Economic and Environmental Contributions of Agricultural Lands to Timber Production in Minnesota

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Abstract

Sharply increasing timber prices in Minnesota reflect an imbalance in the age class distribution of the cover types that are most important to the forest industry. A scheduling model was used to allocate forest and agricultural lands to meet specified forest products demands in various locations and time periods. This research identified potential future timber supply shortages and examined the contributions that short-rotation tree crops grown on specific marginal agricultural lands can make in reducing such shortages. Tree production on agricultural lands provided additional benefits by allowing to reduce harvest on ecologically sensitive forest lands. Additional, direct environmental benefits from agricultural lands under tree cover were not examined.

Keywords: *Agricultural tree production, harvest scheduling,short-rotation forestry, timber supply costs.*

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Introduction

The demand for forest products has grown substantially in recent years and is expected to continue to grow well into the next century. Public concerns over forest industry expansion and its perceived negative impacts on the environment stimulated preparation of a Generic Environmental Impact Statement (Jaako Pöyry, 1992a) of timber harvesting in Minnesota which indicated potential problems in meeting existing and future timber demands in the state. These shortages are expected to be especially severe in aspen between the years 2008 to 2020. The main cause has been the lack of markets prior to 1980 which has resulted in a major age class imbalance. Aspen is the major species

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utilized by Minnesota forest industries with the largest concentration of oriented strand board (OSB) production in the world.

Hybrid poplar has been recognized as one possible solution to overcome the pending supply shortage. Experimentation of growing hybrid poplar began in the mid 1980s and was part of several biomass energy projects funded by the Department of Energy in several Lakes States. Later the interest shifted to producing hybrid poplar as a fiber source to complement native aspen supplies for paper and OSB. The private sector took the lead in promoting hybrid poplar plantations as a source of whole tree fuel for electric power generation. The Minnesota Department of Forest Resources planned and spearheaded the planting of several thousand acres of hybrid poplar in western Minnesota. In 1995, several major forest industries in Minnesota established the Hybrid Poplar Research Cooperative. Also a group of growers in central Minnesota formed the Minnesota Agro-Forestry Cooperative which has focused primarily on the production and sale of hybrid poplar trees.

Production of short rotation woody crops (SRWCs) on marginal agricultural lands such as those set aside under the Conservation Reserve Program (CRP) have the potential to produce timber products, thereby reducing harvest pressures on forest lands. Proponents argue that since most of the agricultural lands in the CRP are going to be released in the very near future, this is the right timing for adoption of policies which will encourage agricultural landowners to grow SRWCs. The use of agricultural lands adjacent to forest lands as fiber plantations might have a positive impact on the economy as well as on the environment. Growing timber could provide farmers with an additional cash crop. Soil erosion and water contamination concerns might also be reduced because of the relatively long rotation periods associated with SRWCs and reduced reliance on pesticides and herbicides which contribute to water contamination.

Before large investments into farm-grown trees are made, it must be understood how such developments would fit with the existing economic and environmental conditions found in Minnesota. In this research, we examine spatial and dynamic interactions among forest resources, agricultural land, and timber production. The linking of location specific agricultural and forestry land resources and production decisions adds a new dimension to previous planning efforts. Expected future timber products demand in six forest markets are modeled for ten 10-year planning periods using forest lands and agricultural lands. Two sets of forest management options representing traditional and environmentally restricted management practices are used, along with hybrid poplar production on agricultural lands. Estimates of transportation costs are generated using actual road distances between analysis areas and the market locations.

This research determines the expected marginal costs, and the location and acreage of lands harvested in each planning period to meet expected timber product requirements at each market, when (1) only commercial forest lands managed under traditional management practices are used, (2) only commercial forest lands with new environmentally sensitive management practices are used, (3) both agricultural and commercial forest lands managed under traditional and environmentally sensitive management alternatives are used.

Harvest Scheduling Model

Generally, the computation size of harvest scheduling model depends on the number of product types, analysis areas, markets and planning periods considered in the formulation. The computational solution becomes more and more difficult as the level of detail incorporated in the model is increased because of the multiplicative effect on the number of constraints and decision variables. A scheduling problem with enough detail to ensure a realistic solution can result in millions of decision variables and thousands of constraints. This can make the problem economically and computationally difficult, if not impossible to solve. These problems are generally avoided by using high levels of data aggregation which compromise the authenticity of the solution obtained.

Hoganson & Rose (1984, 1989) developed a multi-product and multi-period forest management and harvest scheduling model known as DUALPLAN. This model has the ability to solve large forest management scheduling problems and allows for a much greater level of detail than the traditional forest management models. The model used in this study is an extension of DUALPLAN which was later modified to recognize alternative market location and implemented as a computer software program DTRAN (Hoganson & Kapple, 1991). The theoretical formulation of DTRAN, can be understood by considering the following harvest scheduling problem.

$$\text{Primal} \quad \underset{X}{\text{Minimize}} \quad \sum_{i=1}^{I} \sum_{j=1}^{Ji} C_{ij} X_{ij} \tag{1}$$

S. T.

$$\sum_{i=1}^{I} \sum_{j=1}^{Ji} V_{ij} ptm X_{ij} \geq D_{ptm} \qquad \forall ptm$$

$$\sum_{j=1}^{Ji} X_{ij} \leq A_i \qquad \forall i$$

$$X_{ij} \geq 0 \qquad \forall ij$$

Where:

A_i =the number of acres of stand type i that are present in the initial period,

C_{ij} =discounted cost of assigning an acre of stand type i to prescription j. Thisincludes all additively separable costs such as production, harvesting and transportation,

j =a prescription describes all management actions over the entire planning horizon for a specific combination of each product and market,

D_{ptm} =exogenous demand for product p, in time period t, for market m,

I = number of stand types,

J_i = number of management options for stand type i,

V_{ijptm}=the per acre yield of product p, in time period t, for market m from stand typei, if management option j is implemented, and

X_{ij}=number of acres of stand type i assigned to management option j.

The first set of constraints requires the product output levels (demands) to be achieved in each planning period for each market. The second set ensures that the acres in a given analysis area are greater than or equal to the sum of acres assigned to each of its possible management options. Each analysis area has one constraint and it protects against over allocation of land base. The non-negativity of the decision variables is satisfied by the third set of constraints. The product output level constraints are generally less than the analysis area constraints, but they are significant in terms of holding the problem together, for without them, the problem for each analysis area could be solved independently. The Lagrangian function associated with this minimization problem is:

$$L\left(X_{ij}, \lambda_{ptm}, \phi_i\right) = \sum_{i=1}^{I} \sum_{j=1}^{J_i} C_{ij} X_{ij} + \sum_{p=1}^{P} \sum_{t=1}^{T} \sum_{m=1}^{M} \lambda_{ptm} \left(D_{ptm} - \sum_{i=1}^{I} \sum_{i=1}^{J_i} V_{ijptm} X_{ij} \right) + \sum_{i=1}^{I} \phi_i \left(\sum_{j=1}^{J_i} X_{ij} - A_i \right) \quad (2)$$

