KKF(K,KF), SUM([I,H], A.L(I,KF,H,M)));

PARAMETER TLANDM Total land producing biomass by month;
  TLANDM(M) = SUM([I,KF,H], A.L(I,KF,H,M));

PARAMETER TLANDK Total land producing biomass by biomass type;
  TLANDK(K) = SUM(KF$KKF(K,KF), SUM([I,H,M], A.L(I,KF,H,M)));
```

```
PARAMETER TLANDRK Total area harvested annually by region and feedstock type;
  TLANDRK(R,K) = SUM(I$IR(I,R), SUM(KF$KKF(K,KF), SUM([H,M], A.L(I,KF,H,M))));

PARAMETER TLANDR Total area harvested annually by region;
  TLANDR(R) = SUM(K, TLANDRK(R,K));

PARAMETER TOTBIO Total biomass to be made available annually (tons);
  TOTBIO = SUM([I,KF,H,M], X.L(I,KF,H,M));

PARAMETER MBIOHAR Total biomass harvested by month;
  MBIOHAR(M) = SUM([I,KF,H], X.L(I,KF,H,M));

PARAMETER MBIOSTO Total biomass stored at counties by month;
  MBIOSTO(M) = SUM([I,K], XSI.L(I,K,M));

PARAMETER MBIOSHIP Total biomass shipments by month;
  MBIOSHIP(M) = SUM([I,J,S,K], XT.L(I,J,S,K,M));

PARAMETER BIOSHIP Biomass shipments from counties to plants by type and month;
  BIOSHIP(K,M) = SUM([I,J,S], XT.L(I,J,S,K,M));

PARAMETER BIOSHIPIJ Biomass shipments from county i to plant j;
  BIOSHIPIJ(I,J) = SUM([S,K,M], XT.L(I,J,S,K,M));

PARAMETER PLTR Optimal plant locations by region;
  PLTR(J,R)$JR(J,R) = SUM(S, BETA.L(J,S));

PARAMETER MBIOSTJ Total biomass stored on-site;
  MBIOSTJ(M) = SUM([J,S,K], XSJ.L(J,S,K,M));

PARAMETER PROPCAPM "Plant monthly capacity usage (percent)";
  PROPCAPM(J,S,M) = 100*Q.L(J,S,"Ethanol",M)/CAPP(S);

PARAMETER PROPCAP "Plant monthly capacity usage (percent)";
  PROPCAP(J,S) = 100*SUM(M, Q.L(J,S,"Ethanol",M))/(12*CAPP(S));

DISPLAY TOTLAND, TLANDM, TLANDK, TLANDRK, TLANDR, TOTBIO, MBIOHAR, MBIOSTO,
        MBIOSHIP, BIOSHIP, BIOSHIPIJ, PLTR, MBIOSTJ, PROPCAPM, PROPCAP;

***ENERGY BALANCE CALCULATIONS***

PARAMETER NITEN Energy in nitrogen fertilizer in Btu;
  NITEN = NBTU*SUM([I,KF,H,M], A.L(I,KF,H,M)*NIT(KF));

PARAMETER TPTEN Energy expended during biomass shipment in Btu;
 TPTEN = (GPM/17)*DBTU*SUM([I,J,S,K,M], XT.L(I,J,S,K,M)*2*DELTA(I,J));

PARAMETER FLDEN(I,KF) Energy spent per acre of each of the cropping activities;
 FLDEN(I,KF)$(ORD(KF) EQ 22) = SUM([H,M], A.L(I,KF,H,M))*SUM(FA$TFA
                               ("Harvest",FA), FLDIES(FA))*DBTU
                               + SUM([H,M], A.L(I,KF,H,M))*SUM(FA$TFA
                               ("Estab",FA), FLDIES(FA))*DBTU/T;

 FLDEN(I,KF)$(ORD(KF) NE 22) = SUM([H,M], A.L(I,KF,H,M))*SUM(FA$TFA
                               ("Harvest",FA), FLDIES(FA))*DBTU;
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PARAMETER TFLDEN Total energy spent in field activities;
 TFLDEN = SUM([I,KF], FLDEN(I,KF));

**The following parameter calculates energy spent in grinding**
PARAMETER GRDEN Diesel energy spent in grinding the biomass in Btu;
 GRDEN = DBTU*GRDIES*SUM([J,S,M], Q.L(J,S,"Ethanol",M))/IOE;

PARAMETER TOTEN Totatl energy spent in Btu;
 TOTEN = NITEN + TPTEN + TFLDEN + GRDEN;

PARAMETER ENYLD Total energy yield from the produced ethanol (Btu);
 ENYLD = SUM([J,S,M], Q.L(J,S,"Ethanol",M)*EBTU);

PARAMETER NETEN Net energy in Btu;
 NETEN = ENYLD - TOTEN;

DISPLAY FLDIES, NITEN, TPTEN, FLDEN, TFLDEN, GRDEN, TOTEN, ENYLD, NETEN;

************************************************************
*Partitioning total costs into its components              *
************************************************************

PARAMETER FLDCOST Cost of establishing, maintaining and harvesting biomass;
   FLDCOST = SUM(M, SUM((I,K,H,BC), (HC(K,H)+POC(K,BC)+NCOST(K))*
             SUM(KF$KKF(K,KF), A.L(I,KF,H,M))));

PARAMETER HARVCOST Total harvest cost;
   HARVCOST = SUM([I,K,H,M], HC(K,H)*SUM(KF$KKF(K,KF), A.L(I,KF,H,M)));

PARAMETER ESOPCOST Feedstock establishment and land opportunity costs;
   ESOPCOST = SUM([I,K,H,M,BC], POC(K,BC)*SUM(KF$KKF(K,KF), A.L(I,KF,H,M)));

PARAMETER NITCOST(K) Cost of nitrogen fertilizer by feedstock species;
   NITCOST(K)$(ORD(K) EQ 10) = SUM([I,H,M], 25*PN*A.L(I,"SWITCHG",H,M));
   NITCOST(K)$(ORD(K) NE 10) = SUM([I,H,M], NCOST(K)
                               *SUM(KF$KKF(K,KF),A.L(I,KF,H,M)));

PARAMETER NITROCOST Total cost of nitrogen cost;
  NITROCOST = SUM(K, NITCOST(K));

PARAMETER TPTCOST Total cost of transporting the feedstocks;
  TPTCOST = SUM([I,J,S,K,M], TAU(I,J)*XT.L(I,J,S,K,M));

PARAMETER STORCOST Total cost of storing biomass in the field;
  STORCOST = SUM([I,K,M], GAMMA(K)*XSI.L(I,K,M));

PARAMETER FXDCOST(FT) Fixed costs by facility type;
  FXDCOST(FT)$(ORD(FT) EQ 1) = SUM([J,S], TAFC(S,"STORAGE")*BETA.L(J,S))
                              +SUM([J,S,M], Q.L(J,S,"Ethanol",M)/IOE)
                               *GRDIES*(DIEPRI-DIEPRIO);
  FXDCOST(FT)$(ORD(FT) EQ 2) = SUM([J,S], TAFC(S,"PROCESS")*BETA.L(J,S));

PARAMETER TFXDCO Total fixed costs;
  TFXDCO = SUM(FT, FXDCOST(FT));

DISPLAY FLDCOST, ESOPCOST, NITROCOST, HARVCOST, STORCOST, TPTCOST,
        FXDCOST, TFXDCO;
```

```
********************************************************************
**Grid search for the threshold price of ethanol:                  *
********************************************************************

SCALAR IT ;

FOR (IT = 1 TO 10,

     RHO(E)=RHO(E)+ 0.01;

     SOLVE Ethanol MAXIMIZING NPW USING MIP;

     RGAP = ABS(Ethanol.OBJVAL - Ethanol.OBJEST) / Ethanol.OBJEST;

     DISPLAY RGAP, IOE, RHO, BETA.L, Q.L, XP.L, XSJ.L, XT.L, X.L, XSI.L, A.L;

     TOTLAND(K,M) = SUM(KF$KKF(K,KF), SUM([I,H], A.L(I,KF,H,M)));

     TLANDM(M) = SUM([I,KF,H], A.L(I,KF,H,M));

     TLANDK(K) = SUM(KF$KKF(K,KF), SUM([I,H,M], A.L(I,KF,H,M)));

     TLANDRK(R,K)=SUM(I$IR(I,R), SUM(KF$KKF(K,KF), SUM([H,M], A.L(I,KF,H,M))));

     TLANDR(R) = SUM(K, TLANDRK(R,K));

     TOTBIO = SUM([I,KF,H,M], X.L(I,KF,H,M));

     MBIOHAR(M) = SUM([I,KF,H], X.L(I,KF,H,M));

     MBIOSTO(M) = SUM([I,K], XSI.L(I,K,M));

     MBIOSHIP(M) = SUM([I,J,S,K], XT.L(I,J,S,K,M));

     BIOSHIP(K,M) = SUM([I,J,S], XT.L(I,J,S,K,M));

     PLTR(J,R)$JR(J,R) = SUM(S, BETA.L(J,S));

     MBIOSTJ(M) = SUM([J,S,K], XSJ.L(J,S,K,M));

     PROPCAPM(J,S,M) = 100*Q.L(J,S,"Ethanol",M)/CAPP(S);

     PROPCAP(J,S) = 100*SUM(M, Q.L(J,S,"Ethanol",M))/(12*CAPP(S));

     DISPLAY TOTLAND, TLANDM, TLANDK, TLANDRK, TLANDR, TOTBIO, MBIOHAR, MBIOSTO,
             MBIOSHIP, BIOSHIP, PLTR, MBIOSTJ, PROPCAPM, PROPCAP;

     NITEN = NBTU*SUM([I,KF,H,M], A.L(I,KF,H,M)*NIT(KF));

     TPTEN = (GPM/17)*DBTU*SUM([I,J,S,K,M], XT.L(I,J,S,K,M)*2*DELTA(I,J));

     FLDEN(I,KF)$(ORD(KF) EQ 22) = SUM([H,M], A.L(I,KF,H,M))*SUM(FA$TFA
                                   ("Harvest",FA), FLDIES(FA))*DBTU
                                   + SUM([H,M], A.L(I,KF,H,M))*SUM(FA$TFA
                                   ("Estab",FA), FLDIES(FA))*DBTU/T;
     FLDEN(I,KF)$(ORD(KF) NE 22) = SUM([H,M], A.L(I,KF,H,M))*SUM(FA$TFA
                              ("Harvest",FA), FLDIES(FA))*DBTU;
```

```
TFLDEN = SUM([I,KF], FLDEN(I,KF));

GRDEN = DBTU*GRDIES*SUM([J,S,M], Q.L(J,S,"Ethanol",M))/IOE;

TOTEN = NITEN + TPTEN + TFLDEN + GRDEN;

ENYLD = SUM([J,S,M], Q.L(J,S,"Ethanol",M)*EBTU);

NETEN = ENYLD - TOTEN;

