USING LINEAR PROGRAMMING TO INTEGRATE TIMBER MANAGEMENT AND WILDLIFE MANAGEMENT PLANNING

by

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INTRODUCTION

Most forests of substantial size contain a complex array of timber types, ages, growth rates, and stocking levels. The ability to produce timber products may vary widely over a forest. Suitability of a particular area for forest products other than timber (recreation, watershed, aesthetics, etc.) depends to a large extent on the characteristics of the earth's surface and the vegetation present. Since these may vary considerably from area to area within a single forest management unit, the potential to produce products other than timber also varies over a forest.

Until recently there were usually enough forest products available to satisfy most demands. However the increasing population which infringes upon the decreasing and retreating forests mean that optimum use has to be obtained from the forests which are left. Forests can't just be used any more, they have to be used in a manner which will produce the optimum amount of desirable products. The products considered most desirable, from a forest, may be different for every person, however. On one side people may be concerned about a possible timber shortage and a resulting decrease in housing. On the other side may be the millions of people demanding a clean water supply, increased recreation areas, and aesthetic quality.

The above condition creates decision making problems for the forest manager. A forest manager must face the age old economic problem of meeting (seemingly) unlimited wants with limited resources. The forest under management is always limited in size and potential for production of forest products and there is usually a limited budget. The manager is faced with demands for multiple and unlimited products and the need to make optimum use of the diversified and limited forest resources in trying to meet these demands. The manager must decide what to produce, how much to produce, and where to produce it on the forest under his control.

One of the manager's problems is the relative lack of knowledge regarding the production trade-offs between the possible products. That is, there is relatively little known about what a management action undertaken in a forest to increase one product will mean in gain or loss of other products. For example, what will it mean in terms of timber production, if the maximum size of clear-cut is set at 25 acres to increase the area's wildlife potential, etc. Many times, there is not even a rough estimate to answer such a question.

In this study, linear programming (LP) was used as a tool in an attempt to answer questions about trade-offs between timber production and wildlife practices in an actual case study for the Pocomoke State Forest in Maryland.

Objective

The objective of this study was the improvement of multiple forest resources management by integrating timber and wildlife management planning. Specifically, the study attempted to assess the effects on timber production of increasingly intensive wildlife management practices, through a linear programming approach.

Literature Review

LP procedures have been shown useful in forest regulation by Curtis (1962), Kidd, et al. (1966), Navon and McConnen (1967), and Ware and Clutter (1971). Timber yields, allowable cuts, and thinning policies through the use of LP have been proposed and tested by Leake (1963), McConnen, et al. (1967), Navon (1971), and Holmes and Waldrop (1971).

In a comparison of traditional methods of forest control and regulation with regulation by LP, Hennes, et al. (1971) found that LP, while a little more expensive and complex, allows a more realistic definition of timber resources and can analyze a wider spectrum of forest management practices. It also allows smoother periods of transition from old growth to second growth because LP can provide input information which can be used for management planning over an entire, or even several, rotations at a time. Many traditional methods are more static in that they consider only one point in time. LP can be used to determine not only how much timber to cut but what to cut and when.

Some theoretical work has been done using LP as a multiple-use tool by Davis (1967), Foster and Steward (1970), and Navon (1971).

STUDY AREA

The Pocomoke State Forest, located on the Eastern Shore of Maryland (Fig. 1), was used as a case study area to achieve the project's objective. The Forest was composed of ten separate tracts of land and included about 12,000 total acres (Fig. 2).

The climate on the Forest was moderate, tempered by close proximity to the Chesapeake Bay and the Atlantic Ocean.

The soil was predominantly a sandy loam with evidence of fragipan in some places. A rough average site indix for loblolly pine over the whole Forest was approximately 80 (base age 50). The terrain of the land supporting the Forest was relatively flat and poorly drained in some areas.

The predominant timber species was loblolly pine. Much of the area was covered by pure loblolly pine stands or loblolly stands intersperced with oaks. Partially as result of over dense stands and dry weather, a southern pine bark beetle epidemic broke out in 1970. It was estimated that 1900 acres of pine land would be harvested before the epidemic ran its course.

Due partially to much of the area being covered with pine, the predominant game species present on the forest were deer and quail which frequented the open areas.