The Kuhn-Tucker first order necessary and sufficient conditions are as follows:

$$\frac{\partial L}{\partial X_{ij}} = C_{ij} - \sum_{p=1}^{P} \sum_{t=1}^{T} \sum_{m=1}^{M} \lambda_{ptm} V_{ijptm} + \phi_i \geq 0 \quad \forall\, i,j$$

$$\frac{\partial L}{\partial X_{ij}}\left(X_{ij}\right) = \sum_{i=1}^{I} \sum_{i=1}^{J_i} X_{ij} \left(C_{ij} - \sum_{p=1}^{P} \sum_{t=1}^{T} \sum_{m=1}^{M} \lambda_{ptm} V_{ijptm} + \phi_i \right) = 0$$

$$X_{ij} \geq 0 \quad \forall\, i,j$$

$$\frac{\partial L}{\partial \lambda_{ptm}} = D_{ptm} - \sum_{i=1}^{I} \sum_{i=1}^{J_i} X_{ij} V_{ijptm} \leq 0 \quad \forall\, p,t,m$$

$$\frac{\partial L}{\partial \lambda_{ptm}} \left(\sum_{p=1}^{P} \sum_{t=1}^{T} \sum_{m=1}^{M} \lambda_{ptm} \right) = \sum_{p=1}^{P} \sum_{t=1}^{T} \sum_{m=1}^{M} \lambda_{ptm} \left(D_{ptm} - \sum_{i=1}^{I} \sum_{i=1}^{J_i} X_{ij} V_{ijptm} \right) = 0$$

$$\lambda_{ptm} \geq 0$$

$$\frac{\partial L}{\partial \phi_i} = \sum_{j=1}^{J_i} X_{ij} - A_i \leq 0 \quad \forall\, i$$

$$\frac{\partial L}{\partial \phi_i} \left(\sum_{i=1}^{I} \phi_i \right) = \sum_{i=1}^{I} \phi_i \left(\sum_{j=1}^{J_i} X_{ij} - A_i \right) = 0$$

$$\phi_i \geq 0$$

The Lagrange multipliers associated with the output level constraints are λ_{ptm}. These constraints reflect the cost of producing one additional unit of product type p, in time period t, for market m. These multipliers can be interpreted as the shadow prices or marginal costs of production. They include all direct and indirect costs associated with the production and shipment of a given product. There is a direct relationship between these marginal costs and the product output levels. Generally, an increased level for product outputs will result in increased marginal costs and vice versa. The ϕ_i are the Lagrange multipliers associated with the initial area constraints. These are the estimates of the change in the cost of producing required output levels if an additional unit of land corresponding to a given stand type were available.

If a solution exists for the above model, then it would be feasible and optimal. Unfortunately, this solution would require a compromise between the problem size and the level of detail incorporated within the model because of computational limitations. Hoganson & Rose (1984, 1989) suggest that an approach based on the concept of Lagrangian relaxation can be utilized to overcome this problem. A Dantzig-Wolfe decomposition method as described by Nazareth (1980) and a Frank-Wolfe decomposition approach by Gunn *et al*. (1987) use linear programming (LP) to derive optimal solutions. We are certain that problems of the size we are analyzing in this study cannot be handled by Dantzig-Wolfe but can probably be solved by the methodology proposed by Gun *et al*. (1987) which is closely related to the Hoganson-Rose method. Hoganson & Rose (1984) argue that the maintenance of strict feasibility for harvest scheduling models as required by the above model formulation imposes an undue burden on the computational facilities with little gain. Their rationale is that product demands for the future planning periods are approximations at best and therefore, if slight deviation from these output levels provide a close to optimal solution, then it should be an acceptable solution. The DTRAN strategy can be best explained by examining the dual of the forest management scheduling problem developed above:

$$\text{Dual (1)} \qquad \underset{\phi \quad \lambda}{\text{Maximize}} \sum_{p=1}^{P} \sum_{t=i}^{T} \sum_{m=1}^{M} D_{ptm} \lambda_{ptm} - \sum_{i=1}^{I} A_i \phi_i$$

S. T.

$$\sum_{p=1}^{P} \sum_{t=i}^{T} \sum_{m=1}^{M} V_{ijptm} \lambda_{ptm} - \phi_i \le C_{ij} \qquad \forall ij$$

$$\lambda_{ptm} \ge 0 \qquad \forall ptm$$

$$\phi_i \ge 0 \qquad \forall i \tag{3}$$

Where:

P = number of product types,

T = number of planning periods,

M = number of markets,

λ_{ptm} = Lagrange multiplier associated with the primal problem output level constraints,

ϕ_i = Lagrange multiplier associated with the primal problem initial area constraints.

This formulation can be explained as the problem of a principal who wants to purchase all the land from the landowners and in return sell them the outputs from the land. The principal's problem is to determine the price for each output in each planning period for each market (λ_{ptm}) and the compensation to offer for the purchase of each stand type (ϕ_i), so that profits are maximized. The principal's offer price for the purchase of stand types should be such that the landowners consider it profitable to sell the land instead of managing it themselves.

The strategy employed by DTRAN is to make use of the relationships between the primal and the dual in its solution process. It assumes that economic intuition and forecasts outside the model provide some estimates about the future product prices — all the λ_{ptm} variables in the above formulation. This assumption reduces the dual to the following:

$$\text{Dual (2)} \qquad \underset{\phi}{\text{Minimize}} \sum_{i=1}^{I} A_i \phi_i$$

S. T.

$$\phi_i \ge \sum_{p=1}^{P} \sum_{t=1}^{T} \sum_{m=1}^{M} V_{ijptm} \lambda_{ptm} - C_{ij} \qquad \forall\, ij$$

$$\phi_i \ge 0 \qquad \forall\, i \tag{4}$$

This problem can be explained as the principal's problem who wants to minimize land purchase costs. Each constraint represents a lower bound on ϕ_i. This problem can be easily solved by choosing the lowest bound for each ϕ_i. Even though there are J_i constraints on each ϕ_i, since they all represent lower bounds, so all but the lowest will be redundant. The right hand side of each constraint is simply a cash flow analysis of its corresponding management option evaluated by using estimates of shadow prices for each product type. This constraint basically states that the marginal value of each analysis area should be at least as much as the value of any of its management alternatives when evaluated by using shadow prices λ_{ptm}. The actual simulation approach of DTRAN is to follow these steps:

(1) Use outside the model economic forecasts to predict marginal cost of production for each product, in each market, for each planning period i.e., λ_{ptm}.

(2) Use these estimates of λ_{ptm} to solve for the remaining dual variables ϕ_i in Dual (2).

(3) Find the X_{ij}'s in the primal problem that correspond to the optimal dual solution. This solution may not necessarily be feasible.

(4) Calculate the product output levels for the primal solution found in step (3) and test it for feasibility. If the product output levels are close to the desired output levels stop, the primal solution will be a near feasible optimal solution. Otherwise go to step (5).

(5) Re-estimate the shadow prices λ_{ptm} by examining the relationship between the product output levels determined in step 4 and the prior shadow price estimates. Make appropriate changes and return to step (2).

DTRAN requires the estimation of certain variables outside the model. All fixed and variable costs, product types and product quantities from each analysis area under a given set of management options over the entire planning horizon need to be estimated. These estimates are generated by a prescription writer and a transportation cost model discussed below.

SCHEMATIC OVERVIEW OF MODELING FRAMEWORK

Given the data and the modeling system presented in this paper, we are in a position to link the data to the models.