DISPLAY FLDIES, NITEN, TPTEN, FLDEN, TFLDEN, GRDEN, TOTEN, ENYLD, NETEN;
   );
```

APPENDIX D

MAJOR RESULTS FOR VARIOUS COUNTERFACTUAL MODEL SCENARIOS

Table 21. Description of the counterfactual model scenarios and expected response in industry NPW and number of plants

Scenario number	Scenario description	Expected direction of response in NPW and number of plants
I	Proportion of total quantity of each feedstock species produced in each county available for ethanol production was increased from 10 percent to 30 percent	Positive
II	Equation 4.30 (here dubbed competitiveness condition) was imposed to maintain the ethanol-diesel price ratio that would make ethanol competitive, as implied by Wyman	Negative
III	Impose the breakeven price of ethanol	Negative
IV	Reduce ethanol yield from 100 gallons per ton of biomass to 80 gallons per ton of biomass	Negative
V	Reduce ethanol yield from 100 gallons per ton of biomass to 60 gallons per ton of biomass	Negative
VI	Increase opportunity costs of land and crop residues by 100 percent	Negative
VII	Increase plant construction and operating costs by 100 percent	Negative
VIII	Double the slope of the transportation cost equation (Equation 4.22)	Negative
IX	Allow switchgrass to displace some of the cropping activities	Positive

Table 22. Optimal plant size, number and capacity usage, assuming at most 30 percent of each feedstock is available for ethanol production (Scenario I)

Plant size	Annual capacity (gallons ethanol)	Number of plants	Capacity usage (%)	Plant location(s)
Large	100,000,000	9	100%	Canadian, Comanche, Custer, Garfield, Okmulgee, Payne, Washington, Pontotoc, and Woodward
Medium	50,000,000	0	n/a	n/a
Small	25,000,000	0	n/a	n/a

n/a = not applicable

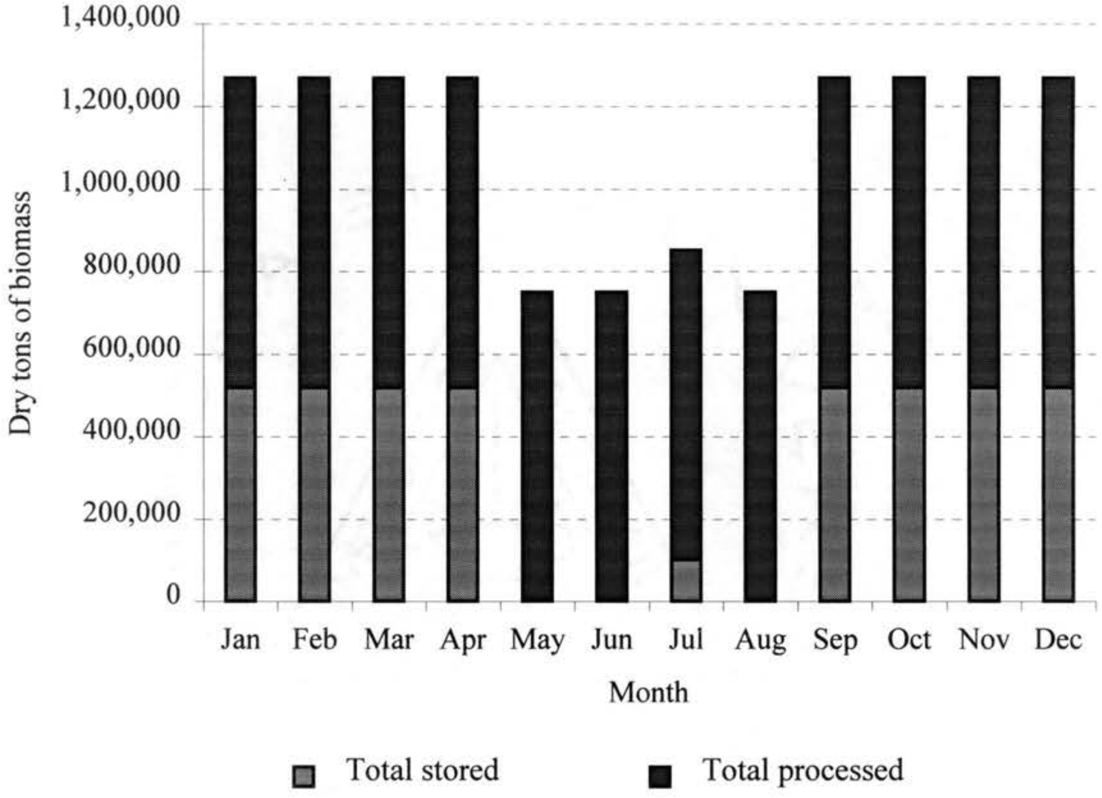

Figure 7. Dry tons of biomass stored and processed on-site by month, assuming at most 30 percent of the feedstocks are available for ethanol production (Scenario I)

Table 23. **Total acres of each feedstock species harvested monthly and annually, assuming at most 30 percent of the feedstock produced in each county is available for ethanol production (Scenario I)**

Feedstock species	Acres harvested/Month						As %
	Jun	Jul	Aug	Sep	Oct	Total	of total
Wheat straw	769,607	560,187	0	0	0	1,329,794	25%
Tall native prairies	0	93,920	219,676	1,866,402	0	2,179,997	40%
Mixed native prairies	0	95,805	90,408	1,340,009	0	1,526,222	28%
Corn stover	0	0	0	0	47,880	47,880	1%
Short native prairies	0	0	29,077	175,574	0	204,651	4%
Bermudagrass (200 lbs. N)	0	14,923	2,680	75,427	0	93,030	2%
Tall fescue (200 lbs. N)	29,420	0	0	0	0	29,420	1%
Total harvested	799,028	764,834	341,841	3,457,412	47,880	5,410,995	100%

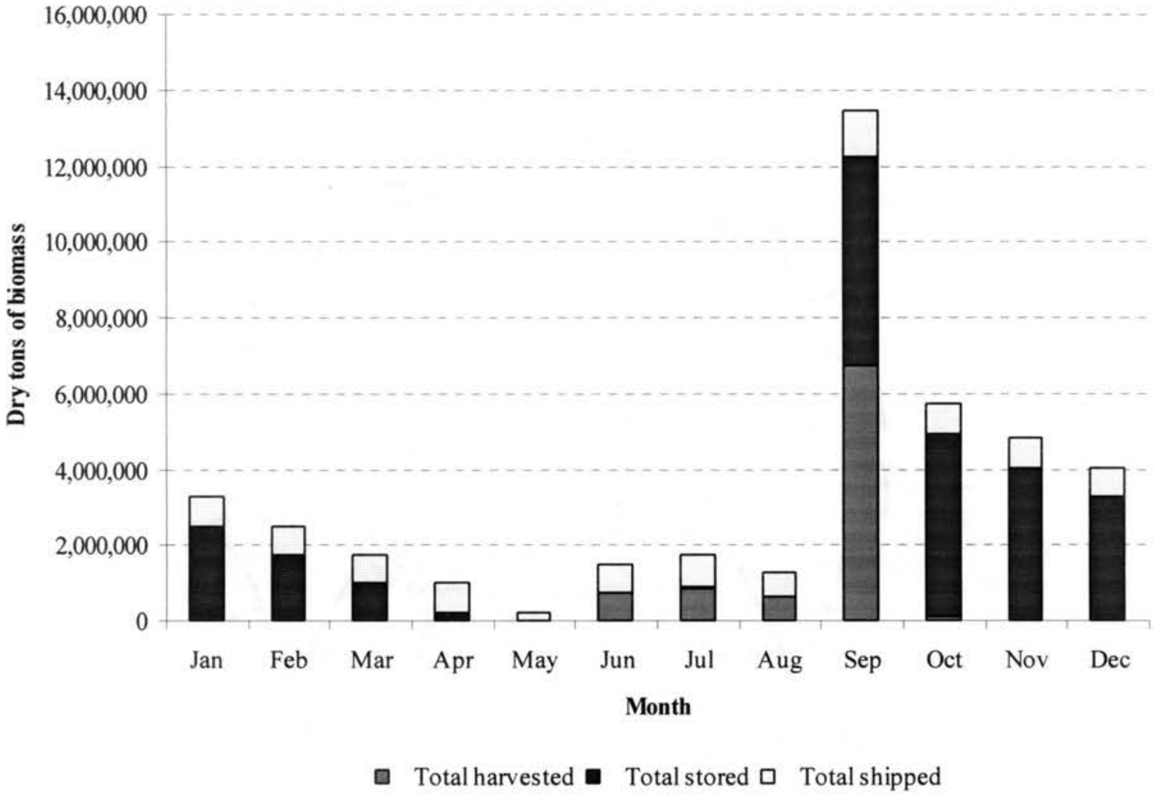

Figure 8. **Total dry tons of biomass harvested, stored and shipped in each month, assuming at most 30 percent of the feedstock produced in each county is available for ethanol production (Scenario I)**

Table 24. Total acres harvested annually in each region of the state, assuming that at most 30 percent of the feedstock produced in each county is available for ethanol production (Scenario I)

Region	Wheat straw	Corn stover	Tall native prairies	Mixed native prairies	Short native prairies	Bermuda grass	Tall fescue	Regional total	As % of total
Panhandle	107,040	27,942	0	0	0	0	0	134,982	2%
Northwest	701,598	2,234	125,627	942,206	188,441	0	0	1,960,107	36%
Northeast	178,512	6,137	976,151	51,377	0	0	29,420	1,241,598	23%
Southwest	330,150	4,180	406,241	457,975	16,209	19,410	0	1,234,166	23%
Southeast	12,494	7,387	671,978	74,664	0	73,619	0	840,142	16%
State total	1,329,794	47,880	2,179,997	1,526,222	204,651	93,030	29,420	5,410,995	100%