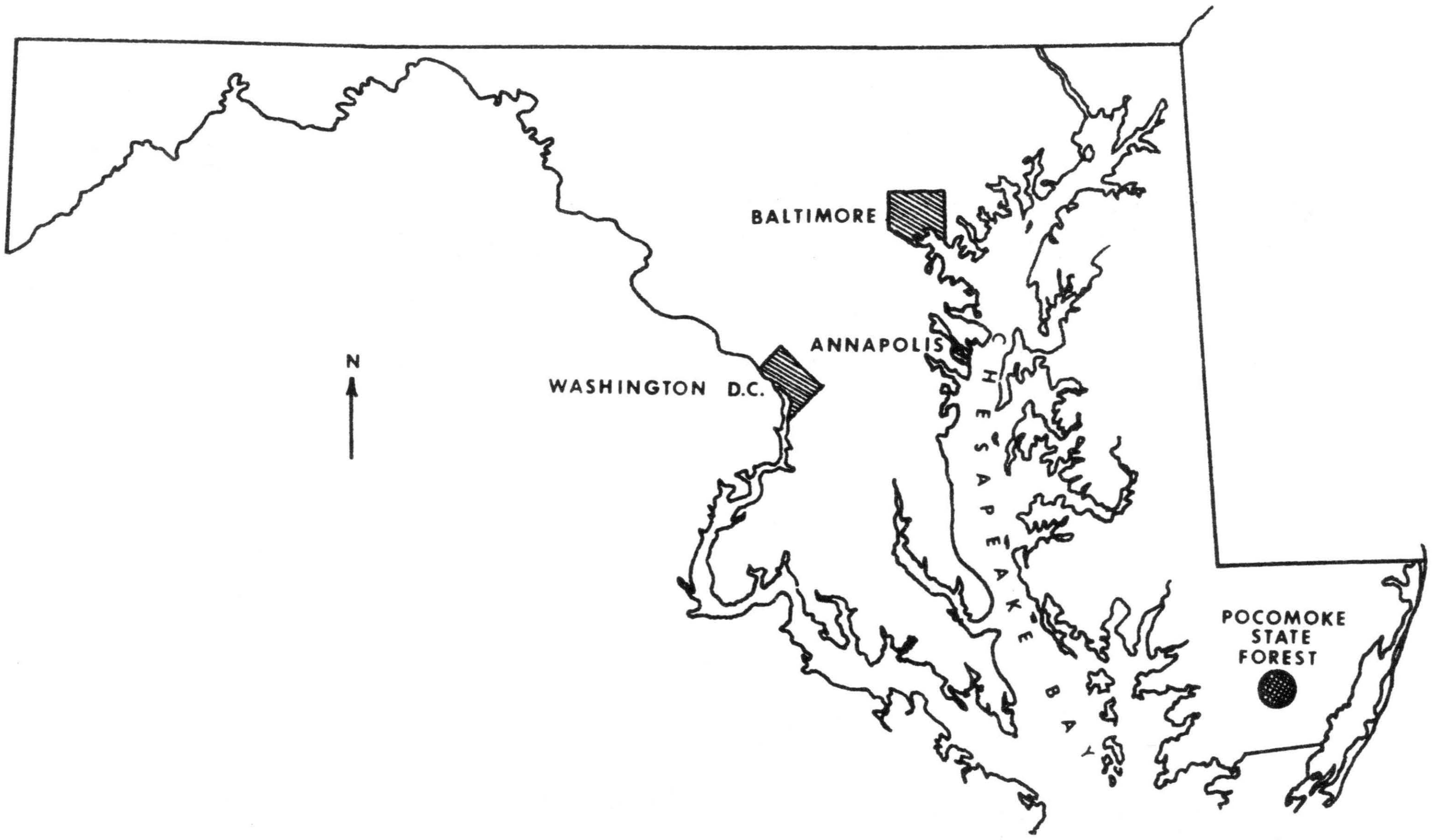

Fig. 1. Map of Maryland showing location of Pocomoke State Forest

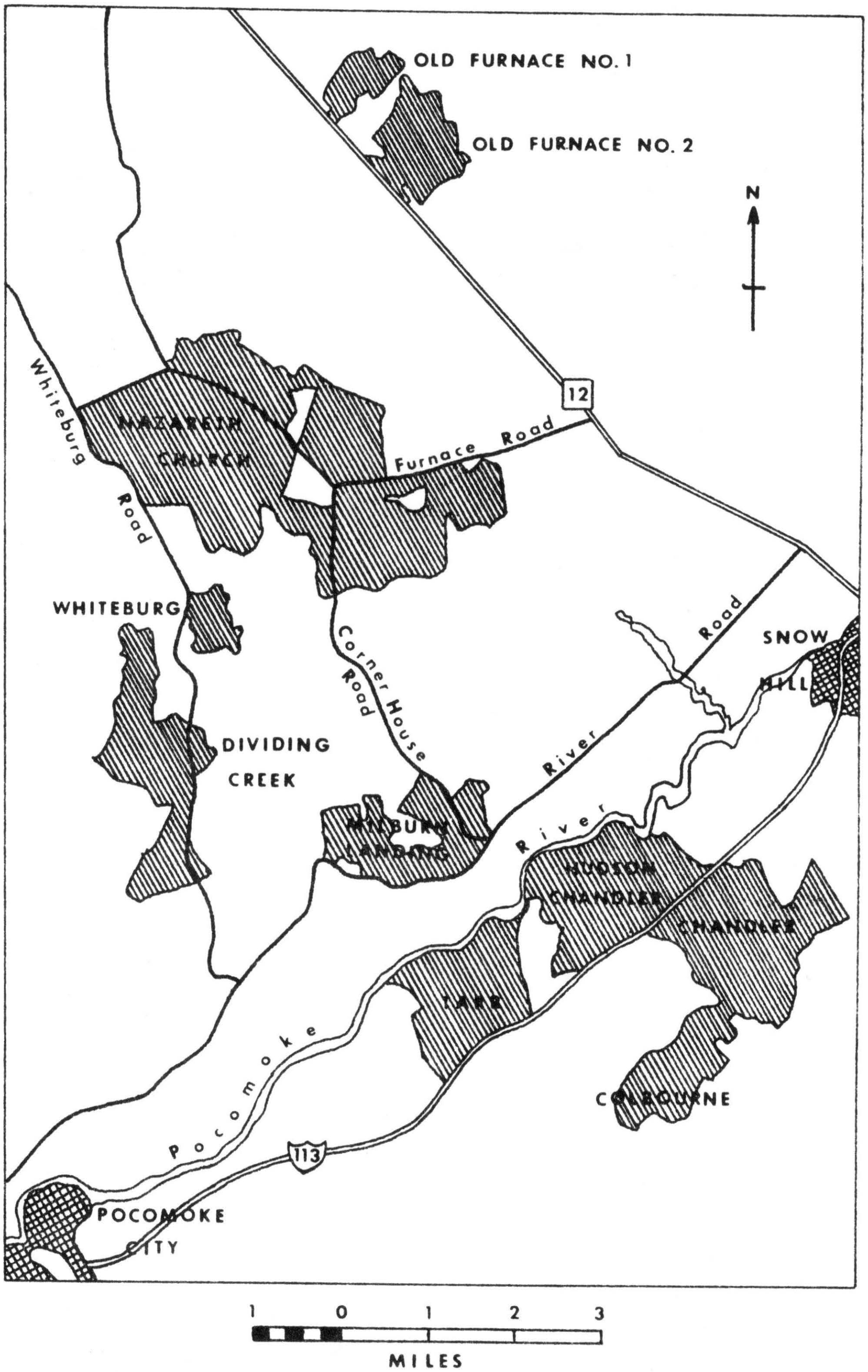

Fig. 2. Pocomoke State Forest in Maryland, consists of 10 tracts

The forest had a network of roads which appeared adequate for most management purposes.

Past Management Plans

The Pocomoke State Forest had not been under intensive management. The only previous timber management plan had been to cut enough timber each year to meet a budget requirement established by the State. The requirement had not been high enough to fully utilize the Forest.

The establishment of game clearings and food patches have been the main wildlife management practices.

Future Management Plans

The Maryland Department of Natural Resources wished to put the Forest on a sustained yield basis for timber and to also intensify wildlife management practices. The Department's basic objective for the Forest was to achieve a maximum, even flow of sawtimber consistent with sound management for other resources, primarily wildlife. This study will attempt to help achieve this objective through a linear programming approach.

Timber

The specific timber management goal is a maximum even annual flow of sawtimber over a 60 year rotation.

Some of the Forest's acreage is excluded from timber harvest: part of one tract includes a state park, and belts of trees are to be left as buffer zones along some of the roads, rivers, parks, and other scenic areas. These exclusions amount to approximately 1,000 acres. In addition, there is another 1,000 acres which is too swampy to harvest efficiently or economically, leaving approximately 10,000 acres of forest land suitable for timber production. The Forest is managed on an even-aged basis with clear-cutting being the predominant method used for harvest cuts.

Wildlife

The specific wildlife management goals include a maximum size limit on clear-cuts, distribution of the cuts over the entire Forest, and carrying some pine land at reduced stocking for quail management purposes.

Applicability as Study Area

As indicated, the Forest is to be managed as a multiple-use area with special emphasis on timber and wildlife production. There is some disagreement between wildlife and forestry officials regarding the levels of timber and wildlife management practices which should be carried out. This was surmised to be due partially to the fact that relatively little is known about the rate of substitution between the two activities. In other words, how much timber will have to be given up if some specific wildlife management practice is carried out and vice versa. Thus, the Pocomoke is a choice area to test the practicality of a multiple use LP model.

PROCEDURE

The first stage of the study was to develop an LP model for scheduling timber harvests on the Pocomoke State Forest. The model was then solved to provide a cutting schedule which maximized the Forest's sawtimber production over the planning period.

The next stage involved including various levels of wildlife management practices as constraints in the LP model. Presumably, actions taken by wildlife managers could have reduced the quantity of timber available from the Forest. The amount of timber foregone, if any was ascertained from the LP solution. Then, knowing the trade-off in timber for a particular wildlife management practice, the two were compared. This was done in a continuous process starting with the least intensive level of wildlife management practice. Presumably, at some point the value gained from the increasingly intensive wildlife practices would equal the loss in timber production. According to economic theory, this would be the optimum point to produce but because of the non-market nature of wildlife output this point must necessarily be a policy judgment by the Maryland officials in charge of the Forest.

LP Description

Linear Programming is a mathematical procedure which can be used to find a combination of constrained inputs which will most closely achieve a specified objective.

The mathematical representation of a linear programming model is as follows (Wagner, 1969:77):

Let X_j be the level of j for j=1, 2, . . ., n

$X_1, X_2, \ldots, X_n$ = activities to be considered

$P_1, P_2, \ldots, P_n$ = unit addition of any activity j to objective function

$a_1, a_2, \ldots, a_n$ = unit addition of any activity j to linear equation

b = constraint level

select values for X_j such that

$P_1X_1 + P_2X_2 + \ldots + P_nX_n$ is maximized or minimized depending on the context of the problem. The X_j's are constrained by a number of relations, each of which is one of the following types:

$$a_1X_1 + a_2X_2 + \ldots + a_nX_n \left.\begin{matrix}\geq \\ = \\ \leq\end{matrix}\right\} b$$

The relation $\geq$ includes the possible restriction that $X_j \geq 0$.

Linear programming can be applied as a procedure for selecting a beginning plan, which is consistent with the two sets of inequalities defining the upper and lower limits to real activities and resources. It allows successive iterations, the systematic selection of plans which increase the value of the objective function until an optimal (maximum or minimum) plan is determined. The optimum plan must be consistent with the linear inequalities which limit the nature of the plan.

The solution to a linear programming problem consists of a most favorable set of values for the various alternatives and some information about deviations from these values.

Data Used

Data was needed so that the Forest could be described in quantitative terms, which was necessary for setting up the linear equations of the LP model. The results of a 1969 timber inventory of the Pocomoke State Forest were used as a basis to provide the necessary input information. Each stand on the Forest was distinguished and defined by its location on a map, size in acres, timber species, present volume (both sawtimber and pulpwood), and growth rate. Since maximizing timber volume was the objective, the hardwood volumes were combined with the pine volumes. If maximizing some monetary value were the objective then the hardwood volumes would have to have been kept separate from the pine volumes.

Stand Definition

Maps obtained from surveyors were used as base maps. The stands were type mapped by pacing as the cruise progressed and a record of plot centers were kept on the type maps. After the cruise was completed the stands which were defined on the type maps were examined. Any stand which did not have at least four plot centers lying within its boundaries was combined with similar stands. It was decided that at least 4 plot centers had to fall within the boundaries of every stand to get a reasonable estimate of volume and growth. There was no prior knowledge of stand delineation or variation of volume or growth in any of these undefined stands when the cruise was carried out. If a stand wasn't at least 25 acres in size it was combined with similar stands. The minimum feasible size clear-cut was considered to be 25 acres by the managers of the Forest. All areas of bare land from all the tracts were combined to make only one stand. This was done because the site index was not known for each separate area of bare land. Therefore an average site index was estimated for all of the bare land and the silvicultural treatment for all of it would be the same. For stands with known bark beetle infestation, the forest manager estimated the size in acres of the part of the stand which would probably be destroyed. This amount was substracted from the stand size and added to the stand which was defined as becoming cleared land within the next 5 years.

After the definition of the stands on the type map was complete, the area of each stand was determined with a planimeter.

Volumes

Local volume tables were constructed for pine sawtimber and pulpwood and also for hardwood sawtimber and pulpwood. This was done for two reasons. Both the double sampling scheme used in the cruise and the stand table projection method of calculating growth, necessitated local volume tables. Cruise data and the following sources were used to construct the local volume tables: Mesavage (1947), Mesavage and Girard (1946), and unpublished volume equations for loblolly pine developed at Virginia Polytechnic Institute and State University.[1/] The sawtimber volume was calculated using International

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[1/] Unpublished results from Virginia Polytechnic Institute and State University Research Division Project Number 200101, "Yield of Loblolly and Virginia Pine".

1/4" rule and the pulpwood volume was computed in standard cords.

The present volume of each defined stand was computed by combining cruise plots which fell within each particular stand. The average number of trees per acre by DBH and species were determined for both pulpwood and sawtimber. Volumes were obtained from the local volume tables and average volume per acre for hardwood sawtimber and pulpwood and also for pine sawtimber and pulpwood were determined for each particular stand.