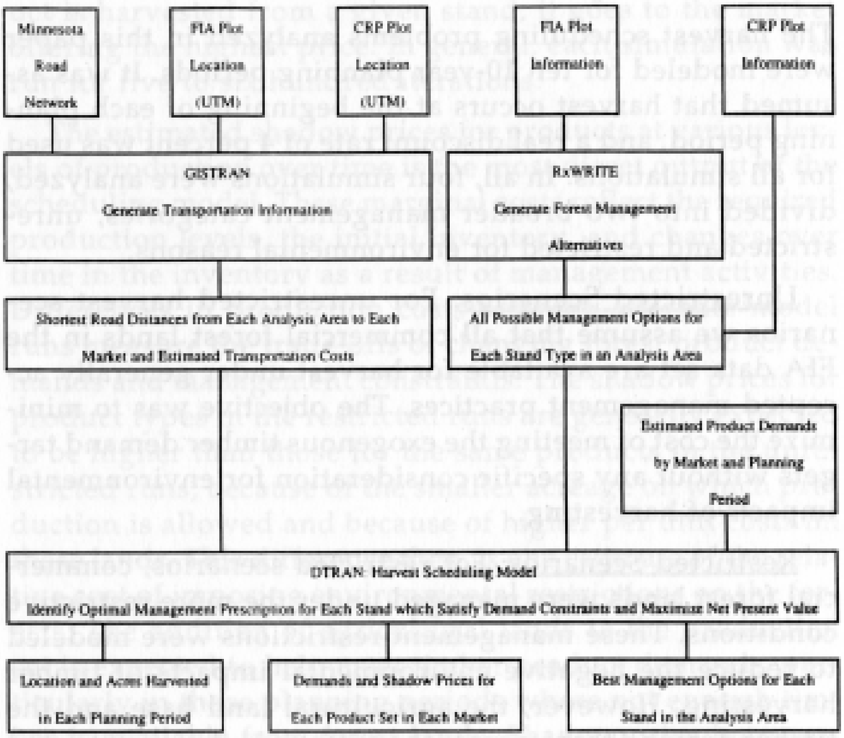


FIGURE 1: A FLOWCHART OF MODELING AND DATA COMPONENTS.

Figure 1 presents a flowchart of this linkage. All location information for the markets, forest analysis areas, and agricultural analysis areas are evaluated by GISTRAN. It uses a road network to determine the transportation distance and costs for all product flows. The management alternatives for forest lands are analyzed by RxWrite. The output is the volume of each product produced under a given management alternative and its expected costs. The management alternatives for agricultural lands were determined outside RxWrite. The output from GISTRAN and RxWrite is input into DTRAN along with the exogenous product demands for all the markets in each planning period. DTRAN determines the best management alternative for each analysis area and determines the location of all harvested acres. DTRAN also estimates the shadow prices for each product type, in each market and planning period.

Simulation Design

The harvest scheduling problems analyzed in this paper were modeled for ten 10-year planning periods. It was assumed that harvest occurs at the beginning of each planning period, and a real discount rate of 4 percent was used for all simulations. In all, four simulations were analyzed, divided into two broader management categories, unrestricted and restricted for environmental reasons.

Unrestricted Scenarios: For unrestricted harvest scenarios we assume that all commercial forest lands in the FIA data set are available for harvest under generally accepted management practices. The objective was to minimize the cost of meeting the exogenous timber demand targets without any specific consideration for environmental impacts of harvesting.

Restricted Scenarios: For restricted scenarios, commercial forest lands were managed under the more restrictive conditions. These management restrictions were modeled to reduce the negative environmental impacts of timber harvesting. However, the agricultural land base and the timber demand targets were the same as in the unrestricted scenarios:

COMPUTATION OF SIMULATIONS

The output for each run provided the estimates of product shadow prices, deviations from product demand targets, the location and amount of acres harvested, and the variable costs associated with each planning period and market. Every simulation had 220 product flow constraints, reflecting the demand for each product set in each market and planning period. Each simulation was run until an acceptable solution was found. The runs were judged acceptable when the deviations from the product demand targets in all markets and planning periods were within 5 percent. There were two exceptions to this rule: (1) when the demand targets for a given product were not met because of actual physical supply shortages, and (2) when the flow for a given product flip flops between iterations even with very small changes in the shadow prices. In some cases, a change of less than a penny between iterations could in fact change the procurement zone for a given product. This is because DTRAN does not allow stand splitting. If a product is harvested from a given stand, it goes to the market offering the highest price. In general, each simulation was run for five to six hundred iterations.

The estimated shadow prices for products at various levels of production over time is the most direct output of the scheduling model. These marginal costs reflect the required production levels, the initial inventory, and changes over time in the inventory as a result of management activities. Differences in production costs between alternate model runs measure the trade-offs of changing forest product demands and management constraints. The shadow prices for product types in the restricted runs are generally expected to be higher than those for the same products in the unrestricted runs, because of the smaller acreage on which production is allowed and because of higher per unit costs on these lands. This difference then, is one estimate of the relative cost of imposing environmental restrictions on the forests. The addition of agricultural lands to the production set is expected to help meet timber product demands, particularly in those planning periods where not enough timber is available from forest lands. Shadow price increases reflect shortages in specific timber products brought on by age class imbalances in the inventory. Simulation results for aspen, for which the age class imbalance is most pronounced in Minnesota, are presented in the following section.

Data and Models

Prescriptions Writer

Scheduling models such as DTRAN require detailed input in terms of physical and economic flows associated with all the management options for a given analysis area for all the planning periods. The physical flows provide information about the timing, quantity, and type of product that can be harvested from a certain analysis area managed under a specific set of management alternatives or prescriptions. The economic flows represent the associated production and harvesting costs. For the model discussed above, wood volumes (V_{ijptm}) and the production and harvesting components of C_{ij} are determined by the prescription writer.

Management options are defined by the analyst: minimum and maximum rotation ages, types and timing of thinning and harvesting, types of regeneration (natural or artificial), and the costs associated with each activity. The range of management options available for a given analysis area may vary by initial stand age, stand conditions, product specifications, growth and yield relationships, and other economic, environmental, and ecological reasons. It is necessary that all possible options must be specified in a scheduling model before it can determine which options can optimally meet the forest wide objectives.

RxWrite (McDill & Rose, 1991), a set of software programs compatible with DTRAN, was used to develop all the management prescriptions necessary for calibrating DTRAN. The prescription writer simulates harvesting and three types of thinnings: from above, from below, and random. For thinning or selective cutting, RxWrite simulates growth of the remaining trees. It utilizes all stand-level inventory data including individual tree records. The Stand and Tree Evaluation and Modeling System (STEMS) which was developed by the USDA Forest Service (Belcher *et al.*, 1982) is used to simulate tree growth over time. A wide range of options concerning thinning intensity, timing and frequency can also be specified by the decision maker. Standard regeneration tree lists, applied following clear cutting, can vary by cover type, site index, and type of regeneration. The transition of stands after clear cutting through natural regeneration is modeled using an empirical matrix of cover type transition probabilities.

Once all the system parameters were set, the model was used to simulate sets of specified management options for a given stand or group of stands. The output from these simulations was converted into input files for later use by DTRAN.

Transportation Modeling

Transportation costs are calculated and input into DTRAN using GISTRAN (Kapple & Hoganson, 1991). This model provides estimates of transportation costs from each analysis area to each defined market. Two databases are used in GISTRAN: one containing all major links in Minnesota's transportation network and one that contains the location of all markets and production analysis areas. All locations (roads, analysis areas and markets) are identified by Universe Transverse Mercator (UTM) coordinates.

In GISTRAN, the lowest cost routes from each analysis area to each market in the study area are generated by using Dijkstra algorithm (Papadimitriou & Steiglitz, 1982). The algorithm, based on graph theory, finds the shortest path from one node (road intersection) to all other nodes in the network. A complete description of the Dijkstra algorithm can be found in Horowitz & Sahni (1976).