Table 25. Primary energy input and energy efficiency, assuming at most 30 percent of the feedstock produced in each county is available for ethanol production (Scenario I)

Activity/item	Total energy[a] (million Btu)	Btu/gallon of ethanol	As a % of total energy input	% change from base
Energy input				
Nitrogen fertilizer	542,674	603	12	-16
Field activities	843,063	937	19	2
Transportation	2,267,600	2,520	51	-15
Biomass grinding	814,980	906	18	0
Subtotal energy input	4,468,317	4,965	100	-10
Energy yield		78,000[b]	1600[c]	11

[a] Based on nine large plants, each producing 100 million gallons of ethanol per year.

[b] Ethanol energy content estimate (Btu/gallon) adopted from Hohmann and Rendleman.

[c] System energy efficiency (output/input) ratio.

Table 26. Optimal plant size, number and capacity usage when the competitiveness condition is imposed (Scenario II)

Plant size	Annual capacity (gallons ethanol)	Number of plants	Capacity usage (%)	Plant location(s)
Large	100,000,000	3	100%	Custer, Pontotoc, and Washington
Medium	50,000,000	0	n/a	n/a
Small	25,000,000	0	n/a	n/a

n/a = not applicable

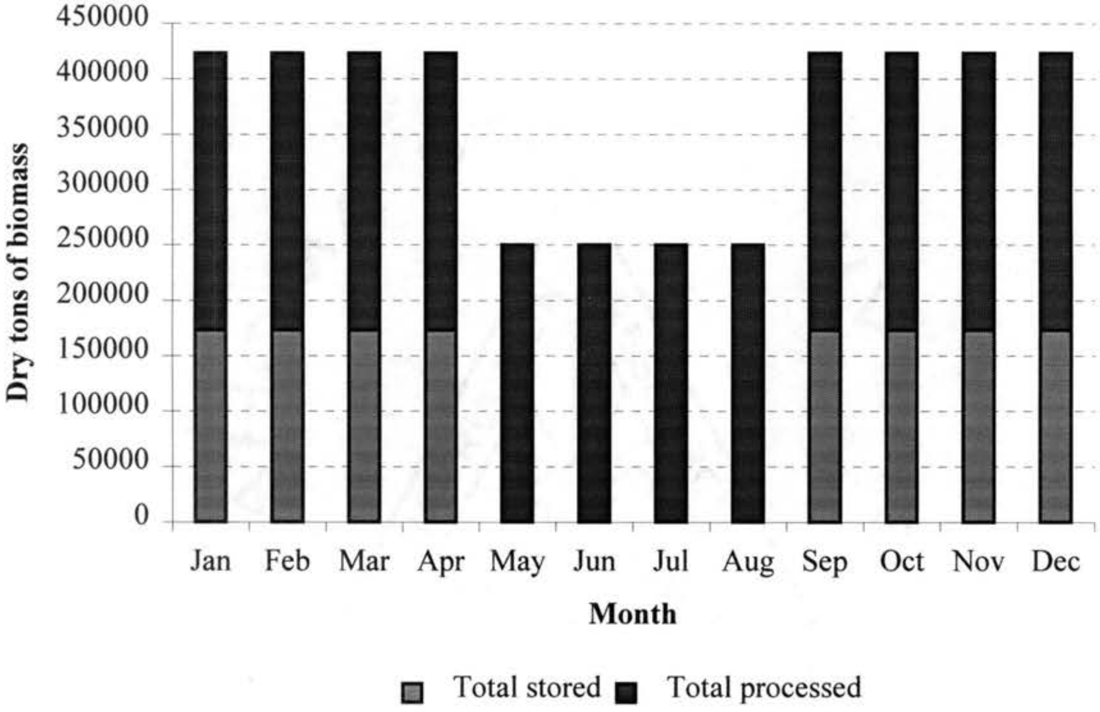

Figure 9. Dry tons of biomass stored and processed at the plant sites by month when the competitiveness condition is imposed (Scenario II)

Table 27. Total acres of each feedstock species harvested monthly and annually when the competitiveness condition is imposed (Scenario II)

Feedstock species	Acres harvested/Month						As %
	Jun	Jul	Aug	Sep	Oct	Total	of total
Wheat straw	247,547	94,493	0	0	0	369,040	22%
Tall native prairies	0	47,383	66,043	613,240	0	726,666	43%
Mixed native prairies	0	20,225	57,821	430,695	0	508,741	30%
Corn stover	0	0	0	0	15,960	15,960	1%
Short native prairies	0	0	0	20,924	0	20,924	1%
Bermudagrass (200 lbs. N)	0	5,365	4,009	41,871	0	51,244	3%
Tall fescue (200 lbs. N)	7,373	0	0	0	0	7,373	0.4%
Total harvested	281,921	167,465	127,873	1,106,729	15,960	1,699,948	100%

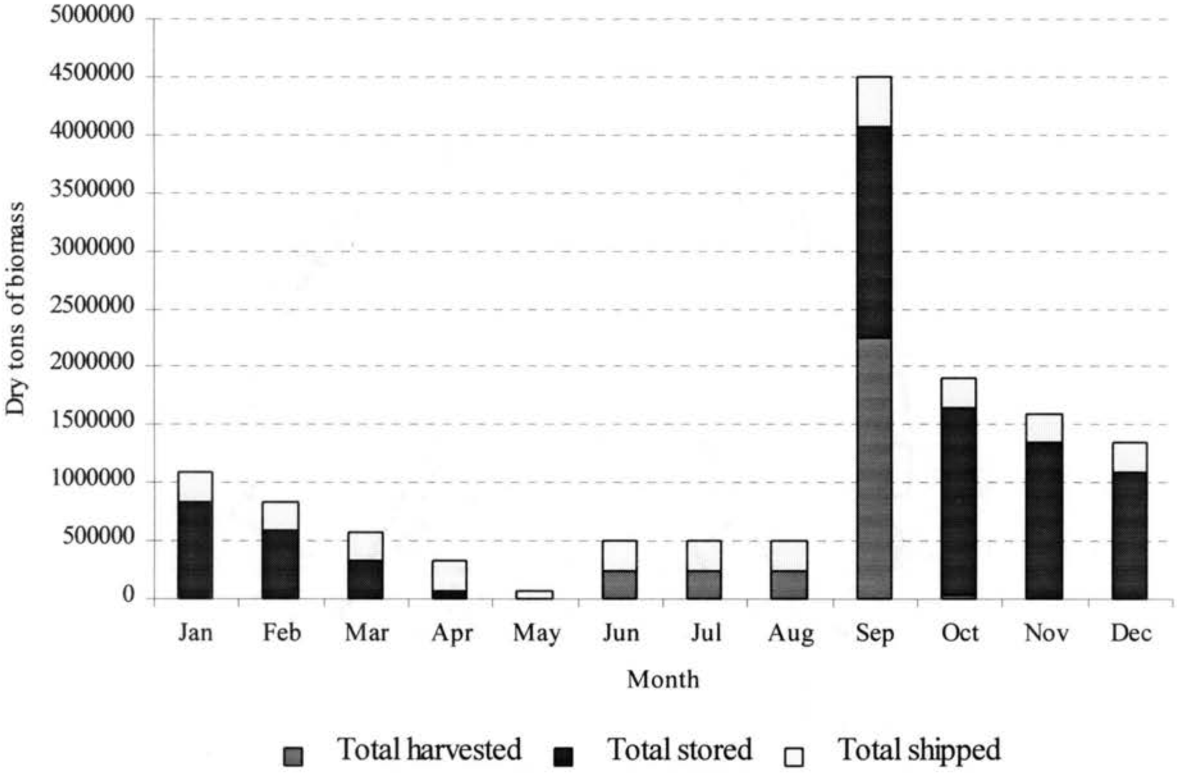

Figure 10. Total dry tons of biomass harvested, stored and shipped in each month when the competitiveness condition is imposed (Scenario II)

Table 28. Total acres harvested annually in each region of the state, assuming the competitiveness condition holds (Scenario II)

Region	Wheat straw	Corn stover	Tal nativ prairie	Mixed native prairies	Short native prairies	Bermuda grass	Tall fescue	Regional total	As % Of total
Panhandle	0	9,314		0	0	0	0	9,314	1%
Northwest	230,320	745	41,87	314,069	20,924	0	0	607,934	36%
Northeast	59,504	2,046	325,38	17,126	0	0	7,373	411,432	24%
Southwest	75,051	1,393	135,41	152,658	0	6,470	0	370,987	22%
Southeast	4,165	2,462	223,99	24,888	0	44,774	0	300,281	18%
State total	369,040	15,960	726,66	508,741	20,924	51,244	7,373	1,699,948	100%

Table 29. Primary energy input and energy efficiency when the competitiveness condition is imposed (Scenario II)

Activity/item	Total energy[a] (million Btu)	Btu/gallon of ethanol	As a % of total energy input	% change from base
Energy input				
Nitrogen fertilizer	259,778	866	15	21
Field activities	264,861	883	16	-3
Transportation	881,433	2,938	53	-1
Biomass grinding	271,660	906	16	0
Subtotal energy input	1,677,732	5,592	100	-1
Energy yield		78,000[b]	1400[c]	-11

[a] Based on three large plants, each producing 100 million gallons of ethanol per year.

[b] Ethanol energy content estimate (Btu/gallon) adopted from Hohmann and Rendleman.

[c] System energy efficiency (output/input) ratio.

Table 30. Optimal plant size, number and capacity usage when price of ethanol is set at breakeven level of $0.78/gallon (Scenario III)

Plant size	Annual capacity (gallons ethanol)	Number of plants	Capacity usage (%)	Plant location(s)
Large	100,000,000	1	100%	Washington