Growth

Growth and yield equations were available for pure even-aged stands of loblolly pine. However, many of the stands on the forest were mixed pine-hardwood. Also age and site index were needed for each stand if growth and yield equations were to be used. Due to the cruise design, site index and age were hard to determine for many stands present on the Forest. For these reasons the stand table projection method of calculating volume growth for each defined stand was used. The cruise plots which fell within each stand were combined and a stand table was constructed for that particular stand. The stand table plus 10 year growth figures obtained from the cruise were used to project volume growth for the next 10 years for each stand. See Davis (1966:89) for further discussion of the stand table projection method of calculating growth. Volume growth estimates for each stand for the entire 60 year rotation period were needed. It was agreed that the best estimate of growth for each succeeding ten year period would be the same as the present 10 year period since a better method was not available for projecting growth for such stands.

Bare Land

Land which had been cleared, or it was estimated woudl be cleared in the near future due to bark beetles, was estimated to be regenerated to loblolly pine in 5 years. Land which was clear when the cruise was carried out was considered to be regenerated to loblolly pine in year one. Productivity of these regenerated areas was calculated using growth and yield equations (Brender and Clutter, 1970). An average site index of 80 and a basal area of 85 at age 20 was assumed for these stands.

The LP Model for Maximum Timber Production

A linear programming model must accurately describe all significant factors and relationships bearing on the particular problem in question. In this particular instance, a forest was the real world biological activity which was described with linear equations in terms of all relevant factors and relationships involving or affecting its ability to produce timber.

On the Forest, a given section of land was distinguished from other sections by its ability to grow trees and by the timber species and volume present upon it. Each one of these sections of land (stand) was defined on a map and represented by a number:

s = any stand

s = 1, 2, . . ., n

where n = maximum number of stands on a particular tract

The Forest was divided into tracts. There were ten tracts which contained varying number of stands. The tracts were designated by capital letters. Stands, from several different tracts, which were similar enough to warrant the same silvicultural treatment were combined to make a single stand. They were given the tract designation of K.

t = any tract

t = A, B, . . ., K

The stands on tract A would be represented as follows:

1A, 2A, . . ., nA

A listing of tracts and number of stands in each tract is provided (Table 1).

Activities

A given stand could be harvested in any year from year one until rotation age. The planning period was the same as the rotation age, which was 60 years in this case. However a stand could be cut only once during the 60 year period. Therefore, with regard to timber production there were 60 alternative ways to utilize each stand. The stand could be harvested in year one, year two, year sixty, or any year in between. These were distinct and separate alternatives because each stand was growing and, therefore, would have a different volume each year.

To keep the LP matrix within reasonable limits, a stand was considered not to have 60 alternatives but 12. The 60 year rotation period was divided into 12 time periods consisting of 5 years each.

u = any time period

$u = 1, 2, . . ., 12$

If one acre of a stand was scheduled for harvest in any year 1-5, it was considered to be harvested in period 1 and as such represented one alternative. Each stand, therefore, had 12 alternatives over the 60 year period.

Table 1. Timber tracts and stands as defined for the Pocomoke State Forest in Maryland

Tract	Tract Designation	No. Stands On Tract	Stand Designation
Old Furnace No. 2	A	6	1A,2A,...,6A
Old Furnace No. 1	B	3	1B,2B,3B
Hudson Chandler	C	4	1C,2C,...,4C
Whiteburg	D	1	1D
Nazareth Church	E	25	1E,2E,...,28E
Colbourne	F	0	*
Milburn Landing	G	5	1G,2G,...,7G
Tarr	H	7	1H,2H,...,7H
Chandler LU	I	0	*
Dividing Creek	J	6	1J,2J,...,6J
Pooled areas	K	9	1K,2K,...,9K

* Tracts clear-cut due to bug kill. Counted as bare land and included under pooled areas.

Each one of these alternatives was considered as an activity to be included in the LP model. Each activity was represented by a stand number, a tract letter, and the time period during which the stand could have been harvested.

stu = any stand (s) on any tract (t) harvested in any time period (u)

s = 1, 2, . . ., n

t = A, B, . . ., K

u = 1, 2, . . ., 12

To make notation simpler the activities defined for each stand were put on a unit, per acre, basis.

X_{stu} = X acres of stand (s) on tract (t) harvested in time period (u)

For example:

X_{1A1} = X acres of stand 1 on tract A cut in time period 1

X_{1A2} = X acres of stand 1 on tract A cut in time period 2

⋮

X_{1A12} = X acres of stand 1 on tract A cut in time period 12

There were 66 stands defined on the Forest. Since each stand had 12 alternatives or activities, there were 792 activities in the LP matrix.

Objective Function

The objective function for the initial model was to maximize the volume of sawtimber cut over a rotation period from the Pocomoke State Forest. The objective was achieved by scheduling the cutting of the stands to time periods in an optimum manner. The unit addition (coefficient) of any activity to the objective function was the average timber volume present per acre on a stand during the particular time period for which the activity was defined.

V_{stu} [2/] = Coefficient for activity X_{stu}. Defined as average volume per acre on stand (s) on tract (t) at the midpoint of time period (u).

The objective function maximized the total, of the average volume per acre, times the number of acres cut, summed over all stands on all tracts in all time periods.

The objective function was stated as:

$$\text{Max.} \sum_{u=1}^{12} \sum_{t=A}^{K} \sum_{s=1}^{n} V_{stu} X_{stu}$$

[2/] Volume is bd. ft. International 1/4" rule. Pulpwood is included and counted as 250 bd. ft./st. cd. The volume per acre is calculated as the average volume at the midpoint of each particular five year time period.

Constraints

There were constraints, however, imposed on meeting the objective function. Some restrictions were set forth by the managers of the forest and some were inherent in the resources under consideration.

The size of the particular forest under consideration was finite. The size of each of the particular stands on the Forest was also limited. Therefore, a maximim size limit had to be included in the model as a constraint on the activities defined for each stand. For each stand there were 12 activities defined. The stand could be harvested in any one of 12 time periods. The acres harvested in all 12 time periods from one stand could not be more than the total acres in that stand. This necessitated the following 66 constraints, one for each stand.

For example, the constraint for stand 1 on tract A was:

$$X_{1A1} + X_{1A2} + \cdot \cdot \cdot + X_{1A12} \leq 78.8$$

The sizes of all stands are given (Table 2).

The Forest's management specified that there should be an approximate even flow of sawtimber during the 60 year period. This constraint could conceivably have been met, either by cutting approximately the same volume each time period (volume control) or by harvesting

Table 2. Size of the individual timber stands on the Pocomoke State Forest

Stand and Tract	Size (acres)	Stand and Tract	Size (acres)	Stand and Tract	Size (acres)
1A	78.8	11E	154.3	1H	128.4
2A	67.7	12E	51.8	2H	93.6
3A	101.5	13E	98.5	3H	79.9
4A	112.7	14E	80.2	4H	87.6
5A	134.3	15E	84.9	5H	67.0
6A	97.2	16E	136.3	6H	62.9
1B	46.7	17E	118.2	7H	63.9
2B	133.5	19E	117.4	1J	155.4
3B	84.8	20E	106.7	2J	73.2
1C	33.7	21E	276.6	3J	126.3
2C	74.3	22E	78.2	4J	43.6
3C	265.5	23E	282.1	5J	57.1
4C	71.4	24E	71.2	6J	48.8
1D	106.3	25E	106.7	1K	749.8
2E	558.4	26E	172.7	2K	749.8
3E	89.0	27E	84.0	3K	749.8
4E	154.6	28E	173.5	4K	1876.5
6E	58.0	1G	112.3	5K	1876.5
7E	245.5	2G	127.8	6K	1876.5
8E	106.3	3G	47.5	7K	252.1
9E	105.5	6G	92.4	8K	252.1
10E	51.7	7G	70.9	9K	252.1

approximately the same number of acres each time period (area control). Each of these were included in the model as constraints, separately, and then both were included together, to see which would produce the highest obtainable timber volume over the rotation without undue fluctuations in periodic cut.

To effect volume control an upper limit was placed on the total volume cut each time period. The volume control constraint for period 1 was:

$$\sum_{t=A}^{K} \sum_{s=1}^{n} V_{st1} X_{st1} \leq AVC \quad \text{where AVC = allowable periodic volume cut}$$

The sum of volumes cut over all stands over all tracts in period 1 was less than or equal to the periodic allowable volume cut.

Twelve such constraints were needed, one for each time period.

Area control was included in the model in basically the same way. An upper limit was placed on the acres cut each time period. The area control constraint for period 1 was:

$$\sum_{t=A}^{K} \sum_{s=1}^{n} X_{st1} \leq AAC \quad \text{where AAC = allowable acreage cut}$$

The sum of acres cut over all stands and all tracts in period 1 was less than or equal to the allowable periodic cut.

Again, there were 12 such constraints, one for each time period.