In order to calculate the distance from an analysis area to the nearest point on the road network, the identifier of the closest arc (road segment), the distance to the closest arc, and the distance from the nearest point on the closest arc to the beginning of the closest arc were calculated. This procedure, which is largely automated, can be summarized in the following five steps (Kapple, 1995).

(1) Calculate the distance from each analysis area to each node in the road network and make a list of 16 closest nodes.

(2) Make a list of arcs incident on these nodes.

(3) For each arc in the list, calculate the distance from the analysis area to each point along the arc and make an ordered list of eight closest pairs of adjacent points.

(4) Calculate the perpendicular distance from the analysis area to the line segment defined by each pair of adjacent points in the list.

(5) If the plot is closer to the current arc, update nearest arc information.

Once all the relevant distances are determined, then the calculation of transportation costs is straightforward. These costs then become the third component of C_{ij} in the harvest scheduling model.

Market Locations and Timber Products Demand

Six aggregated forest product markets are considered in this study. These markets are assumed to be located in Brainerd, Bemidji, Cook, Duluth, Grand Rapids, and International Falls. These locations represent the concentration of major forest industries in Minnesota. The timber product requirements modeled in this study are similar to those modeled

Table 1: Aggregated Annual Timber Product Demands by Market (thousands of Cords).

	Market						
Produkt	Bemidji	Brainerd	Cook	Duluth	G. Rapids	I. Falls	*Total*
Aspen	580	319	203	590	519	458	2669
Pine							
Pulpwood	57.78	-	-	162.78	-	42.78	263.34
Spruce	-	100	-	379.5	163.5	-	643
Northern Hardwoods	89	198	59	355	69	49	819
Pine Bolts and Sawlogs	102.61	27.61	27.61	27.61	27.61	27.61	240.66
Total	829.39	644.61	289.6	1514.9	779.11	577.39	4635

in the Minnesota GEIS medium scenario (Jaakko Pöyry, 1992a). These demands reflect the future raw material requirements of the existing forest industries as well as those which are projected to begin production in 1997. Table 1 shows the summary of modeled timber products demand by market. For this research, these demands are treated as exogenous to the market and enter as the constraint constants in the harvest scheduling model. The aggregated aspen product set reflects the demand for both aspen sawlogs and pulpwood. The demand for pine pulpwood and pine bolts and sawlogs was modeled separately because of differences in their prices and physical qualities. Since the demand for pine bolts and sawlogs in individual markets is relatively small therefore only the total demand of 240.66 thousand cords was modeled in this study. The spruce product set represents the demand for spruce bolts and pulpwood. The northern hardwoods sets reflect the demand for sawlogs, pulpwood and red oak sawlogs.

Agricultural Land Database

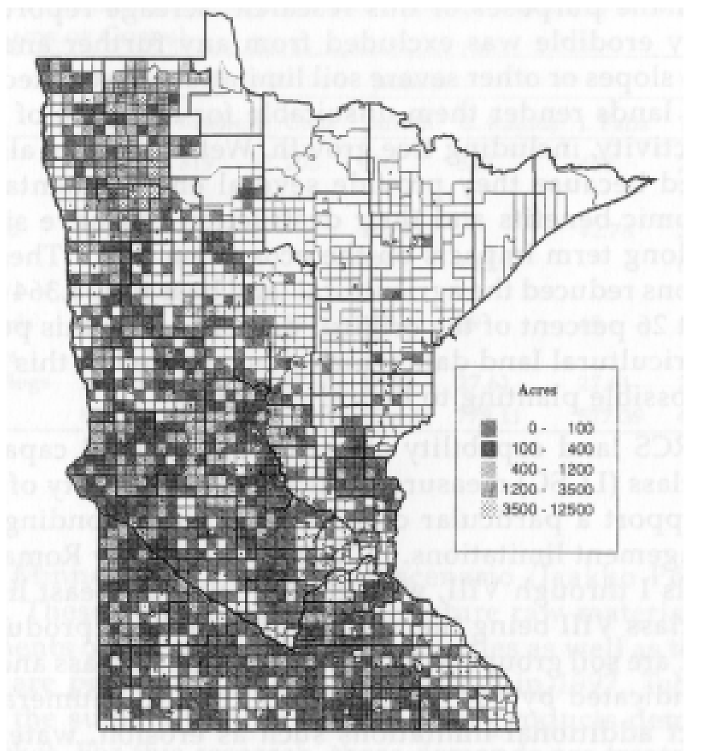
The farm land data set for this study was obtained from the Minnesota Department of Agriculture (MDA). This tabular database was created by each county's Farm Services Agency (FSA) office by running a standard query on county CRP records in September of 1994. According to FSA's summary statistics, there are 1.8 million acres of land enrolled in Minnesota.

For the purposes of this research, acreage reported as highly erodible was excluded from any further analysis. Steep slopes or other severe soil limitations associated with these lands render them unsuitable for any type of farming activity, including tree growth. Wetlands were also excluded because they provide several environmental and economic benefits and their destruction can have significant long term impacts on the ecosystem itself. These exclusions reduced the agricultural land base to 438,364 acres, about 26 percent of the original database. It is this portion of agricultural land data which was modeled in this study for possible planting to hybrid poplar.

NRCS land capability class (LCC) and land capability sub-class (LCSC) measures indicate the suitability of a soil to support a particular crop and the corresponding crop management limitations. LCC are indicated by Roman numerals I through VIII, with class I being the least limited and class VIII being the most limited for crop production. LCSC are soil groups within a land capability class and they are indicated by adding a letter to the LCC numeral and reflect additional limitations such as erosion, water, soil type and climate.

Data on combinations of land capability classes and subclasses was aggregated on the basis of geographical location of the CRP parcels. The acreage of all land parcels within the same township with exactly the same combinations of land class and subclass was aggregated to calculate the total acreage of that combination for the specified township. Essentially, then a "land unit" for this study's purposes is all lands in a township that share a common LCC and LCSC.

The UTM coordinate system was used to represent the location of the aggregated land parcels within a township. Each parcel was treated as if it was located at the geographic center of the township. These coordinates provided the linkage between the land parcels and the transportation network (GISTRAN) used in this analysis. UTMs were calculated using a software known as SECTIC-24K, developed by the Minnesota Land Management Information Center (LMIC 1995). Map 1 shows the acreage of CRP lands by township considered in this analysis.



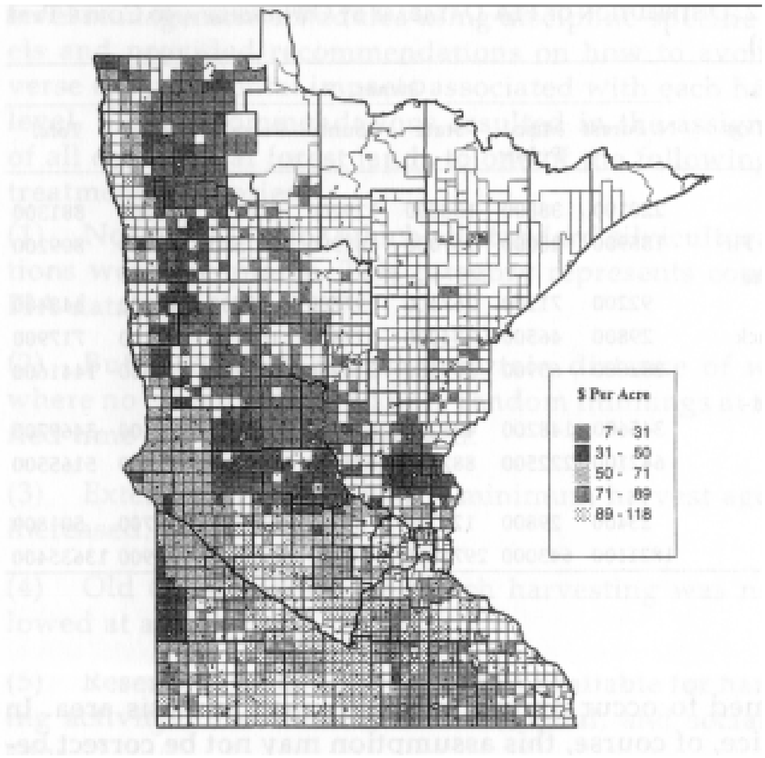
MAP 1: ACREAGE OF AGRICULTURAL LANDS BY TOWNSHIP.