Medium	50,000,000	0	n/a	n/a
Small	25,000,000	0	n/a	n/a

n/a = not applicable

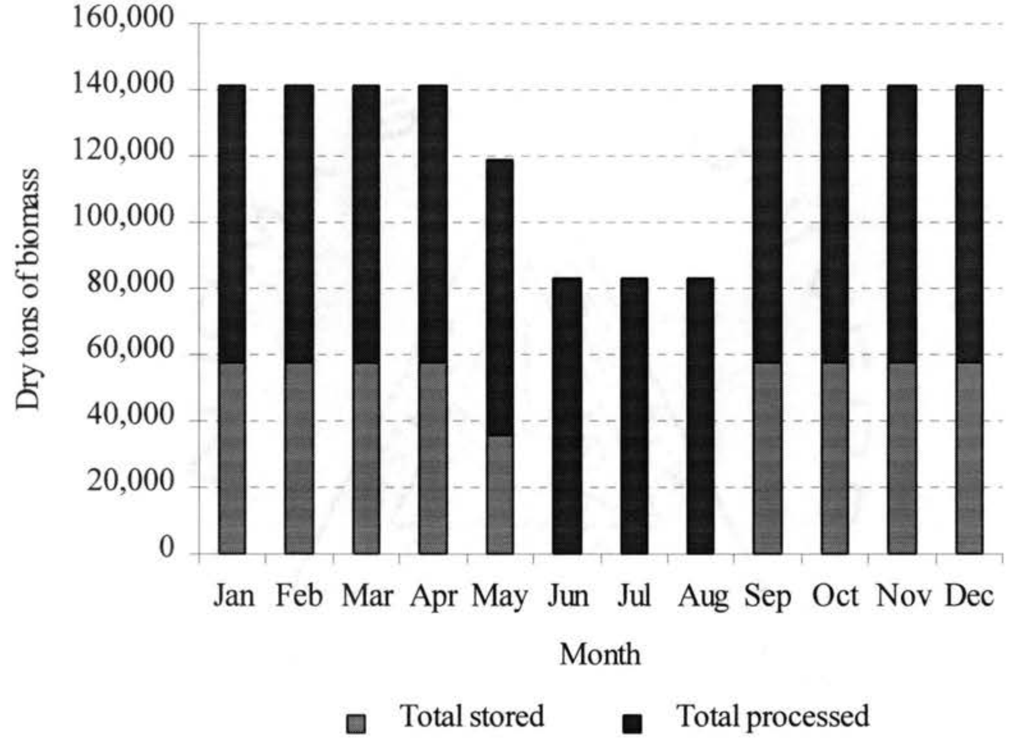

Figure 11. **Dry tons of biomass stored and processed at the plant sites by month, assuming the price of ethanol is at breakeven level of $0.78/gallon (Scenario III)**

Table 31. Total acres of each feedstock species harvested monthly and annually, assuming the price of ethanol is $0.78/gallon (Scenario III)

Feedstock species	Acres harvested/Month								As %
	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	of total
Wheat straw	55,196	0	0	0	0	0	0	55,196	13%
Tall native prairies	0	27,778	26,788	44,164	27,368	48,106	156,142	348,459	83%
Mixed native prairies	0	0	1,563	4,491	1,550	1,565	5,203	14,372	3.4%
Corn stover	0	0	0	0	2,059	0	0	2,059	0.5%
Total	55,196	27,778	28,351	48,655	30,977	49,671	161,345	420,086	100%

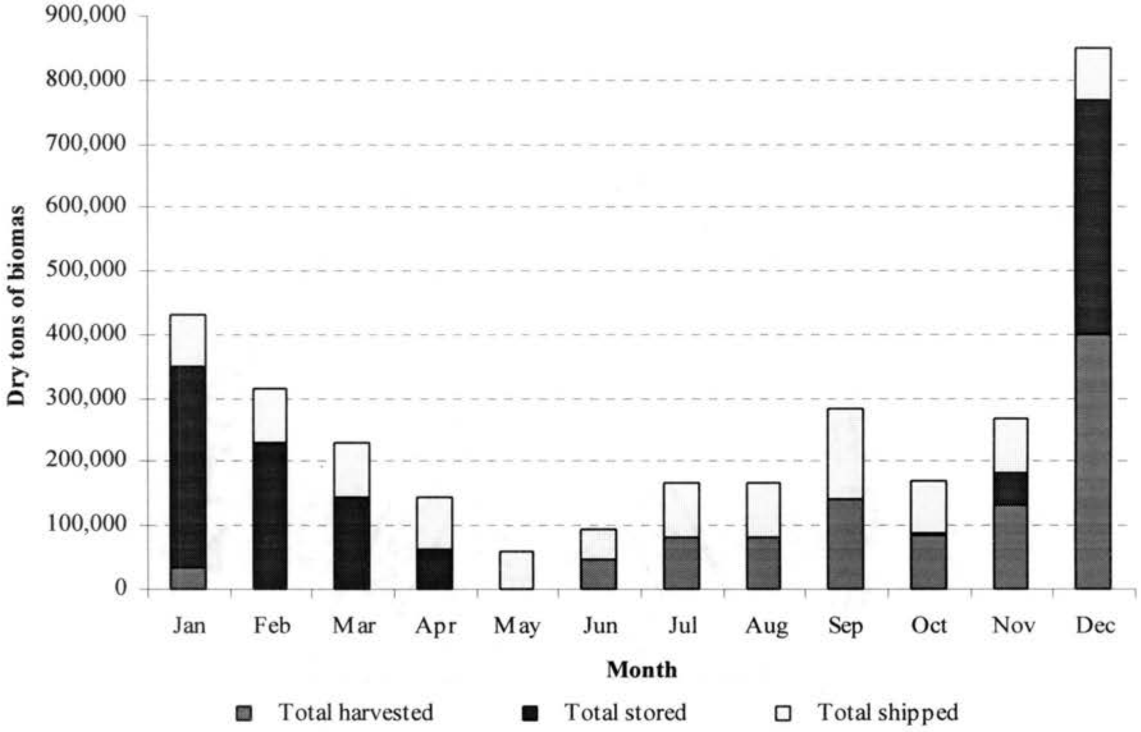

Figure 12. Total dry tons of biomass harvested, stored and shipped from all supplying counties in each month, assuming the price of ethanol is $0.78 per gallon (Scenario III)

Table 32. Total acres harvested annually in each region of the state, assuming the price of ethanol is $0.78 per gallon (Scenario III)

Region	Wheat straw	Corn stover	Tall native prairies	Mixed native prairies	Regional total	As % of state total
Northeast	54,540	1,690	325,384	14,372	395,986	94%
Southeast	656	369	23,075	0	24,100	6%
State total	55,196	2,059	348,459	14,372	420,086	100%

Table 33. Primary energy input and energy efficiency, assuming the price of ethanol is $0.78 (Scenario III)

Activity/item	Total energy[a] (million Btu)	Btu/gallon of ethanol	As a % of total energy input	% change from base
Energy input				
Nitrogen fertilizer	0	0	0	-100
Field activities	65,452	655	15	-28
Transportation	288,714	2,887	65	-3
Biomass grinding	90,553	906	20	0
Subtotal energy input	444,719	4,447	100	-19
Energy yield		78,000[b]	1800[c]	24

[a] Based on one large plant operating at full capacity.

[b] Ethanol energy content estimate (Btu/gallon) adopted from Hohmann and Rendleman.

[c] System energy efficiency (output/input) ratio.

Table 34. Optimal plant size(s), number and capacity usage when ethanol yield is reduced to 80 gallons per ton of biomass (Scenario IV)

Plant size	Annual capacity (gallons ethanol)	Number of plants	Capacity usage (%)	Plant Location(s)
Large	100,000,000	2	100%	Canadian, Washington
Medium	50,000,000		100%	
Small	25,000,000	0	n/a	n/a

n/a = not applicable

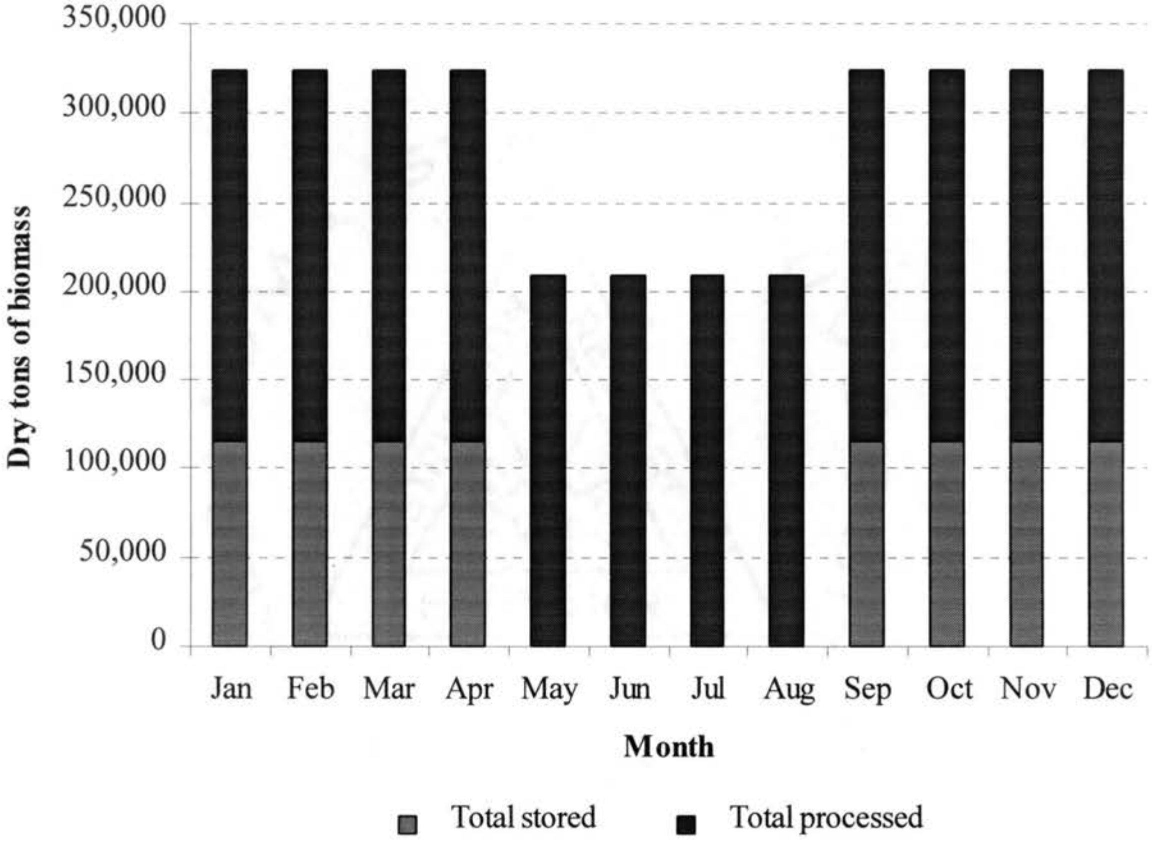

Figure 13. **Dry tons of biomass stored and processed at the plant sites, assuming ethanol yield is reduced to 80 gallons per ton of biomass (Scenario IV)**

Table 35. Total acres of each feedstock species harvested monthly and annually, assuming ethanol yield drops to 80 gallons per ton of biomass (Scenario IV)

Feedstock	Acres harvested/Month							As %
species	Jun	Jul	Aug	Sep	Oct	Nov	Total	of total
Wheat straw	259,258	25,319	0	0	0	0	284,577	20%
Tall native prairies	0	54,468	74,760	578,627	9,860	8,952	726,666	50%
Mixed native prairies	0	40,785	15,403	364,186	1,096	995	422,464	29%
Corn stover	0	0	0	0	15,960		15,960	1%
Short native Prairies	0	2,357	0	0	0	0	2,357	0.2%
Total harvested	259,258	122,928	90,162	942,813	26,915	9,946	1,452,023	100%

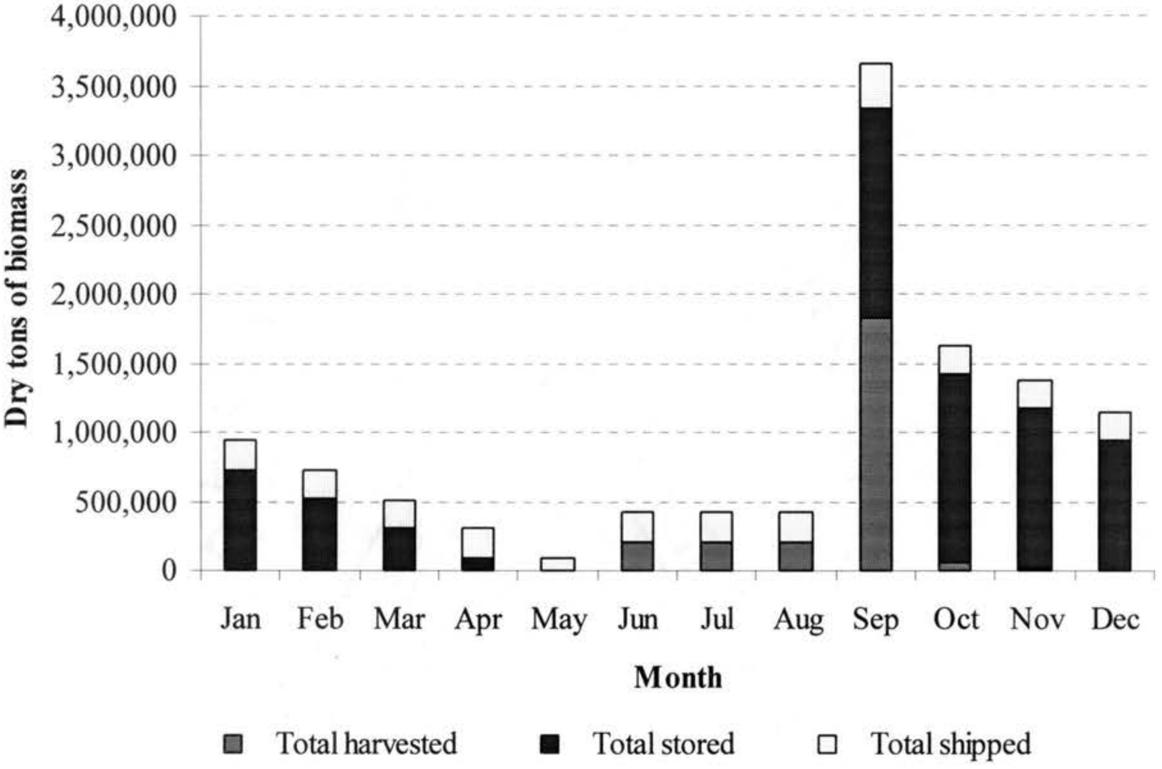

Figure 14. Total dry tons of biomass harvested, stored and shipped from all supplying counties in each month, assuming ethanol yield drops to 80 gallons per ton of biomass (Scenario IV)

Table 36. Total acres harvested annually in each region of the state, assuming ethanol yield drops to 80 gallons per ton of biomass (Scenario IV)

Region	Wheat straw	Corn stover	Tall native prairies	Mixed native prairies	Short native prairies	Regional total	As % of total