Volume control only was included in the model initially and an upper limit on periodic volume cut was placed low enough that the limit could be reached in each of the 12 time periods. This gave a cut which was equal each period. However this solution did not necessarily give the highest even periodic cut obtainable and it certainly did not allow the maximum potential over a rotation to be reached if small fluctuations in periodic cut were considered feasible. Therefore the upper limit on the allowable periodic volume cut was raised in a stepwise process by parametric programming procedures until the upper limit was well above the point where it could be reached in each period.[3/] A new solution to the LP problem was obtained each time the upper limit was raised. A series of solutions with steadily increasing total cut over the rotation was obtained (Appendix Table I). However, after the point was reached where the upper limit could not be met in each time period, the periodic cut started to fluctuate. The cut was concentrated at the end of the rotation to

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[3/] For a discussion of parametric programming see Vandermullen (1971:78-111) and IBM Data Processing Application (1964:23-27).

take advantage of growth, with the cut in the initial periods decreasing.

It was a responsibility of management to choose the solution which balanced, the increasing total cut over the rotation against the steadily increasing fluctuations in periodic cut, in the most satisfactory manner. It was not possible, in all cases, for the Forest managers to choose the "best" solutions as the study progressed. However, based on previous discussions with the Forest managers, inferences were made by the author as to what would be a satisfactory balance and which solutions would be acceptible and which would not.

A lower limit could also have been placed on periodic volume cut. This would have prohibited the periodic cut in the initial time periods from dropping below any level prescribed by the manager. In this particular case, a lower limit was not considered necessary.

With area control included in the model, instead of varying the allowable periodic volume cut, the allowable periodic cut in acres was raised in steps by parametric programming. Another series of solutions similar to the ones obtained with volume control were obtained. The difference being that the periodic volume cut fluctuated more when only area control was used. When only volume control was used, the periodic cut in acres fluctuated rather widely. This can be noted when comparing Table 3 with Table 4. Again, a lower limit on area cut could have been included but was considered undesirable.

The results showed the area control, while yielding a relatively high total volume over the rotation and only small fluctuations in periodic acres cut, provided rather wide fluctuations in periodic volume cut. Volume control yielded a satisfactory total volume over the rotation and rather small fluctuations in volume cut, however the fluctuations in periodic acres cut were rather large. For these reasons area and volume control were both included in the model at the same time to see if a satisfactory total volume over the rotation could be achieved with fluctuations, in both periodic volume cut and periodic acres cut, held within acceptable limits. The upper periodic limit on acres cut was set at a maximum limit high enough that the limit could not be reached in all time periods and yet low enough so the acres cut wouldn't fluctuate too widely from period to period. The upper limit on the periodic volume cut was then raised in a stepwise process by parametric programming until the limit was well above the point where it could be reached in each period. A

Table 3. Example partial solution to timber maximization LP problem showing timber volume and acres cut each time period, volume control only

Time period	Volume cut (M board feet)*	Area cut (acres)
1	354	16
2	16000	1044
3	16000	1063
4	16000	1024
5	16001	931
6	16001	893
7	16000	668
8	16000	587
9	16000	540
10	16000	930
11	16000	901
12	16000	786
TOTAL	176,356	9,383

* International 1/4" rule

Table 4. Example partial solution to timber maximization LP problem showing timber volume and acres cut each time period, area control only

Time period	Volume cut (M board feet)*	Area cut (acres)
1	0	0
2	761	123
3	9500	900
4	11590	900
5	14057	900
6	18166	900
7	22555	900
8	26834	900
9	25808	900
10	15181	900
11	15980	900
12	32840	900
TOTAL	193,278	9,123

* International 1/4" rule

new series of solutions was obtained with fluctuations, in both periodic volume and acres cut, held within acceptible limits. An example of these solutions is given in Table 5.

Thinning

For each stand there were 12 activities defined, each with its average volume per acre. It was assumed the stands would grow at the same rate all through the rotation period and the coefficient (average volume per acre per time period: V_{stu}) of each activity in the objective function was simply the average volume per acre of the previous activity or period plus growth except the volume for the first period which was obtained from the timber inventory. When thinning was carried out in a stand, the volume present and the stand's growth rate changed. This meant that when thinning was included in the model, the coefficients of all activities defined for a stand after thinning, were different from the coefficients defined for the same stand without thinning. Therefore, to include thinning in a particular stand, 12 new activities with new coefficients had to be defined.

Activities for an unthinned stand were mutually exclusive from the activities for the same stand when it was thinned. If both sets of activities for the same stand

Table 5. Example partial solution to timber maximization LP problem showing timber bolume and acres cut each time period, volume and area control

Time period	Volume cut (M board feet)*	Area cut (acres)
1	3540	422
2	11685	825
3	16000	825
4	16000	825
5	16001	825
6	16001	825
7	16000	825
8	16000	825
9	16000	752
10	16000	825
11	16000	826
12	16000	786
TOTAL	175,228	9,386

* International 1/4" rule

were included in the model at the same time, it would have been possible for the solution to choose several activities from the stand unthinned and several with the stand thinned. These could have been two different activities defined for the same stand in the same time period. When thinning was included for a stand, the old coefficients were dropped and new ones were used. Because new coefficients had to be defined for a stand each time it was thinned, a thinning in "feasible stands"[4/] was included only at age 30 and 40.

A maximum total cut obtainable over the rotation was found for each solution. These solutions were then compared with the solution obtained when thinning was not included to see if thinning was advantageous in terms of timber volume produced and if so, at which age was it most advantageous.

Modifications in the Timber Maximization Model to Include Wildlife Objectives

Timber production and wildlife production were in competition for the same limited resources. However, both of these objectives were partially achieved. Due to the nature of LP, only one objective could be maximized

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[4/] In this study it was considered feasible to thin a stand if it was possible to predict the growth characteristics for the stand after thinning was carried out. It was not possible to make such growth predictions for many of the stands on the Forest.

at any one time. The objective of maximizing the timber volume obtainable over a rotation had already been included in the LP model in the objective function. Other objectives could have been met, at least to a degree, by including them in the LP model as constraints. Wildlife objectives were included in this manner. These constraints when included, may have decreased the previous optimum solution. The magnitude of this decrease could be determined and judgment could then be made by management whether the inclusion of a particular wildlife constraint was justifiable.

Wildlife Objectives

The Maryland personnel in charge of wildlife management on the Pocomoke State Forest were questioned about the practices they would like to introduce on the Forest. Those practices which potentially conflicted with maximum timber production were included as constraints in the LP model. There were three such practices: (1) limit the size of all clear-cuts (2) distribute the cuts over the entire forest, and (3) carry the nearly 1,900 acres of land, presently clear due to bark beetle activity, at reduced stocking for quail management purposes. The timber maximization model with feasible stands thinned at age 30 and with area and volume control both included, was the model chosen by the Forest managers in which to introduce the wildlife objectives as constraints.

Installation of Wildlife Objectives into Model as Constraints

The wildlife managers wanted to test three different maximum size limits on clear-cuts. The limits chosen were 150, 100, and 50 acres for clear-cuts in pine and pine hardwood stands. In addition, an upper limit of 25 acres was set for clear-cuts in all hardwood stands. Each of the three limits on pine and pine hardwood clear-cuts was included in the model by itself and a solution obtained. The 25 acre limit on clear-cuts in hardwood stands was included along with each of the limits on pine and pine hardwood.

The inclusion of these constraints was quite simple. The number of acres which could be cut in each activity was simply limited to less than or equal to the upper limit size set for clear-cuts.

Example constraint:

$X_{1A1} \leq MCC$ where MCC = maximum clear-cut size

Number of acres cut in stand 1 on tract A in time period 1 is less than or equal to the upper limit.

This would mean the inclusion of 792 constraints in the model. The resulting LP matrix would have become cumbersome very fast with so many constraints. However, in some LP computer programs an upper or a lower limit, or both, can be set for the value at which an activity can enter the solution. This was done and the size of the LP matrix remained the same as it was before.

Since there was no restriction on where the clear-cuts could occur, limiting of the size of each clear-cut did not effectively limit the amount of contiguous area clear-cut. No matter what the size of each clear-cut, if several occurred side by side, the total effect would be a large clear-cut. Therefore a method had to be devised to prevent clear-cuts from occurring side by side within certain time limits. This was compatible with the set of constraints which were included to distribute cuts over the forest.