Opportunity Cost of Landowner's Participation

Annual cash rental rates were used to determine the land owner's opportunity cost of participation in a program to grow hybrid poplar. These per-acre rental rates were calculated for each township from the 1995 estimates of average market value of tillable land (AMVTL), total agricultural tillable land (TATL) and the capitalization rate for a specified region (4 % in this case). Capitalization rate is defined as the average estimated cash rent as a percentage of the county assessor's estimated market value of the farmland. Estimates of county level AMVTL and TATL were reported by Lazarus (1995). For this research, the following relationship was used to calculate the per acre cash rental rates for each civil township:

$$(AMVTL/TATL) * CAPRATE = RENT/ACRE$$

Estimated per acre rental rates for all the townships are presented in Map 2. These rates range between $7/acre and



MAP 2: ESTIMATED ANNUAL CASH RENTS BY TOWNSHIP ($/ACRE).

$118/acre. Lower rental rates are associated with poorer agricultural lands in the north-central and northern regions of Minnesota. The higher rental rates represent prime agricultural land in the south, south-west and west central parts of the state.

Minnesota Forest Inventory Analysis Database

The data representing the forest sector in this research was taken from the latest North Central Forest Inventory and Analysis (NCFIA) project conducted by the USDA Forest Experiment Stations. This is the latest form of disaggregated forest data available for Minnesota. The northern portion of the state is represented by 11,184 individual sample plots. Each plot represents about 1,000 to 1,500 similar acres. In all, over 13 million acres are represented in the data set. All similar stands represented by a given sample plot are treated identically in the model and are considered as a single analysis area. Management activities are

TABLE 2: DISTRIBUTION OF FIA DATABASE BY OWNERSHIP AND COVER TYPE (ACRES).

	Owner						
COVER TYPE	N. Forest	Misc. Public	State	County	Private	Forest. Industry	*Total*
Pines	220100	38800	158000	129200	248800	86400	881300
Balsam Fir	185900	20000	167000	181900	182500	71900	809200
N. White Cedar	92200	71300	267500	97700	70700	49000	648400
Tamarack	29800	46500	334000	127800	100700	9100	717900
Spruce	282000	65900	599400	218100	200700	75500	1441600
N. Hard-woods	345600	148200	435200	615300	1786500	138900	3469700
Aspen	642100	222500	887200	1034100	2086200	293400	5165500
Balsam Poplar	23400	29800	127700	88500	206700	25700	501800
Total	1821100	643000	2976000	2492600	4952800	749900	13635400

assumed to occur uniformly across each analysis area. In practice, of course, this assumption may not be correct because of the heterogeneity within a given analysis area or if the number of analysis areas is not significant. However, large data sets can sufficiently smooth the results to provide a strong statistical basis for this assumption.

The FIA data set also provides detailed information about forest land ownership, cover type, and age class distribution. The summary of major ownership classes by cover types are presented in Table 2. The acreage of aspen and northern hardwoods is substantially greater than any other cover type. Although the forest industry is the largest consumer of timber, it owns the least amount of land. Most of the forest land in northern Minnesota is publicly owned. The private ownership is about 36 percent and the Superior and Chippewa National Forest own about 13 percent of the total land.

In the Minnesota GEIS, wildlife, recreation, water, soils, and biodiversity experts were given a detailed description of forest management activities based on an initial set of simulations. These descriptions included the timing and location of all scheduled forest management activities at each planning interval. The experts analyzed the stand-level management schedules using discipline-specific models and provided recommendations on how to avoid adverse environmental impacts associated with each harvest level. Their recommendations resulted in the assignment of all commercial forest lands to one of the following five treatment categories:

(1) Normal: Plots for which all standard silvicultural options were acceptable. This category represents complete FIA data set.

(2) Buffered: Plots within a certain distance of water, where no clear cutting and only random thinnings at specified time intervals were allowed.

(3) Extended: Plots on which minimum harvest age was increased.

(4) Old Growth: Plots on which harvesting was not allowed at all.

(5) Reserved: Plots which were not available for harvesting activity for economic, environmental, and social reasons.

In this study, two types of forest management prescriptions were modeled: "unrestricted" and environmentally "restricted". For the restricted management simulations, the FIA database was truncated by 1,028,000 acres, consisting of over one thousand analysis areas that fell into the reserved treatment classification. These forest lands were excluded from any harvesting activity in order to provide provisions for environmental services. Furthermore, no-clear-cutting constraints were imposed on forest lands in buffered and old growth treatment classes. These constraints are especially restrictive because thinnings or selective cuttings are generally more expensive than clear cutting on a per unit basis.

Availability of forest lands for harvesting varies by owner. Small private owners have varying management objectives and income needs. Environmental concerns also exclude timber production on much of the public forest land. Availability was implemented in the model by randomly removing stands from the forest base with availability varying by ownership. Note that about 27 percent of miscellaneous public lands are reserved while no land is

TABLE 3: DISTRIBUTION OF FIA DATABASE BY OWNERSHIP AND TREATMENT CLASS (ACRES).

OWNER	TREATMENT					
	Normal	Buffers	Extended	Old Growth	Reserved	*Total*
N. Forests	1315800	112900	364900	27500	0	1821100
Misc. Public	402600	10200	0	0	230200	643000
State	2127200	99800	597300	0	151700	2976000
County	2224300	141800	0	0	126500	2492600
Other Private	4188400	263600	0	0	500800	4952800
F. Industry	723700	7400	0	0	18800	749900
Total	10982000	635700	962200	27500	1028000	13635400

reserved in the national forests. Extended rotations are generally applied on the state and the national forest lands. Buffered lands in all ownership categories are less than five percent. There are no old growth limitations in any category except the national forests. Table 3 shows the distribution of FIA database by treatment class and ownership.

Hybrid Poplar

For this study, agricultural landowners are modeled as if they face a choice: (1) don't grow trees and rent the land or (2) grow hybrid poplar and sell it to forest product markets. Since hybrid poplar and aspen have similar product characteristics, it is assumed that they can be substituted for each other in all markets. In compliance with existing practices, an 8 X 8 spacing and an optimal rotation age of 10 years is assumed.

On going research on intensively managed plantations provides some reliable information on the production potential of short-rotation hybrid poplar clones. In Minnesota, yield rates are expected to range between 2 to 5 dry tons/acre/year, according to soil and climatic conditions. These estimates are mostly derived from a network of research plantations which were established in a five state region of the north central U.S during the 1980s (Hansen et al 1994). In the present study, yield rates are modeled as a function of NRCS land capability classes and subclasses, rainfall, and soil types. In general, soils with a higher productivity rating (a lower LCC number) for agricultural crops will also be more suitable for hybrid poplar. However, this link is not expected to hold for soils with poor drainage conditions, because hybrid poplar still tends to grow well under such conditions (Berguson, 1994).