Panhandle	0	9,314	0	0	0	9,314	1%
Northwest	193,449	745	41,876	240,535	2,357	478,961	33%
Northeast	56,640	2,046	325,384	17,126	0	401,195	28%
Southwest	32,050	1,393	135,414	139,915	0	308,772	21%
Southeast	2,438	2,462	223,993	24,888	0	253,781	17%
State total	284,577	15,960	726,666	422,464	2,357	1,452,023	100%

Table 37. Primary energy input and energy efficiency assuming ethanol yield drops to 80 gallons per ton of biomass (Scenario IV)

Activity/item	Total energy[a] (million Btu)	Btu/gallon of ethanol	As a % of total energy input	% change from base
Energy input				
Nitrogen fertilizer	0	0	0	-100
Field activities	226,233	1,131	17	24
Transportation	892,848	4,464	66	50
Biomass grinding	226,383	1,132	17	25
Total energy input	1,345,464	6,727	100	22
Energy yield		78,000[b]	1200[c]	-18

[a] Based on two large plants, each operating at full capacity.

[b] Ethanol energy content estimate (Btu/gallon) adopted from Hohmann and Rendleman.

[c] System energy efficiency (output/input) ratio.

Table 38. Optimal plant size(s), number and capacity usage when ethanol yield is reduced to 60 gallons per ton of biomass (Scenario V)

Plant size	Annual capacity (gallons ethanol)	Number of plants	Capacity usage (%)	Plant Location(s)
Large	100,000,000	0	n/a	n/a
Medium	50,000,000	1	100%	Washington
Small	25,000,000	0	n/a	n/a

n/a = not applicable

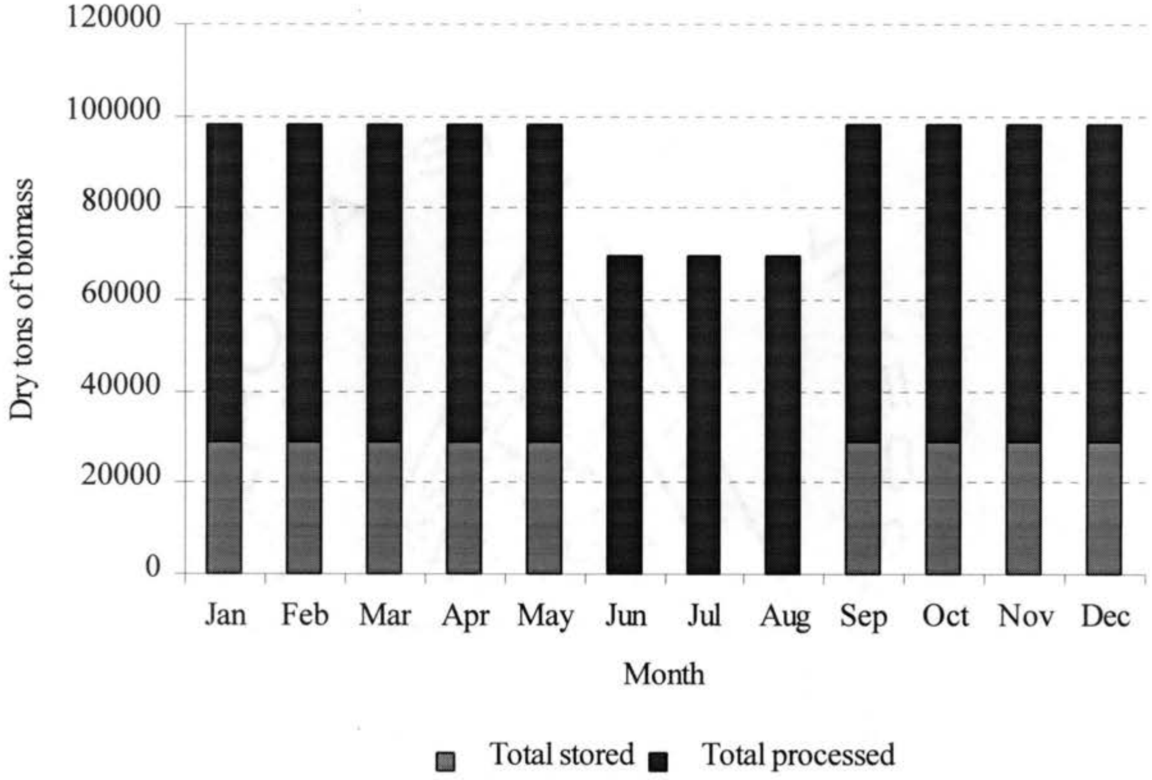

Figure 15. Dry tons of biomass stored and processed at the plant sites, assuming ethanol yield is reduced to 60 gallons per ton of biomass (Scenario V)

Table 39. Total acres of each feedstock species harvested monthly and annually, assuming ethanol yield drops to 60 gallons per ton of biomass (Scenario V)

Feedstock	Acres harvested/Month										As %
species	Jan	Feb	Jun	Jul	Aug	Se	Oct	Nov	Dec	Total	of total
Wheat straw	0	0	4,646	0	0		0	0	0	4,646	1%
Tall native Prairies	28,947	140,727	0	22,892	23,148	32,31	24,377	25,731	27,244	325,384	98%
Mixed native prairies	0	0	0	405	0	70	0	0	0	1,108	0.3%
Total	28,947	140,727	4,646	23,148	23,148	32,76	24,377	25,731	27,244	331,138	100%

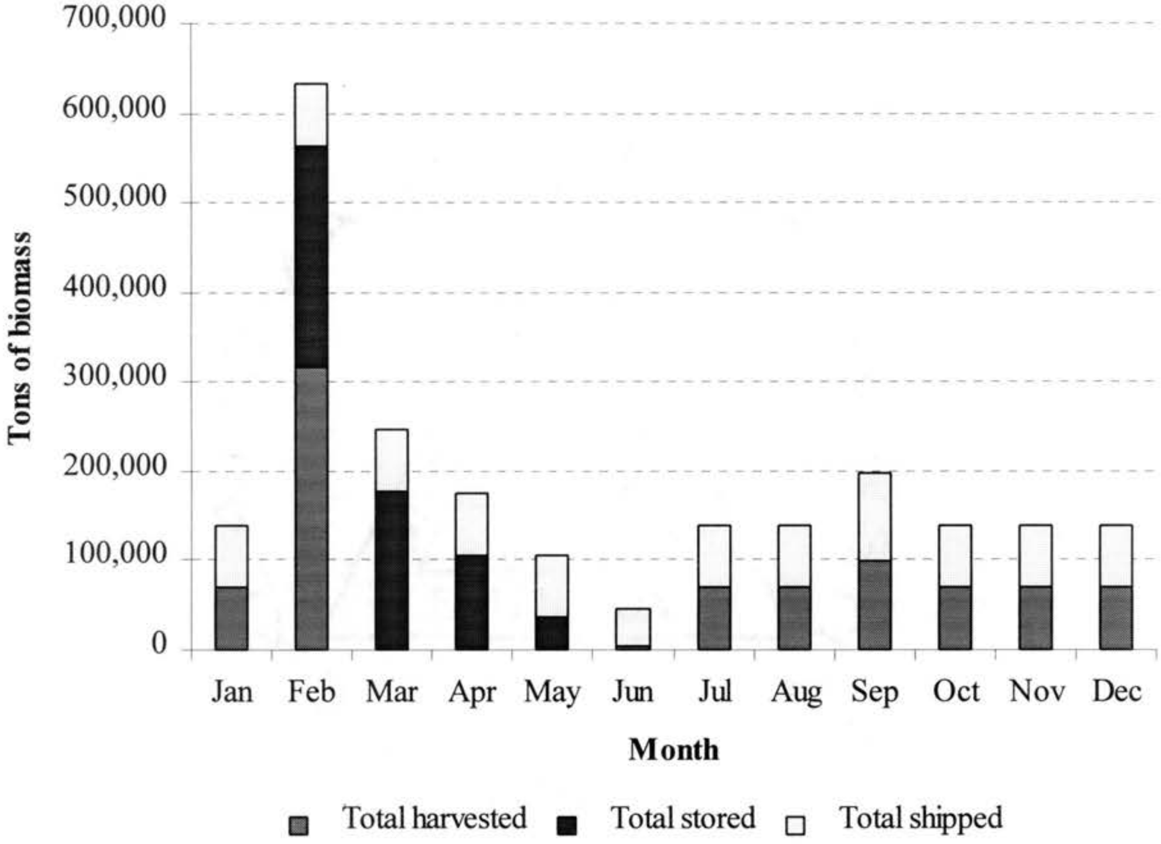

Figure 16. Total dry tons of biomass harvested, stored and shipped from all supplying counties in each month, assuming ethanol yield drops to 60 gallons per ton of biomass (Scenario V)

Table 40. Total acres harvested annually in each region of the state, assuming ethanol yield drops to 60 gallons per ton of biomass (Scenario V)

Region	Wheat straw	Tall native prairies	Mixed native prairies	Regional total	As % of state total
Panhandle	0	0	0	0	0%
Northwest	0	0	0	0	0%
Northeast	4,646	325,384	1,108	331,138	100%
Southwest	0	0	0	0	0%
Southeast	0	0	0	0	0%
State total	4,646	325,384	1,108	331,138	100%

Table 41. Primary energy input and energy efficiency assuming ethanol yield is 60 gallons per ton of biomass (Scenario V)

Activity/item	Total energy[a] (million Btu)	Btu/gallon of ethanol	As a % of total energy input	% change from base
Energy input				
Nitrogen fertilizer	0	0	0	-100
Field activities	51,593	1,032	15	13
Transportation	228,640	4,573	64	54
Biomass grinding	75,461	1,509	21	67
Subtotal energy input	355,694	7,114	100	29
Energy yield		78,000[b]	1100[c]	-22

[a] Based on one medium plant, operating at full capacity.

[b] Ethanol energy content estimate (Btu/gallon) adopted from Hohmann and Rendleman.

[c] System energy efficiency (output/input) ratio.

Table 42. Optimal plant size(s), number and capacity usage, assuming the opportunity costs of land and crop residues are doubled (Scenario VI)

Plant size	Annual capacity (gallons ethanol)	Number of plants	Capacity usage (%)[a]	Plant Location(s)