The wildlife managers desired at least 10 years between cuts on adjacent areas. By leaving the constraints which limited the maximum size of clear-cut in the model while including constraints to prohibit cuts from occurring on adjacent areas with less than 10 years between cuts, it was thought cutting would be distributed over the forest in a desired manner. Stands were examined on the map and all stands which had substantial common boundaries were noted. As an example, stands 4A and 5A occurred side by side (Fig. 3). They were both pine stands. There were three possible cutting patterns which

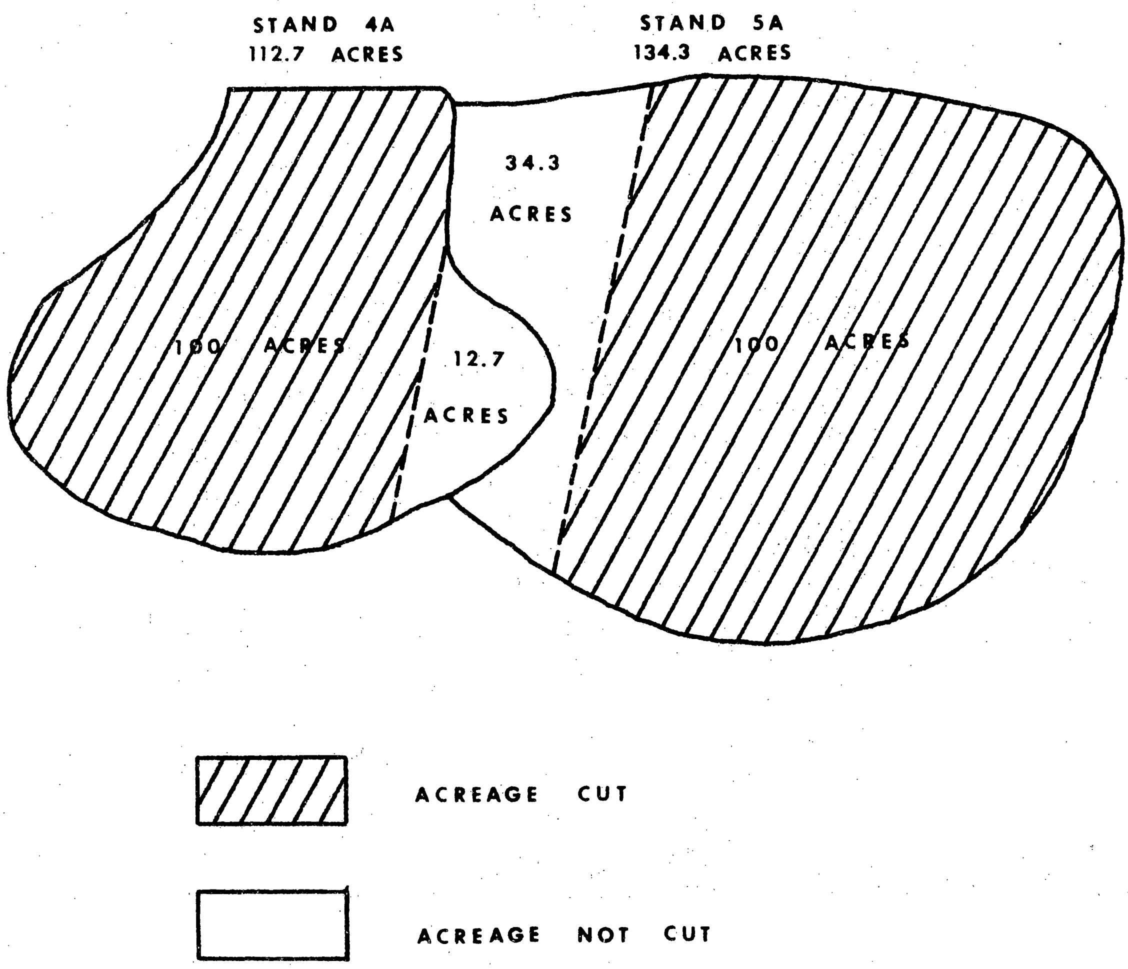

Fig. 3. Possible cutting patterns which could occur in stands 4A and 5A which are adjacent

could have been followed at any one time in these two stands. Cutting could have occurred in stand 4A only, in 5A only, or in both stands at the same time. It was desired to cut in the stand and time period which were most optimal and yet not allow cuts to occur side by side with less than 10 years between cuts. Using the 100 acre upper limit on clear-cuts, if cutting occurred in stand 4A only, not more than one 100 acre cut could have been allowed to occur within any subsequent 15 year period without the possibility of cutting the remaining adjacent acreage within 10 years (Fig. 3). The same would be true if cutting occurred only in stand 5A (Fig. 3). If cutting occurred in both stands, up to two 100 acre cuts could have been allowed to occur within any subsequent 15 year time period without the possibility of cutting the remaining adjacent acreage within 10 years (Fig. 3). By limiting cutting, to less than or equal to, 100 acres in these two stands for every possible time length of 15 consecutive years, the objective was met. A series of 10 overlapping constraints was included in the model for each pair of stands to accomplish this purpose. A constraint was included for every possible 15 year time length composed of three successive 5 year time periods. This constraint was a little more restrictive than necessary because if the optimum solution indicated that cutting should occur in both stands in the same 15 year period, up to two 100 acre cuts could have been allowed to occur. The set of constraints for stand 4A and 5A were:

Constraint for time periods 1-3

$$X_{4A1} + X_{4A2} + X_{4A3} + X_{5A1} + X_{5A2} + X_{5A3} \leq 100$$

Constraint for time periods 2-4

$$X_{4A2} + X_{4A3} + X_{4A4} + X_{5A2} + X_{5A3} + X_{5A4} \leq 100$$

$$\vdots$$

Constraint for time periods 10-12

$$X_{4A10} + X_{4A11} + X_{4A12} + X_{5A10} + X_{5A11}$$

$$+ X_{5A12} \leq 100$$

Several stands which were larger than the maximum size clear-cut also had a similar series of constraints included for the single stand. There were 53 such series of constraints included in the model or a total of 530 constraints.

The land which was bare due to bark beetle activity had been assumed to be regenerated within five years to loblolly pine and carried at full stocking over the rotation period. Solutions to the problem were obtained with the land included in the model at full stocking. The wildlife managers wished to see what effect, on timber production, would be produced by carrying this land at less than full stocking over the rotation period. This was to propagate quail in a manner which is being done in the South. The coefficients (average volume present per acre per time period: V_{stu}) in the objective function for the stand in question were changed to reflect the decreased volume present over the rotation period. Brender and Clutter's (1970) growth and yield equations were used with the basal area assumed to remain at 40 over the entire rotation and solved for the volume attainable at each 5 year time period. These coefficients were included in the LP model and a new solution obtained. This solution was compared to the one obtained with the land carried at full stocking to determine the timber given up to introduce this constraint.

RESULTS

Parametric programming was used to find a series of solutions for each variation of the model. An example solution, which best seemed to balance the increasing total volume obtainable over the rotation against the increasing fluctuations in periodic cut, was chosen for each alternative. Again, this was a choice to be made by management, however example solutions which the author felt best reflected the desires of the Forest managers were presented.

Each solution to the LP problem, or one of its variations, gave the total timber volume obtainable from the Forest over the rotation period and a cutting schedule which stipulated the volume to cut each time period in each stand to obtain that total.

Timber Maximization Model

Solutions were obtained for the model with volume control only, area control only, and with both area and volume control. Thinning in feasible stands at age 30 and 40 was included along with area and volume control.

Volume Control

With volume control only, the volume obtainable from the forest over the rotation period ranged from 144,000 MBF to 198,306 MBF as the upper limit on periodic volume cut was raised from 12,000 MBF to 22,000 MBF. The upper limit on periodic volume cut was raised in successive steps of 2,000 MBF by parametric programming procedures. This gave six different solutions with increasing volume obtainable over the rotation but also increasing fluctuations in periodic volume cut. When the periodic allowable volume cut was placed at 12,000 MBF the upper limit was reached in all time periods with the total cut of 144,000 MBF. There were absolutely no fluctuation in periodic volume cut. When the upper periodic limit on volume cut was placed at 22,000 MBF, the periodic volume cut ranged from 0 MBF in the first two time periods to 22,000 MBF the last several time periods, with a total cut of 198,306 MBF. A solution with the periodic allowable cut at 16,000 MBF appeared to give the best balance of increasing total obtainable cut against the increasing fluctuations in periodic volume cut. This solution with its periodic cut in both volume and acres is shown (Table 3).

Area Control

When area control only was included, the volume obtainable from the Forest ranged from 173,591 MBF to 215,374 MBF as the upper periodic limit on acres cut was raised in steps of 200 acres by means of parametric programming. This gave six different solutions with increasing volume obtainable over the rotation but also increased fluctuation in periodic acres cut. When the upper limit on periodic acres cut was placed at 700, the upper limit could be reached in all time periods. There were no fluctuations whatsoever in periodic acres cut, except in the first time period when none were cut in any of the solutions. When the upper limit on periodic acres cut rose to 1200, the periodic acres actually cut ranged from zero in the first 4 time periods to 1200 the last 7 time periods, with a total volume cut of 215,374 MBF. A solution which best seemed to balance the increasing total available volume against the increasing fluctuations in periodic acres cut was obtained when the upper limit in periodic acres cut was set at 900 (Table 4).

Area and Volume Control

When area and volume control were both included, periodic cut fluctuations, in both acres and volume, were held within certain limits. As before there was a series of six solutions obtained.

The volume obtainable over the rotation ranged from 144,002 MBF to 185,775 MBF. A solution which seemed to reach the highest total volume without undue fluctuations in periodic volume or periodic acres cut is given in Table 5. An example cutting schedule for the stands, by time period, is shown for this solution (Appendix Table II).

Computer printouts of cutting schedules are available for all solutions.

Thinning

Thinning in feasible stands at age 30 and 40 was included in the model. When thinning was carried out in feasible stands at age 30 the total volume obtainable ranged from 144,002 MBF to 178,770 MBF as the upper limits on periodic cuts were raised in the stepwise process by parametric programming. When feasible stands were thinned at age 40 the obtainable volume ranged from 144,002 MBF to 177,095 MBF over the range of allowable periodic cuts chosen.

The solution chosen when thinning at age 30 was included in the model gave a total volume obtainable over the rotation of 170,492 MBF (Table 6). This is a loss of 5,736 MBF when compared to the model with thinning not included (Table 5).

When thinning was included at age 40 the solution chosen gave a total obtainable volume over the rotation of 168,901 MBF (Table 7). When compared to the same model without thinning included (Table 5), the loss in volume over the rotation was 6,627 MBF.