For the purposes of this study, hybrid poplar yield rates for all agricultural land parcels were determined by consultation with researchers at the US Forest Service hybrid poplar project at Rhinelander, Wisconsin. The average for the entire study area was 3.5 dry tons per acre (one dry ton is approximately equal to one cord). There are 10 different yield levels which reflect all the land capability class and sub-class combinations. The minimum and the maximum yields considered are 2.2 and 5 dry tons respectively.

Estimates of variable production costs for hybrid poplar production were obtained from the Natural Resources Research Institute (NRRI), based on actual cost data associated with a network of plantations in Minnesota and Wisconsin. Table 4 shows the break down of these production costs for the first three years of operation. In general most expenses incurred in the production of hybrid poplar occur during the establishment phase. After successful establishment usually there are no other significant costs until

Table 4: Production Cost Estimates for Hybrid Poplar ($/acre).

Activity	Cost	Year
Clip/Mow	7.50	0
Herbicide	20.00	0
Plow	13.42	0
Disk	14.00	0
Plant Cover	7.50	0
Cover Seed	3.00	0
Harrow	10.00	1
Planting	34.00	1
Cutting	68.00	1
Herbicide	20.00	1
Cultivation	11.19	1
Herbicide	24.00	2
Fertilization	30.00	3
Land Rent	variable	1-10

Source: Berguson (1994)

harvest. The only exception might be in case of disease which may result in additional costs but are not modeled in this research.

Harvest and Transportation Costs

Harvest and transportation costs are extremely significant components of the timber production process. In general, transportation costs are approximately one third of the total costs associated with the procurement of timber. In some cases these costs can be actually higher than the stumpage value of a given stand. Despite this, transportation costs are often not considered in the timber management and modeling studies. This omission can be justified because a given timber stand might produce several products, each of which may have several market destinations. Incorporating multiple products and market locations along with the traditional complexities of long term planning usually makes the transportation problem unmanageable in the context of harvest scheduling.

Forest harvesting costs vary by several factors which makes their estimation difficult. The location, condition, area, volume, and harvest type (thinning or clear cutting) are some of the factors which influence harvesting costs. Generally these factors differ on a stand by stand basis and therefore, using a fixed per acre estimate of harvesting costs in the modeling process is generally not realistic.

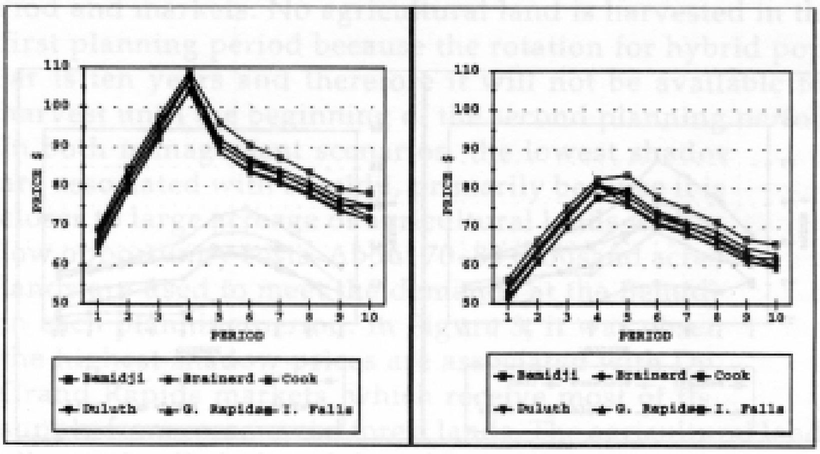
In this study, a specific harvest cost model was implemented which accounted for factors such as clear-cut or thinning, average tree size, volume per acre, off road distance, and total volume harvested. This model was specifically designed for the forest harvest conditions encountered in Minnesota (Jaakko Pöyry, 1992b). The model starts with a base harvest cost of $22 per cord, which is then adjusted to reflect stand characteristics. All stands are individually assessed by the model and the output is used as the harvesting cost estimates. The resulting estimated harvesting costs ranged between 16 and 29 dollars per cord for thinning and between 11 and 22 dollars per cord for clear cutting. In addition to the above harvesting costs, a loading cost of $4.75 per cord and a one way transportation cost of $0.15 per cord per mile was applied to all harvested products.

In Minnesota, data on hybrid poplar harvesting costs is rare because most of the large scale plantations are still below harvesting age. Therefore, this study utilized harvesting cost estimates generated by the Oak Ridge National Laboratories (ORNL) for the Great Lakes region (Walsh, 1994). Appropriate adjustments were made to reflect the regional conditions and specific assumptions of this research. The accuracy of the adjusted harvest cost estimates was determined by using the above harvesting cost model as well as discussions with the experts in this field. The conventional harvest costs were estimated to be \$450 per acre with an additional loading and processing cost of 4.75 per dry ton.

Results

Aspen

The demand targets for aspen products in any of the six markets could not be met when only forest lands were available for harvest. Figure 2(a) and (b) illustrates the aspen shadow prices for the six markets and planning periods when only commercial forest lands, managed with and without environmental restrictions, were available for harvest. The shadow prices in all markets rise over the first five periods, then begin to decline. In spite of relatively



(a): Scenario with forest management restrictions. (b): Scenario without forest management restrictions.
Note: * indicates infeasible cases

Figure 2: Aspen Shadow Prices - Only Forest Lands* (\$/cord).

high shadow prices, the average deviations from the demand goals in all markets and initial planning periods was as much as 30 percent. This case demonstrates the situation where demand is not met because of actual physical supply limitations. Further increase in shadow prices at any given market does not ensure additional product supply. In such situations, shadow prices are meaningless, in that they do not reflect the actual marginal costs of delivered products. Future supply cannot be met and forest industries either will have to reduce production through partial or total shut-down or will have to rely on additional supplies generated through imports, or the use of intensified or short-rotation forestry on forest and/or agricultural lands.

The introduction of agricultural lands for hybrid poplar production changes the results substantially. Since there is little difference between the physical and chemical properties of aspen and hybrid poplar, they can be modeled as if their markets were identical. Figure 3 (a) and (b) depicts the aspen shadow prices when agricultural lands are added to the forest lands managed with and without environmental restrictions. The inclusion of agricultural lands substantially reduces aspen shadow prices for both scenarios. The demand targets for all markets and planning periods are satisfied. Shadow prices for both scenarios generally rise for the first four periods before they begin to steadily de-