Large	100,000,000	3	100%	Custer, Pontotoc, and Washington counties
Medium	50,000,000	0	n/a	n/a
Small	25,000,000	0	n/a	n/a

n/a = not applicable

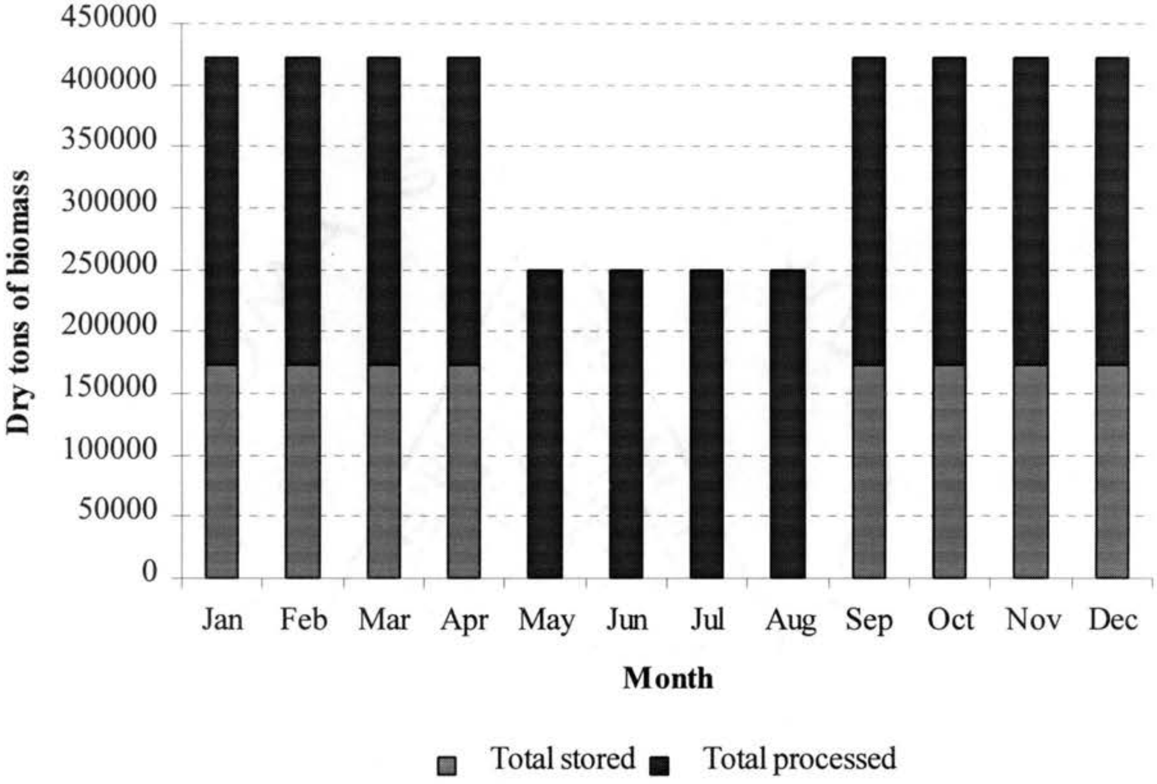

Figure 17. Dry tons of biomass stored and processed at the plant sites, assuming land and crop residue opportunity costs are doubled (Scenario VI)

Table 43. Total acres of each feedstock species harvested monthly and annually, land and crop residue opportunity costs are doubled (Scenario VI)

Feedstock	Acres harvested/Month						As a %
species	Jun	Jul	Aug	Sep	Oct	Total	of total
Wheat straw	285,365	62,969	0	0	0	348,334	21%
Tall native prairies	0	58,510	62,801	605,355	0	726,666	43%
Mixed native prairies	0	3,129	47,765	457,847	0	508,741	30%
Corn stover	0	0	0	0	15,960	15,960	1%
Short native prairies	0	5,497	0	9,277	0	14,775	1%
Bermudagrass (200 lbs. N)	0	8,715	7,540	40,736	0	56,992	3%
Tall fescue (200 lbs. N)	4,706	0	0	0	0	4,706	0.3%
Total harvested	290,071	138,820	118,105	1,113,216	15,960	1,676,172	

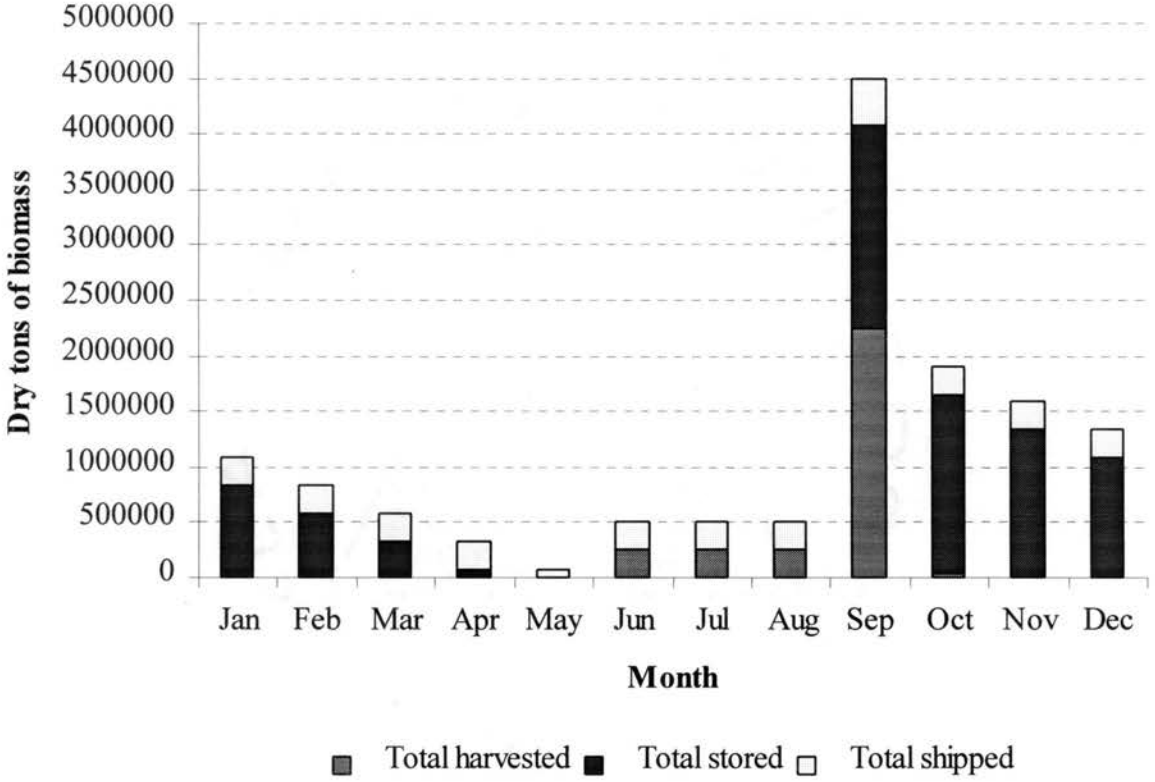

Figure 18. **Total dry tons of biomass harvested, stored and shipped from all supplying counties in each month, assuming land and crop residue opportunity costs are doubled (Scenario VI)**

Table 44. Total acres harvested annually in each region of the state, assuming land and crop residue opportunity costs are doubled (Scenario VI)

Region	Wheat straw	Corn stover	Tal nativ prairie	Mixed native prairies	Short native prairies	Bermuda grass	Tall fescue	Regional total	As a % of total
Panhandle	0	9,314		0	0	0	0	9,314	1%
Northwest	230,320	745	41,87	314,069	14,775	0	0	601,784	36%
Northeast	59,230	2,046	325,38	17,126	0	0	4,706	408,491	24%
Southwest	54,738	1,393	135,41	152,658	0	6,470	0	350,673	21%
Southeast	4,046	2,462	223,99	24,888	0	50,522	0	305,910	18%
State total	348,334	15,960	726,66	508,741	14,775	56,992	4,706	1,676,172	100%

Table 45. Primary energy input and energy efficiency, assuming land and crop residue opportunity costs are doubled (Scenario VI)

Activity/item	Total energy[a] (million Btu)	Btu/gallon of ethanol	As a % of total energy input	% change from base
Energy input				
Nitrogen fertilizer	273,430	911	16	27
Field activities	261,157	871	15	-5
Transportation	886,891	2,956	52	-1
Biomass grinding	271,660	906	16	0
Subtotal energy input	1,693,138	5,644	100	2
Energy yield		78,000[b]	1400[c]	-2

[a] Based on three large plants, each operating at full capacity.

[b] Ethanol energy content estimate (Btu/gallon) adopted from Hohmann and Rendleman.

[c] System energy efficiency (output/input) ratio.

Table 46. Optimal plant size(s), number and capacity usage, assuming plant construction and operating costs are doubled (Scenario VII)

Plant size	Annual capacity (gallons ethanol)	Number of plants	Capacity usage (%)	Plant Location(s)
Large	100,000,000	1	100%	Washington County
Medium	50,000,000	0	n/a	n/a
Small	25,000,000	0	n/a	n/a

n/a = not applicable

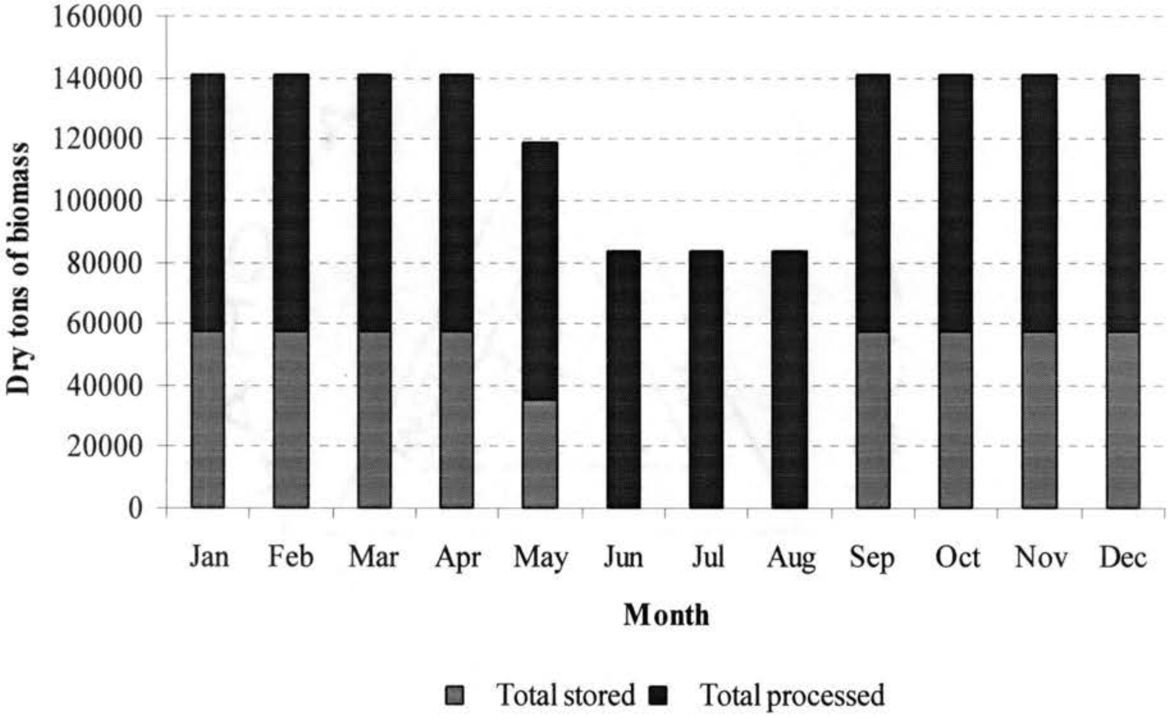

Figure 19. Dry tons of biomass stored and processed at the plant sites, assuming plant construction and operating costs are doubled (Scenario VII)

Table 47. Total acres of each feedstock species harvested monthly and annually, assuming plant construction and operating costs are doubled (Scenario VII)

Feedstock	Acres harvested/Month									As a %
species	Jan	Jun	Jul	Aug	Sep	Oct	No	Dec	Total	of total
Wheat straw	0	55,196	0	0	0	0		0	55,196	13%
Tall native prairies	18,114	0	27,778	23,944	47,008	28,169	47,30	156,142	348,459	83%
Corn stover	0	0	0	0	0	2,059		0	2,059	0.5%
Mixed native prairies	0	0	0	6,054	0	284	2,83	5,203	14,372	3.4%
Total	18,114	55,196	27,778	29,998	47,008	30,513	50,13	161,345	420,086	100%

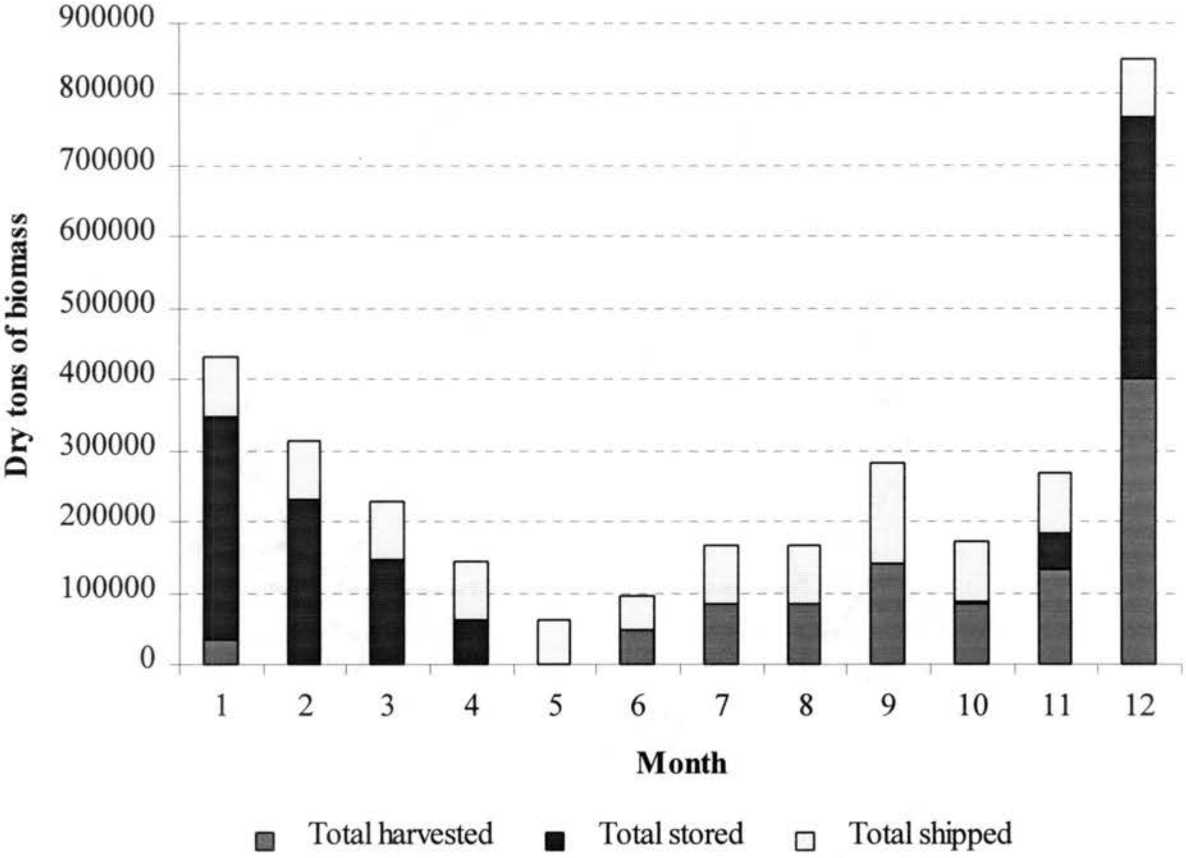