Table 6. Example partial solution to timber maximization LP problem showing timber volume and acres cut each time period, volume and area control, thinned age 30

Time period	Volume cut (M board feet)*	Area cut (acres)
1	1993	310
2	8239	825
3	15248	825
4	16000	825
5	16001	825
6	16001	825
7	16000	825
8	16000	825
9	16000	825
10	16000	825
11	16000	826
12	16000	826
TOTAL	160,492	9,387

* International 1/4" rule

Table 7. Example partial solution to timber maximization LP problem showing timber volume and acres cut each time period, volume and area control, thinned age 40

Time period	Volume cut (M board feet)*	Area cut (acres)
1	2063	310
2	8432	825
3	14404	825
4	16000	825
5	16001	825
6	16001	825
7	16000	825
8	16000	825
9	16000	825
10	16000	825
11	16000	826
12	16000	826
TOTAL	168,901	9,387

* International 1/4" rule

Model with Wildlife Constraints Included

Each time a constraint (or constraints) was added to the model to include a wildlife objective, a new solution was obtained. Three main wildlife objectives were added to the model. Two of the wildlife objectives had several different levels to be tested in the model.

Maximum Limit on Clear-cuts

When the 150 acre maximum limit was imposed on clear-cuts, the solution chosen indicated an available cut of 166,947 MBF over the planning period (Table 8). This can be compared to the solution which was obtained for the same model before the limit was imposed (Table 6). The resulting decrease in timber volume over the rotation was 3,545 MBF.

When the 100 acre limit was used, the solution chosen indicated 165,871 MBF available over the rotation (Table 9). When compared to the solution without the constraint (Table 6) there was a net decrease of 4,621 MBF.

The solution chosen when a 50 acre limit was imposed on clear-cuts gave a total obtainable volume of 165,311 MBF over the planning period (Table 10). When compared to the model without the constraint (Table 6), the loss in timber amounted to 5,181 MBF over the planning period.

Table 8. Example partial solution to LP problem showing timber volume and acres cut each time period, volume and area control, thinned age 30, 150 acre limit on clear-cuts

Time period		Volume cut (M board feet)*	Area cut (acres)
1		0	0
2		7855	800
3		14489	850
4		16000	850
5		16001	850
6		16001	850
7		16000	850
8		16000	850
9		16000	850
10		16000	850
11		16000	845
12		16000	709
	TOTAL	166,947	9,154

* International 1/4" rule

Table 9. Example partial solution to LP problem showing timber volume and acres cut each time period, volume and area control, thinned age 30, 100 acre limit on clear-cuts

Time period	Volume cut (M board feet)*	Area cut (acres)
1	0	0
2	7471	746
3	13997	850
4	16000	850
5	16000	850
6	16000	850
7	16000	850
8	16000	850
9	16000	850
10	16000	850
11	16000	829
12	16000	705
TOTAL	165,871	9,080

* International 1/4" rule

Table 10. Example partial solution to LP problem showing timber volume and acres cut each time period, volume and area control, thinned age 30, 50 acre limit on clear-cuts

Time period		Volume cut (M board feet)*	Area cut (acres)
1		73	8
2		7536	720
3		13499	850
4		16000	850
5		16001	850
6		16001	850
7		16000	850
8		16000	850
9		16000	850
10		16000	850
11		16000	787
12		16000	695
	TOTAL	165,311	9,010

*International 1/4" rule

Table 11. Example partial solution to LP problem showing timber volume and acres cut each time period, volume and area control, thinned age 30, 150 acre limit on clear-cuts, cuts distributed over forest

Time period	Volume cut (M board feet)*	Area cut (acres)
1	5559	573
2	13845	850
3	14000	850
4	14000	850
5	14001	850
6	14001	850
7	14000	850
8	14000	850
9	14000	850
10	14000	706
11	14000	671
12	14000	636
TOTAL	160,006	9,386

*International 1/4" rule

Distribution of Cuts

When constraints were included to distribute cuts over the Forest along with the limit of 150 acres on clear-cuts, the solution allowed 160,006 MBF to be cut over the rotation (Table 11). This is a drop in volume of 6,941 MBF from the solution to the model before the constraints to distribute cuts were included (Table 8).

When constraints were imposed to distribute cuts over the Forest along with the 100 acre limit maximum on clear-cuts, the solution chosen gave a total volume of 156,247 MBF obtainable over the rotation (Table 12). This is a drop of 9,624 MBF when compared to the solution to the same model without the constraints to distribute the cuts (Table 9).

When the 50 acre maximum size limit on clear-cuts was included in the model along with constraints to distribute cuts over the Forest, solutions were not obtained due to limited time and budget.

Acreage Carried at Reduced Stocking

The model, with a 100 acre limit on clear-cuts and constraints to distribute cuts over the Forest included, was chosen as the model in which to include the wildlife objective of carrying nearly 1,900 acres of

Table 12. Example partial solution to LP problem showing timber volume and acres cut each time period, volume and area control, thinned age 30, 100 acre limit on clear-cuts, cuts distributed over forest

Time period		Volume cut (M board feet)*	Area cut (acres)
1		2813	274
2		13032	850
3		14000	850
4		14000	850
5		14001	850
6		14001	850
7		14000	850
8		14000	850
9		14000	836
10		14000	722
11		14000	682
12		14000	608
	TOTAL	156,247	9,072

* International 1/4" rule

pine land at less than full stocking.[5/] The solution to the model, with this constraint included, which appeared to give the highest total volume obtainable over the rotation without undue fluctuation in periodic cut is given in Table 13. This solution allowed 148,444 MBF to be cut over the rotation. There was a loss of 7,803 MBF attributed to the inclusion of this objective when compared to the model without the constraint included (Table 12).

[5/] It would have been worthwhile to include this constraint, as well as others, in the model at an earlier time to see if the result would have been the same, but it was not done because of limiting time and budget. This would have been a rough check on interaction between the practices.

Table 13. Example partial solution to LP problem showing timber volume and acres cut each time period, volume and area control, thinned age 30, 100 acre limit on clear-cuts, cuts distributed over forest, 1,900 acres carried at reduced stocking

Time period	Volume cut (M board feet)*	Area cut (acres)
1	218	25
2	8908	622
3	14000	850
4	14000	850
5	14001	850
6	14001	850
7	14000	850
8	14000	850
9	14000	623
10	14000	614
11	14000	522
12	14000	428
TOTAL	148,444	7,934

*International 1/4" rule

DISCUSSIONS AND RECOMMENDATIONS

The first part of this section will be concerned with the performance of the model. Both the benefits obtained from the model and the problems encountered in its use will be discussed. Then some suggestions will be given for collecting data, necessary for setting up an LP model of this type.

Discussion of Results

Benefits of Model

The objective for this study was to improve multiple forest resource planning. As indicated previously, one of the big problems in planning for multiple uses on a forest is determining what combination of the desired products will provide optimum benefits from the forest. Information was provided by solutions to the LP model which could be used as an aid in answering this question about timber and wildlife on the Pocomoke State Forest. Solutions to the model provided the timber volumes which would have to be given up to implement each specific wildlife management practice (Table 14).

The placing of a maximum limit of between 50 and 150 acres on the size of clear-cuts in pine and pine-hardwood stands and a limit of 25 acres on clear-cuts in

Table 14. Summary of results, showing variations of model and the solution chosen for that variation, including the loss in timber volume necessitated to include each variation in model

Model and variations	Volume obtainable over planning period for solution chosen (M board feet)*	Loss in timber volume attributed to inclusion of constraint (M board feet)*	Comments
Timber production maximization model	‡	‡	Solutions were not obtained without some form of forest regulation included
(1) Area control	193,278	‡	Wide fluctuation in volume cut per period
(2) Volume control	176,356	16,922	Wide fluctuation in acres cut per period, compared to variation (1)**
(3) Area and volume control	175,228	18,050	This and all following solutions have volume cut each period about equal and also acres cut each period about equal, compared to variation (1)**

Table 14 (Continued)

Model and variations	Volume obtainable over planning period for solution chosen (M board feet)*	Loss in timber volume attributed to inclusion of constraint (M board feet)*	Comments
(4) Thin age 30	170,492	4,736	This and all following solutions included area and volume, compared to variation (3)**
(5) Thin age 40	168,901	6,327	Compared to variation (3)**
Wildlife objectives instilled in model			
(6) 150 acre limit on clear-cuts in pine and pine-hardwood stands	166,947	3,545	This solution and all following it have a 25 acre limit on clear-cuts in hardwood stands and stands are thinned at age 30, compared to variation (4)**
(7) 100 acre limit on clear-cuts in pine and pine-hardwood stands	165,871	4,621	Compared to variation (4)**

Table 14 (Continued)

Model and variations	Volume obtainable over planning period for solution chosen (M board feet)*	Loss in timber volume attributed to inclusion of constraint (M board feet)*	Comments
(8) 50 acre limit on clear-cuts in pine and pine-hardwood stands	165,311	5,181	Compared to variation (4)**
(9) Distribute cuts over forest with 150 acre limit on clear-cuts in pine and pine-hardwood stands	160,006	6,941	Compared to variation (6)**
(10) Distribute cuts over forest with 100 acre limit on clear-cuts in pine and pine-hardwood stands	156,247	9,624	Compared to variation (7)**

Table 14 (Continued)

Model and variations	Volume obtainable over planning period for solution chosen (M board feet)*	Loss in timber volume attributed to inclusion of constraint (M board feet)*	Comments
(11) 1,900 acres carried at less than full stocking, 100 acre limits on clear-cuts in pine and pine-hardwood stands, cuts distributed over forest	148,444	7,803	Compared to variation (10)**

* International 1/4" rule

ǂ A solution could have been obtained with no regulation constraints included. This was not considered a feasible alternative.