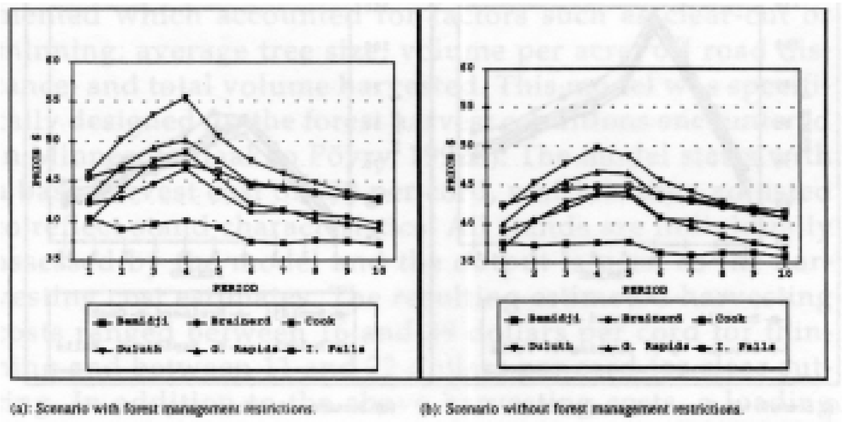
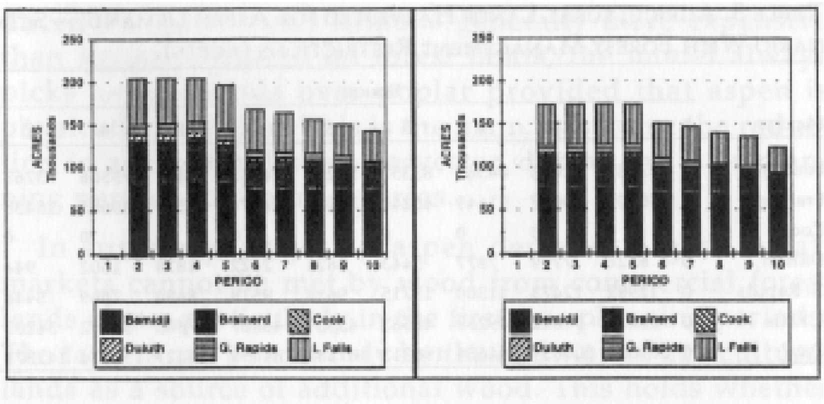


FIGURE 3: ASPEN SHADOW PRICES — FOREST AND AGRICULTURAL LANDS ($/CORD).



(a): Scenario with forest management restrictions.

(b): Scenario without forest management restrictions.

FIGURE 4: AGRICULTURAL LANDS HARVESTED FOR ASPEN (ACRES).

cline, but their patterns are not uniform across markets. In general, the prices associated with the unrestricted scenario are nearly five dollars per cord less than the restricted scenario. Those markets that bought wood from agricultural lands generally exhibit the lowest shadow prices. As a rule, these markets are located closer to agricultural lands with low opportunity costs and high yield rates.

Figure 4 (a) and (b) shows the acreage of these lands utilized to meet aspen product demands for all planning period and markets. No agricultural land is harvested in the first planning period because the rotation for hybrid poplar is ten years and therefore it will not be available for harvest until the beginning of the second planning period. In both management scenarios, the lowest shadow prices are associated with Bemidji, primarily because it is located closer to large acreage of agricultural lands with relatively low opportunity costs. About 70–80 thousand acres of these lands are used to meet the demands at the Bemidji market in each planning period. In Figure 3, it was observed that the highest shadow prices are associated with Duluth and Grand Rapids markets, which receive most of their aspen supply from commercial forest lands. The agricultural lands allocated to Duluth and Grand Rapids markets is relatively insignificant. The only market which does not receiveany supply from these lands is Cook. This market is located in the north-eastern part of the state. There are very few agri-

TABLE 5: AGRICULTURAL LANDS HARVESTED FOR ASPEN DEMAND — SCENARIO WITH FOREST MANAGEMENT RESTRICTIONS (ACRES).

	PERIOD									
MARKET	1	2	3	4	5	6	7	8	9	10
Bemidji	0	83082	82643	84569	83351	74298	74382	74467	75506	73263
Brainerd	0	50307	50097	51649	45241	34147	34170	33547	30685	28438
Cook	0	0	0	0	0	0	0	0	0	0
Duluth	0	6126	7799	7877	5443	3821	2622	1818	1302	944
G. Rapids	0	12962	12473	11300	13715	9614	9518	8690	7069	5448
I. Falls	0	52177	51642	49259	48563	45801	43367	37805	35472	34282
Total	0	204654	204654	204654	196313	167681	164059	156327	150034	142375

cultural lands in the vicinity of this market and therefore, all its aspen requirements are met by aspen stands located nearby.

The breakdown of agricultural lands utilized to meet aspen demands in all markets and planning periods for both restricted and unrestricted scenarios is presented in Table 5 and Table 6, respectively. The restricted case requires approximately 20 thousand additional acres than the unrestricted case over the entire planning horizon. This is true because more restrictive management practices on the forest lands including the exemption of over a million acres from any type of harvest activity are modeled under the restricted scenario. It is interesting to note that after the first four periods the harvested acreage of agricultural lands starts to decline, reflecting the fact that the age class imbalance of aspen stands will begin to improve in about 40 years. As a result, its ability to provide industrial quality aspen becomes more stable. Because, hybrid poplar pro-

TABLE 6: AGRICULTURAL LANDS HARVESTED FOR ASPEN DEMAND — SCENARIO WITHOUT FOREST MANAGEMENT RESTRICTIONS (ACRES)

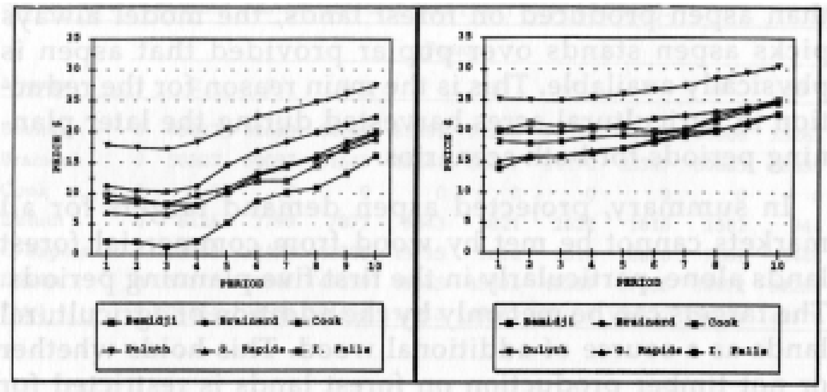
	PERIOD									
MARKET	1	2	3	4	5	6	7	8	9	10
Bemidji	0	76142	74374	74311	74330	69011	69469	69777	69940	69027
Brainerd	0	38731	38767	38811	38822	30873	30374	28859	27447	21762
Cook	0	0	0	0	0	0	0	0	0	0
Duluth	0	3609	3620	3620	3609	2425	1818	944	739	585
G. Rapids	0	8580	10450	10469	10450	8744	7110	5195	3724	3601
I. Falls	0	45293	45144	45144	45144	38672	37577	34383	33069	27458
Total	**0**	**172355**	**172355**	**172355**	**172355**	**149725**	**146348**	**139158**	**134919**	**122433**

duced on agricultural lands is generally more expensive than aspen produced on forest lands, the model always picks aspen stands over poplar provided that aspen is physically available. This is the main reason for the reduction in agricultural acres harvested during the later planning periods for both scenarios.

In summary, projected aspen demand targets for all markets cannot be met by wood from commercial forest lands alone, particularly in the first five planning periods. The targets can be met only by the addition of agricultural lands as a source of additional wood. This holds whether or not timber production on forest lands is restricted for environmental reasons. Shadow prices range between $37 and $56 per cord for the restricted scenario and within $35 and $50 per cord for the unrestricted scenario. In both cases highest prices are observed in the Duluth market, and the lowest prices are observed in the Bemidji market. The maximum amount of agricultural lands harvested in any given period is nearly 205 thousand acres in the restricted scenario, and 172 thousand acres in the unrestricted case. These high acreages are associated with the initial four planning periods. The least amount of acreage harvested is about 142 thousand acres and 122 thousand acres corresponding to the restricted and unrestricted scenarios, respectively.