Figure 20. Total dry tons of biomass harvested, stored and shipped from all supplying counties in each month, assuming plant construction and operating costs are doubled (Scenario VII)

Table 48. Total acres harvested annually in each region of the state, assuming plant construction and operating costs are doubled (Scenario VII)

Region	Wheat straw	Corn stover	Tall native prairies	Mixed native prairies	Regional total	As % of state total
Panhandle	0	0	0	0	0	0%
Northwest	0	0	0	0	0	0%
Northeast	54,540	1,690	325,384	14,372	395,986	94%
Southwest	0	0	0	0	0	0%
Southeast	656	369	23,075	0	24,100	6%
State total	55,196	2,059	348,459	14,372	420,086	100%

Table 49. Primary energy input and energy efficiency, assuming plant construction and operating costs are doubled (Scenario VII)

Activity/item	Total energy[a] (million Btu)	Btu/gallon of ethanol	As a % of total energy input	% change from base
Energy input				
Nitrogen fertilizer	0	0	0	-100
Field activities	65,452	655	15	-28
Transportation	288,714	2,887	65	-3
Biomass grinding	90,553	906	20	0
Subtotal energy input	444,719	4,447	100	-19
Energy yield		78,000[b]	1800[c]	24

[a] Based on one large operating at full capacity.

[b] Ethanol energy content estimate (Btu/gallon) adopted from Hohmann and Rendleman.

[c] System energy efficiency (output/input) ratio.

Table 50. Optimal plant size(s), number and capacity usage, assuming the slope of the transportation cost function is doubled (Scenario VIII)

Plant size	Annual capacity (gallons ethanol)	Number of plants	Capacity usage (%)	Plant Location(s)
Large	100,000,000	3	100%	Custer, Pontotoc, Washington
Medium	50,000,000	0	n/a	n/a
Small	25,000,000	0	n/a	n/a

n/a = not applicable

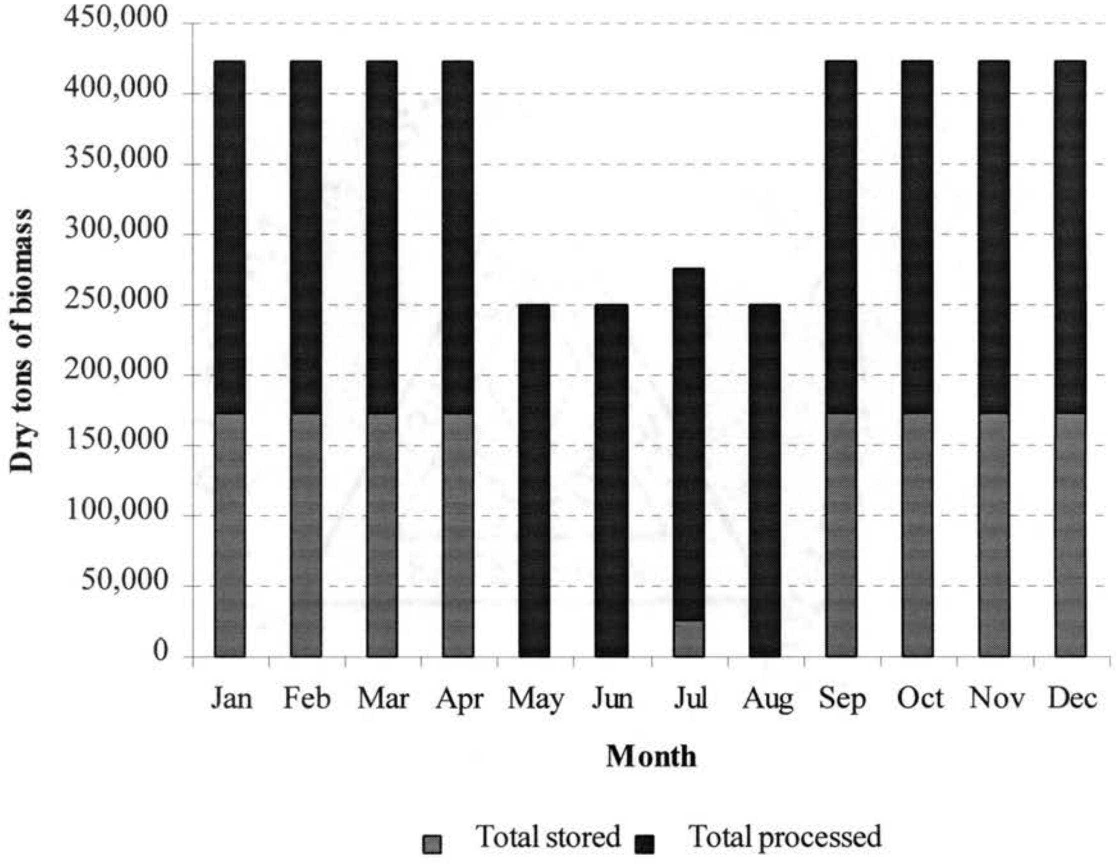

Figure 21. Dry tons of biomass stored and processed at the plant sites, assuming the slope of the transportation cost function is doubled (Scenario VIII)

Table 51. Total acres of each feedstock species harvested monthly and annually, assuming the slope of the transportation cost function is doubled (Scenario VIII)

Feedstock	Acres harvested/Month						As a %
species	Jun	Jul	Aug	Sep	Oct	Total	of total
Wheat straw	249,017	144,849	0	0	0	393,866	23%
Tall native prairies	0	48,397	69,549	588,843	19,878	726,666	42%
Mixed native prairies	0	11,792	6,808	487,932	2,209	508,741	29%
Corn stover	0	0	0	0	13,878	13,878	1%
Short native prairies	0	0	8,252	19,979	0	28,231	2%
Bermudagrass (200 lbs. N)	0	4,518	7,736	32,375	0	44,629	3%
Tall fescue (200 lbs. N)	12,232	0	0	0	0	12,232	3%
Total harvested	261,249	209,556	92,345	1,129,129	35,964	1,728,243	100%

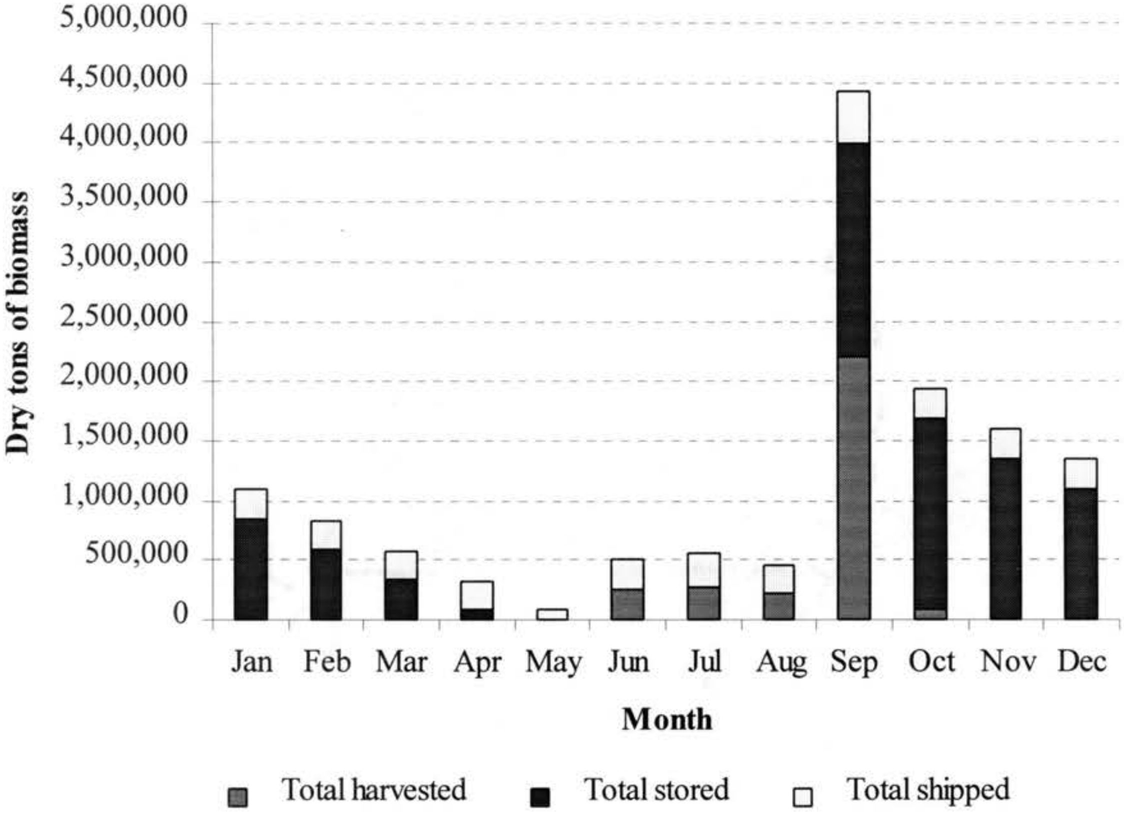

Figure 22. Total dry tons of biomass harvested, stored and shipped from all supplying counties in each month, assuming the slope of the transportation cost function is doubled (Scenario VIII)

Table 52. Total acres harvested annually in each region of the state, assuming the slope of the transportation cost function is doubled (Scenario VIII)

Region	Wheat straw	Corn stover	Tall native prairies	Mixe nativ prairie	Short native prairies	Bermuda grass	Tall fescue	Regional total	As % of state total
Panhandle	0	7,232	0		0	0	0	7,232	0.4%
Northwest	233,866	745	41,876	314,06	28,231	0	0	618,786	36%
Northeast	59,504	2,046	325,384	17,12	0	0	10,859	414,919	24%
Southwest	96,331	1,393	135,414	152,65	0	6,470	0	392,267	23%
Southeast	4,164	2,462	223,993	24,88	0	38,159	1,373	295,039	17%
State total	393,865	13,878	726,666	508,74	28,231	44,629	12,232	1,728,243	100%

Table 53. Primary energy input and energy efficiency, assuming the slope of the transportation cost function is doubled (Scenario VIII)

Activity/item	Total energy[a] (million Btu)	Btu/gallon of ethanol	As a % of total energy input	% change from base