** The solution to the model after a constraint was included was compared to the solution to the same model before the constraint was included to determine the loss in timber of including the constraint.

hardwood stands did not seem to decrease the total volume cut over the rotation by an appreciable amount. If the wildlife managers have good reason to believe that the increase in wildlife value over the 60 year period, obtained from setting a maximum limit on clear-cuts, is more than the value of 5,181 MBF of timber then there would be justification for setting a maximum size limit on clear-cuts. As a basis for comparison which is more familiar to many persons, the timber volumes will be changed to monetary values. To do this the following assumptions were made:

1. All stumpage sold was worth \$25/MBF.
2. The values were considered as occurring at the present time even though they would probably be spread over the rotation.

The following are provided strictly as examples of the type of analyses which could be carried out with information such as provided by this LP model.

Changing the 5,181 MBF to monetary units:

$$\begin{array}{r} 5181 \text{ MBF} \\ \$25/\text{MBF} \\ \hline \end{array}$$

\$129,522/60 year period ≃ \$2,159 year

Thompson et al. (1967) found that the average hunter in Virginia spends approximately \$227 in the pursuit of hunting yearly and some 15 percent, or \$34 of this was attributed to deer hunting. Using the average Virginia hunter-success ratio, about 10 hunters harvest one deer, each harvested deer then generates about \$340 of expenditures by hunters. Using this value for a harvested deer and dividing it into the yearly value of timber given up to set a limit on clear-cuts we obtain:

$$\$2,159/\$340 = 6.3$$

Assuming this study had been carried out in Virginia and that expenditures were an acceptible means of measuring value we could say that if the wildlife managers had reason to believe that setting a maximum limit on clear-cut size would provide an increase in deer harvested per year of at least 6.3, there would be justification for setting a maximum size limit on clear-cuts. Expenditures at best, are an imperfect measure of value but they are a method which could be used. This followed a line of reasoning used by Davis (1967:678).

Using the timber volumes given up to distribute cuts over the forest when there was a 150 and 100 acre limit on clear-cuts respectively, the monetary values would be:

6,941 MBF using the 150 acre limit
\$25/MBF

\$173,025/60 year period ≃ \$2,883/year

9,624 MBF using the 100 acre limit
$25/MBF

$240,600/60 year period ≃ $4,014/year

A public opinion survey could be conducted among the people using the forest, or among the people in the immediate vicinity, to determine whether they felt the increase in wildlife brought about by distributing cuts over the forest, projected by the wildlife managers, would be worth more than $2,883 or $4,014 per year. After all they are the people for whom optimum use of the forest is to be decided.

The loss in timber volume over the planning period attributed to carrying the nearly 1,900 acres of land at reduced stocking for quail propagation was 7,803 MBF. When placed in dollar units:

7,803 MBF
$25/MBF

$195,075/60 year period ≃ $3,251/year

The number of quail per acre which could be carried on this type of land could be estimated from past studies. Then a judgment could be made whether the increase in hunting value would be more than $3,251 per year. It would appear that a strong case could be made that 1,900 acres of prime quail land would be worth more than $3,251 per year.

There are many other considerations which have to be taken into account when making the decision of what level of wildlife and timber management should be carried out, however. For example, in the last case mentioned above it may require periodic treatment to keep hardwoods from encroaching on the land being carried at reduced stocking. There may be a cost of getting quail established on the area. It must be kept in mind that information, such as provided by solutions to the LP model, can be used only as an aid in the decision making process. However information provided by the model is useful in that some consequences of management alternatives can be put in quantitative terms and are known without having to spend time and money in empirical testing.

A very important fringe benefit of this model was the fact that an optimum cutting schedule for the entire Forest was determined. A cutting schedule is very important in that it determines: stability of timber flows and workloads, future development of the Forest both with respect to timber production and other uses, and if the full potential of the Forest is being utilized with respect to timber production. The model handled this very nicely. Different methods of regulation were tested to see which one most closely allowed the objective for the Forest to be met. It was found that area and volume control were both needed to provide the desired flow of timber from the Forest. Thinning was considered to see if it was desirable. The LP solutions indicated that thinning did not have much effect on the timber volume obtainable from the Forest over a rotation. Other silvicultural operations could just as well have been tested in the model.

The LP setup optimizes an objective subject to constraints. If the situation is adequately modeled, the solutions obtained are the best available given the inadequacies of the data and the imperfections inherent in any model. Therefore, these solutions are compatible with the desire to make optimum use of the Forest.

Problems Encountered

The main problem with this particular model was its size. The size of the matrix ranged from less than a hundred rows when only timber was considered to over 600 rows after the wildlife constraints were included. There were 792 activities or columns in the model. This large matrix necessitated long computer runs which became quite expensive and any change in the model became intricate. Also sensitivity analysis was almost impossible when the matrix was so large.

As with all LP models, the lower level at which activities could enter the solution could not be limited unless the activity was required to enter at a certain level or higher. This would have taken away the options of the program to include activities at any level which would provide an optimum solution. A lower limit was not provided for any of the activities and for this reason some of the activities required the cutting of very small acreages. These small acreages will either have to be ignored or cut along with some larger cut.

The inclusion of the wildlife objectives as constraints increased the number of small cuts which appeared in the solution. This was especially true of the constraints included to distribute cuts over the Forest.

This model included only the effects of wildlife practices on timber production. The implementation of many wildlife practices have implications besides their effect on timber production.

There was only one rotation considered in this model. Therefore the composition of the Forest over the second rotation was not implicitly considered although the application of both area and volume control on the Forest over the present rotation will ensure that a reasonably, even flow of timber will be available over the next rotation.

Recommendations

This model assumes everything in the future is known with certainty. This is unrealistic and, therefore, new solutions should be obtained every five years or so to take into account unforeseen circumstances and new developments. This should require only minor modifications of the model, however a new inventory or an updating of the old one, is necessitated. The following recommendations make some suggestions on carrying out an inventory for this type LP model and then suggest some helpful modifications in the model.

Data Collection

The typical methods of obtaining the actual cruise data will not be discussed but rather the design of the data collection scheme and the type of data needed.

Stands which are sufficiently different to require different silvicultural treatment need to be defined as to their location on a map, size in acres, timber species, present volume, and growth rate. If possible, stands should be defined before the actual on the ground cruise starts. Some stands have more variance in timber volume, density, age, and growth than other stands. If a specified degree of precision is required for the data from each stand, the appropriate number of plots must fall within the boundaries of each stand. A preliminary check of stand size and variation in density, volume, and age could be used to set up the cruise grid so that the appropriate number of plots would fall accordingly.

Since each stand needs to be treated as a separate entity a stratified sampling procedure would be the most efficient.

Another important matter to decide before the actual cruise starts, is what method will be used to calculate growth. If the stands are relatively homogeneous and if growth and yield equations are available for the timber species present, then the growth and yield equations are probably the most accurate and the fastest method to use. The only data needed for each stand to calculate growth in this case would be present age, measure of average stand density, and site index. If stands contain mixed species, or growth and yield equations are not available, then the stand table projection method of calculating growth must be used. This necessitates that more information be obtained during the cruise. The diameter size distribution, periodic radial growth by diameter class, present volume, bark thickness, mortality by DBH class, and ingrowth, all need to be obtained if the stand table projection method is used to predict volume growth. Local volume tables are needed for the stand table projection method. If they are not available, they must be constructed.

The methods used to actually collect the needed data are left up to the individual's preference and desired degree of precision.

Suggestions for Future Study

The method provided by this study for making available information about trade-offs between multiple uses on a forest seems to have promise but some refinements of the model would be very helpful.

If this model could be scaled down to smaller proportions the computer time and resulting cost would be much shorter and the time needed to set up the model would be greatly shortened. Stands which were silviculturally similar could be combined to greatly reduce the size of matrix required. A desirable alternative to this would be that a more efficient method be developed for handling LP problems with the computer.

Other wildlife practices and multiple use practices could be tested to see if they could be fitted into the model as constraints. The model could conceivable be made very general.

Different types of silvicultural systems could be tested besides clear-cutting. This may become important as more and more emphasis is placed on ecology and aesthetics.

If production functions for wildlife were available, the actual numbers of animals gained or lost, for various management alternatives involving other products would be known. This would add immensely to the value of a model of this type.

Different objectives could be used in the objective function. Maximizing present net worth or some other monetary objective could be used instead of maximizing the timber volume obtainable. This would allow many additions to the model such as accessibility costs, management and protection costs, planting costs, operating costs, budget constraints and discounting of future values. The use of some monetary value in the objective function would make a more useful and realistic model in many circumstances. If monetary value can ever be placed on presently nonmarket goods then this type of model could become even more important.