Northern Hardwoods

The varying use of northern hardwoods across scenarios and across planning periods provides an example of the complexity associated with harvest scheduling and the interaction of different product types. Figure 5 (a) shows shadow prices for northern hardwoods when only forest land, without restrictions on management, is available for harvest. Marginal costs are relatively low and stable during the initial 4–5 period, and then they begin to increase. Earlier we had established that aspen demand targets were not being met during these initial planning periods, in spite of high aspen shadow prices. Now consider Figure 5 (b) which represents hardwood shadow prices when both forest and agricultural lands are available for harvest. Here, as noted in earlier section, aspen demands were met in all markets and planning periods. A comparison between Figure 5 (a) and (b) shows that the hardwood shadow prices



(a): Forest land only available.
Note: * indicates infeasible case

(b): Forest and agricultural lands available.

FIGURE 5: HARDWOOD SHADOW PRICES ($/CORD) — SCENARIO WITHOUT FOREST MANAGEMENT RESTRICTIONS.

increase by at least $5/cord in early planning period when agricultural lands are also available and aspen demands are met. This difference in shadow prices reflects the over harvest of hardwood stands which was necessary to get aspen within these stands to meet the aspen requirements. The result is that the marginal costs for hardwoods decrease, and the aspen shadow prices increase reflecting the small quantities acquired by the harvest of hard wood stands which would otherwise not be harvested. When agricultural lands are available for harvest, aspen demands are met by them and therefore, there is no need for over harvesting of hardwood stands. This increases the shadow prices for hardwoods and at the same time decreases the shadow prices for aspen.

All Other Timber Products

In addition to aspen, and northern hardwoods, demand for spruce, pine pulpwood, and pine bolts and sawlogs were also modeled in this study. Demand targets for these products in all markets and planning periods were successfully met. The shadow prices associated with the unrestricted scenarios were lower than those corresponding to the restricted forest land scenarios. The addition of agricultural lands to the production set did not have any significant impact on the marginal costs of these products, because these lands only produced hybrid poplar used in place of aspen.

Comparison of Harvested Acres

The acreage of forest and agricultural lands harvested to meet all timber product requirements is presented in Table 7. There is no clear pattern between the acres harvested from forest lands, managed with or without environmental restrictions. When forest land management is restricted, it is not necessarily the case that less acreage will be harvested in aggregate, because harvest can be shifted to areas which while more expensive are less restricted.

The inclusion of agricultural lands has a substantial impact on harvest of forest acreage. The range of forest lands involved in any given scenario and planning period is between 1.3 and 2.2 million acres. In comparison, the agricultural lands harvested are 140–200 thousand acres in each planning period. Recall that this acreage is less than half of the total acreage of agricultural lands analyzed in this study. The amount of forest land harvested is reduced by as much as 400 thousand acres in some planning periods. Relatively more agricultural lands are harvested (some 20-30 thousand acres in each planning period) when forest lands are managed with environmental restrictions. The

TABLE 7: COMPARISON OF HARVESTED ACRES FOR ALL CASES.

	Forest Lands		Forests and Ag. Lands					
	Unrestricted Management*	Restricted Management*	Unrestricted Management*			Unrestricted Management		
*Planning Period	Forest Acres	Forest Acres	Forest Acres	Ag. Acres	Total Acres	Forest Acres	Ag. Acres	Total Acres
1	2131700	2139200	2058600	0	2058600	2063200	0	2063200
2	1912700	1896900	1630700	172355	1803055	1670200	204654	1874854
3	1763700	1811600	1582600	172355	1754955	1595800	204654	1800454
4	1811600	1829700	1590000	172355	1762355	1625700	204654	1830354
5	2058800	2032800	1701100	172355	1873455	1752800	196313	1949113
6	1985400	1994300	1547000	149725	1696725	1522100	167681	1689781
7	1826900	1843900	1431000	146348	1577348	1462100	164059	1626159
8	1806300	1822800	1435200	139158	1574358	1468700	156327	1625027
9	1825100	1694400	1432000	134919	1566919	1459500	150034	1609534
10	1689500	1756200	1364400	122433	1486833	1389700	142375	1532075

Note: * indicates infeasible cases.

inclusion of these lands is most significant in the early planning periods where the shortages in the aspen supply are more pronounced. The harvested acreage of agricultural and forest lands decreases in the subsequent planning periods as the age class imbalance improves.

The realization of Minnesota's timber and biomass demand targets modeled in this study require some sort of harvesting activity on about 1.5–2 million acres of forest lands in each planning period. Generally, higher acreages are harvested in the early planning periods and as the age class imbalance of forests improves the harvested acreage begins to decline. Imposing management restrictions on forest lands does not necessarily reduce the number of acres harvested but sometimes changes the location of the harvest. These changes result in higher shadow prices which reflect the cost of environmental mitigation.

CONCLUSION

Modeling timber supply from traditional forest lands and agricultural lands managed under short-rotation production alternatives adds a new dimension to previous Minnesota forest planning efforts. The present study's use of location specific information and realistic estimates of production, harvesting, and transportation costs can provide decision makers with reliable estimates of marginal costs for delivered timber products.

Best management guidelines that can effectively deal with the complex issues such as wildlife, water, recreation, biodiversity, and timber production are rare. This research dealt with this issue by excluding certain forest lands considered environmentally sensitive from any harvesting activity and by restricting management options on many of the remaining forest lands. The comparison between the marginal costs of delivered timber products from the restricted and unrestricted scenarios reflects the cost of imposing environmental restrictions. The study identified existing and future timber supply problems and made recommendations for their mitigation.

The results indicate that the industrial demand for all timber products analyzed in this study can be satisfied over the planning horizon, only if some agricultural lands are devoted to poplar production. Otherwise, existing industrial requirements for aspen cannot be sustained over the planning horizon. These shortages are especially high in the initial four to five decades largely because of age class imbalances in the aspen inventory. Shortages are illustrated by shadow prices that increase for several decades. Since initial shadow prices are only about 5–10 percent higher than observed market prices, policy recommendations developed by this study appear acceptable.

Shadow prices between the scenarios that include agricultural lands increase by about $5/cord when management restrictions are imposed on forest lands. The total cost of producing the fixed demand increases, however, by only $83 million over 100 years which represents a less than one percent difference in total costs. More significant, however, is the shift in production to different land parcels and the overall reduction in harvest acreage due to SRWCs.

The use of agricultural lands particularly in the initial planning periods has a significant impact on aspen prices and the acreage of forest lands harvested. Production of hybrid poplar results in large quantities of wood in relatively short time and thus significantly reduces the harvest of traditional forest lands. At most about two hundred thousand acres of these lands provide hybrid poplar to the timber markets in each planning period. It should be noted that not every township with agricultural acreage is allocated to timber production. The combination of land owner's opportunity cost, the transportation costs to timber demand markets, and the soil productivity influence the economics of timber production and determine the relative advantage of one township versus another.

If forest lands are required to be managed under environmentally restrictive prescriptions without agricultural lands, infeasibilities in meeting specified industrial demands occur, and other steps to meet demands become necessary. Short of shutting down operations, forest industries can either import the balance of their aspen requirements from other states or use substitutes for aspen from sources within the state. Importing aspen can be an increasingly expensive operation because of transportation costs. It will also result in additional pressures on the forest resources of the exporting areas. The use of aspen substitutes such as hybrid poplar from locations within Minnesota will require forest industries to invest in the modification or purchase of new compatible processing equipment. These investments might also be significant but will generally be required only once. Therefore, in the long run, use of aspen substitutes available within the state might be less expensive than the import of aspen.

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