Energy input				
Nitrogen fertilizer	251,998	840	15	17
Field activities	269,270	898	16	-2
Transportation	870,977	2,903	52	-3
Biomass grinding	271,660	906	16	0
Subtotal energy input	1,663,905	5,546	100	1
Energy yield		78,000[b]	1400[c]	-1[d]

[a] Based on three large plants, each operating at full capacity.

[b] Ethanol energy content estimate (Btu/gallon) adopted from Hohmann and Rendleman.

[c] System energy efficiency (output/input) ratio.

[d] Change in energy efficiency ratio.

Table 54. Optimal plant size(s), number and capacity usage when switchgrass establishment is permitted (Scenario IX)

Plant size	Annual capacity (gallons ethanol)	Number of plants	Capacity usage (%)	Plant Location(s)
Large	100,000,000	6	100%	Canadian, Custer, Garfield Okmulgee, Pontotoc, Washington
Medium	50,000,000	0	n/a	n/a
Small	25,000,000	0	n/a	n/a

n/a = not applicable

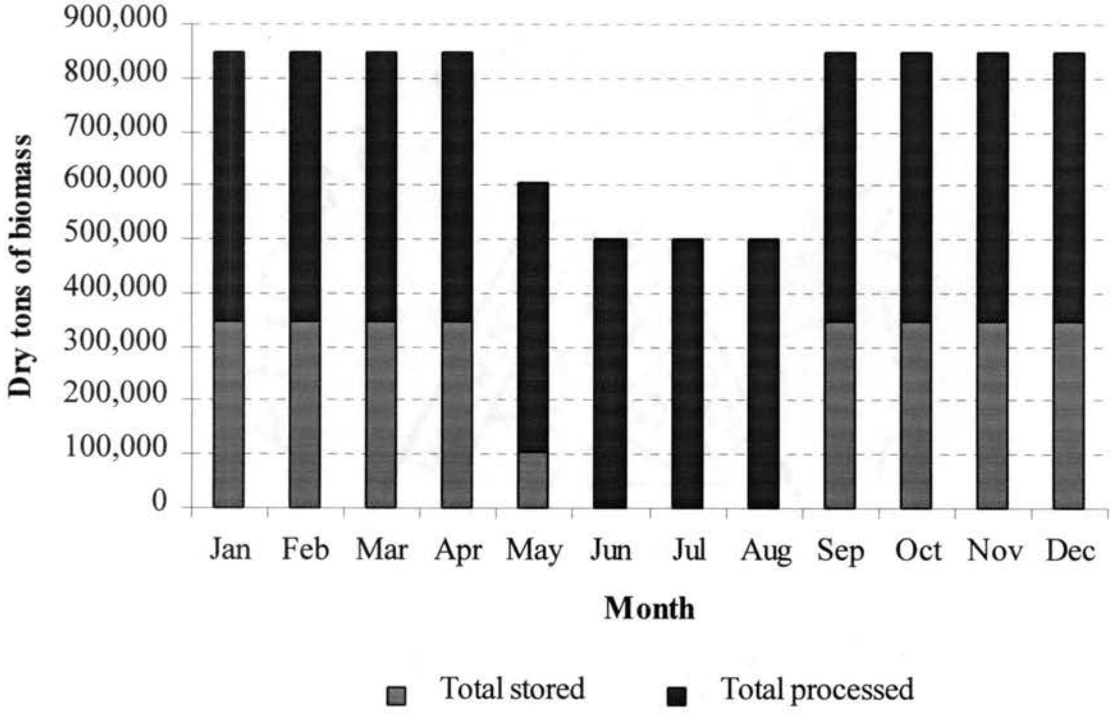

Figure 23. **Dry tons of biomass stored and processed at the plant sites when switchgrass establishment is permitted (Scenario IX)**

Table 55. Total acres of each feedstock species harvested monthly and annually, when switchgrass establishment is permitted (Scenario IX)

Feedstock species	Acres harvested/Month					Total	As a % of total
	Jun	Jul	Aug	Sep	Oct		
Wheat straw	214,970	0	0	0	0	214,970	10%
Tall native prairies	0	59,880	57,537	609,249	0	726,666	34%
Mixed native prairies	0	17,579	49,082	442,081	0	508,741	24%
Corn stover	0	0	0	0	9,760	9,760	0.5%
Short native prairies	0	3,352	7,648	31,812	0	42,812	2%
Bermudagrass (200 lbs. N)	0	8,373	0	49,173	0	57,547	3%
Tall fescue (200 lbs. N)	46,916	0	0	0	0	46,916	2%
Switchgrass	0	53,453	52,791	431,651	0	537,894	25%
Total harvested	261,886	142,637	167,057	1,563,966	9,760	2,145,305	100%

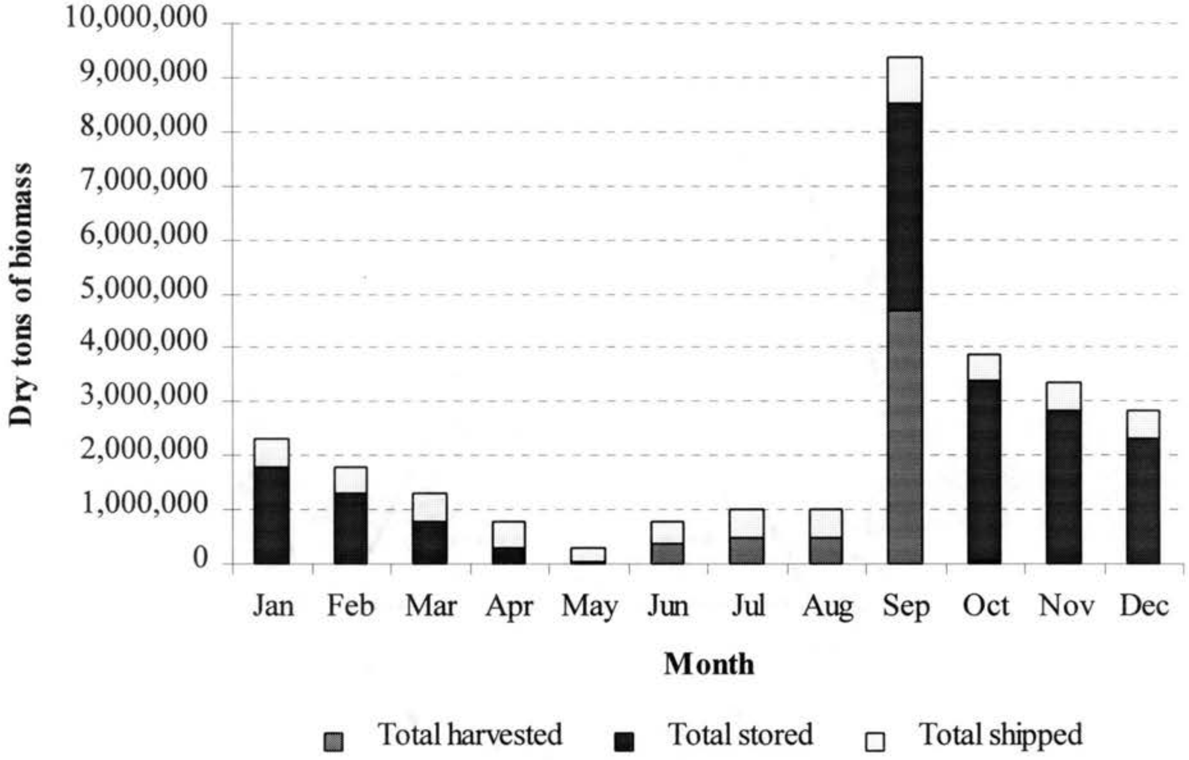

Figure 24. Total dry tons of biomass harvested, stored and shipped from all supplying counties in each month when switchgrass establishment is permitted (Scenario IX)

Table 56. Total acres harvested annually in each region of the state when switchgrass establishment is permitted (Scenario IX)

Region	Wheat straw	Corn stover	Tall native Prairies	Mixed native prairies	Short native prairies	Bermuda grass	Tall fescue	Switch -grass	Regional total	As % of total
Panhandle	35,680	9,314	0	0	0	0	0	0	44,994	2
Northwest	71,286	363	41,876	314,069	42,812	0	0	202,812	673,217	4
Northeast	0	0	325,384	17,126	0	0	45,543	166,898	554,951	45
Southwest	108,004	84	135,414	152,658	0	6,470	0	86,705	489,334	21
Southeast	0	0	223,993	24,888	0	51,077	1,373	81,480	382,810	30
State total	214,970	9,760	726,666	508,741	42,812	57,547	46,916	537,894	2,145,305	100

Table 57. Primary energy input and energy efficiency when switchgrass establishment is permitted (Scenario IX)

Activity/item	Total energy[a] (million Btu)	Btu/gallon of ethanol	As a % of total energy input	% change from base
Energy input				
Nitrogen fertilizer	462,956	772	16	8
Field activities	340,191	567	12	-38
Transportation	1,496,120	2,494	53	-16
Biomass grinding	543,320	906	19	0
Subtotal energy input	2,842,587	4,738	100	-14
Energy yield		78,000[b]	1600[c]	16[d]

[a] Based on six large plants, each operating at full capacity.

[b] Ethanol energy content estimate (Btu/gallon) adopted from Hohmann and Rendleman.

[c] System energy efficiency (output/input) ratio.

[d] Change in energy efficiency ratio.

VITA

Gelson Tembo

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Doctor of Philosophy

Thesis: INTEGRATIVE INVESTMENT APPRAISAL AND DISCRETE CAPACITY OPTIMIZATION OVER TIME AND SPACE: THE CASE OF AN EMERGING RENEWABLE ENERGY INDUSTRY

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