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Appendix Table I. Example series of partial solution to timber maximization LP problem when the upper limit on periodic cut is raised in steps by parametric programming, shows timber volume and acres cut each time period, volume and area control

Solution 1: Upper limit on periodic cut = 12,000 MBF

Time period		Volume cut (M board feet)*	Area cut (acres)
1		12000	825
2		12000	825
3		12000	825
4		12000	680
5		12001	770
6		12001	710
7		12000	523
8		12000	493
9		12000	444
10		12000	484
11		12000	557
12		12000	483
	TOTAL	144,002	7,619

Appendix Table I (Continued)

Solution 2: Upper limit on periodic cut = 14,000 MBF

Time period		Volume cut (M board feet)*	Area cut (acres)
1		11518	825
2		14000	825
3		14000	825
4		14001	825
5		14001	825
6		14000	825
7		14000	825
8		14000	652
9		14000	657
10		14000	825
11		14000	788
12		14000	688
	TOTAL	165,520	9,385

Appendix Table I (Continued)

Solution 3: Upper limit on periodic cut = 16,000 MBF

Time period		Volume cut (M board feet)*	Area cut (acres)
1		3540	422
2		11685	825
3		16000	825
4		16000	825
5		16001	825
6		16001	825
7		16000	825
8		16000	825
9		16000	752
10		16000	825
11		16000	826
12		16000	786
	TOTAL	175,228	9,386

Appendix Table I (Continued)

Solution 4: Upper limit on periodic cut = 18,000 MBF

Time period		Volume cut (M board feet)*	Area cut (acres)
1		1993	310
2		8026	825
3		10351	825
4		18000	825
5		18001	825
6		18001	825
7		18000	825
8		18000	825
9		18000	825
10		18000	825
11		18000	826
12		18000	826
	TOTAL	182,374	9,387

Appendix Table I (Continued)

Solution 5: Upper limit on periodic cut = 20,000 MBF

Time period		Volume cut (M board feet)*	Area cut (acres)
1		539	107
2		7583	825
3		9344	825
4		11406	825
5		16207	825
6		20001	825
7		20000	825
8		20000	825
9		20000	825
10		20000	826
11		20000	826
12		20000	826
	TOTAL	185,082	9,184

Appendix Table I (Continued)

Solution 6: Upper limit on periodic cut = 22,000 MBF

Time period		Volume cut (M board feet)*	Area cut (acres)
1		0	0
2		4024	510
3		9411	825
4		10361	825
5		13792	825
6		17057	825
7		22000	825
8		22000	825
9		22000	825
10		21128	825
11		22000	826
12		22000	826
	TOTAL	185,775	8,762

* International 1/4" board rule

Appendix Table II. Example partial solution to timber maximization LP problem showing cutting schedule of stands by time period, volume and area control

(Acres) cut in each stand by time period

Time period	Stand 1A	Stand 2A	Stand 3A	Stand 4A
1	0.0	0.0	0.0	87.5
2	0.0	0.0	101.5	0.0
3	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0
5	78.8	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0
8	0.0	67.7	0.0	25.2
9	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0
11	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0

(Acres) cut in each stand by time period

Time period	Stand 5A	Stand 6A	Stand 1B	Stand 2B
1	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0
3	134.3	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0
7	0.0	0.0	46.7	133.5
8	0.0	97.2	0.0	0.0
9	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0
11	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0

Appendix Table II (Continued)

(Acres) cut in each stand by time period				
Time period	Stand 3B	Stand 1C	Stand 2C	Stand 3C
1	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0
3	0.0	33.7	74.3	0.0
4	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	125.6
6	0.0	0.0	0.0	92.7
7	0.0	0.0	0.0	0.0
8	84.8	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	7.2
11	0.0	0.0	0.0	39.9
12	0.0	0.0	0.0	0.0

(Acres) cut in each stand by time period				
Time period	Stand 4C	Stand 1D	Stand 2E	Stand 3E
1	0.0	0.0	0.0	0.0
2	0.0	0.0	167.5	0.0
3	71.4	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0
6	0.0	106.3	338.1	0.0
7	0.0	0.0	52.8	0.0
8	0.0	0.0	0.0	89.0
9	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0
11	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0

Appendix Table II (Continued)

(Acres) cut in each stand by time period				
Time period	Stand 4E	Stand 6E	Stand 7E	Stand 8E
1	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0
4	0.0	0.0	245.5	73.4
5	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0
7	0.0	58.0	0.0	0.0
8	0.0	0.0	0.0	0.0
9	154.6	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0
11	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0

(Acres) cut in each stand by time period				
Time period	Stand 9E	Stand 10E	Stand 11E	Stand 12E
1	0.0	0.0	0.0	0.0
2	60.5	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	51.8
5	45.0	0.0	0.0	0.0
6	0.0	0.0	154.3	0.0
7	0.0	0.0	0.0	0.0
8	0.0	51.7	0.0	0.0
9	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0
11	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0

Appendix Table II (Continued)

(Acres) cut in each stand by time period

Time period	Stand 13E	Stand 14E	Stand 15E	Stand 16E
1	0.0	80.2	0.0	136.3
2	0.0	0.0	80.6	0.0
3	98.5	0.0	0.0	0.0
4	0.0	0.0	4.3	0.0
5	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0
11	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0

(Acres) cut in each stand by time period

Time period	Stand 17E	Stand 19E	Stand 20E	Stand 21E
1	118.2	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0
7	0.0	109.5	106.7	87.6
8	0.0	7.9	0.0	189.0
9	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0
11	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0

Appendix Table II (Continued)

	(Acres) cut in each stand by time period			
Time period	Stand 22E	Stand 23E	Stand 24E	Stand 25E
1	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0
5	0.0	282.1	0.0	106.7
6	0.0	0.0	0.0	0.0
7	0.0	0.0	71.2	0.0
8	78.2	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0
11	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0

	(Acres) cut in each stand by time period			
Time period	Stand 26E	Stand 27E	Stand 28E	Stand 1G
1	0.0	0.0	0.0	0.0
2	0.0	84.0	0.0	112.3
3	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0
8	71.4	0.0	0.0	0.0
9	101.2	0.0	173.5	0.0
10	0.0	0.0	0.0	0.0
11	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0

Appendix Table II (Continued)

(Acres) cut in each stand by time period

Time period	Stand 2G	Stand 3G	Stand 6G	Stand 7G
1	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	70.9
3	127.8	0.0	0.0	0.0
4	0.0	0.0	92.4	0.0
5	0.0	47.5	0.0	0.0
6	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0
11	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0

(Acres) cut in each stand by time period

Time period	Stand 1H	Stand 2H	Stand 3H	Stand 4H
1	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0
3	128.4	0.0	0.0	0.0
4	0.0	93.6	0.0	0.0
5	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0
7	0.0	0.0	79.9	0.0
8	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	87.6
11	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0

Appendix Table II (Continued)

(Acres) cut in each stand by time period

Time period	Stand 5H	Stand 6H	Stand 7H	Stand 1J
1	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	104.1
3	0.0	0.0	0.0	51.3
4	0.0	0.0	63.9	0.0
5	0.0	0.0	0.0	0.0
6	67.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0
8	0.0	62.9	0.0	0.0
9	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0
11	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0

(Acres) cut in each stand by time period

Time period	Stand 2J	Stand 3J	Stand 4J	Stand 5J
1	0.0	0.0	0.0	0.0
2	0.0	0.0	43.6	0.0
3	40.0	0.0	0.0	57.1
4	33.2	126.3	0.0	0.0
5	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0
11	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0

Appendix Table II (Continued)

	(Acres) cut in each stand by time period			
Time period	Stand 6J	Stand 1K	Stand 2K	Stand 3K
1	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0
3	8.2	0.0	0.0	0.0
4	40.6	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	173.1
7	0.0	0.0	0.0	79.1
8	0.0	0.0	0.0	0.0
9	0.0	323.2	0.0	0.0
10	0.0	426.6	303.5	0.0
11	0.0	0.0	786.0	0.0
12	0.0	0.0	786.9	0.0

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USING LINEAR PROGRAMMING TO INTEGRATE TIMBER MANAGEMENT AND WILDLIFE MANAGEMENT PLANNING

by

Bernard G. Halterman

ABSTRACT

Linear Programming (LP) was used to provide information about trade-offs between timber production and wildlife practices for Maryland's Pocomoke State Forest. The information was to be used as an aid by the Forest managers to find the combination of desired products which would most closely meet the overall goal for the Forest. The objective for the Forest over the rotation was maximum sawtimber production consistent with sound management practices for other products, mainly wildlife.

An initial LP model of the Pocomoke Forest was developed with the objective function to maximize the sawtimber production over a 60 year rotation. Different methods of forest regulation were tried in the model to see which would give the highest volume obtainable over the rotation without undue fluctuations in periodic volume and acres cut. Thinning in feasible stands was included in the model at age 30 and 40. Solutions to the

model when thinning was included were compared with solutions to the model without thinning.

Wildlife management practices were then included in the model as constraints. Any wildlife management practice which the managers wished to consider, and which potentially interfered with maximum sawtimber production, was included in the model. When each wildlife objective was added to the model, a new solution was obtained. This solution was compared to the one obtained before the constraint was included. The amount of timber given up to introduce each wildlife management practice on the Forest was determined.

If the wildlife managers can estimate the increase in wildlife benefits brought about by a specific wildlife management practice, a decision can then be made, whether or not the introduction of the wildlife management practice on the Forest is justifiable.

Advantages and problems of the model were discussed with some suggestions for future study.