FOREST PLANNING REVIEW

by

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INTRODUCTION

Forest management can be defined as the practical application of scientific, economic and social principles to the administration and working of a forest for specified objectives. Forest management is not a cut and dry cookbook-type science. In planning for the future, managers must account for the differences in goals from owner to owner, long-term planning horizons and a diversity of products produced by the forest. No two forests are exactly alike so each management problem must be analyzed separately to account for these differences.

In addition, forest management on public and private lands involves management for multiple uses. Under these circumstances, managers must not only be familiar with timber management but also with watershed, range, wildlife, recreation and people management. Therefore, the management of forest lands and the preparation of an accompanying management plan requires the knowledge of policy, economics, hydrology, mensuration, silviculture, forest protection and other sciences. Also of great importance are accurate data collection, data compilation and good judgement. A basic knowledge of available models and appropriate linking of these models can greatly facilitate the planning job. A basic knowledge of concepts is absolutely necessary to develop forest management plans.

Purpose of Forest Management

The heart of timber management is the organization of a forest to provide a continuous flow of products through time. The process of determining "what, when, where, and how much" to cut is the essence of harvest scheduling. The latter is composed of two fundamental decisions: the determination of rate of harvest, and the scheduling of land parcels for harvest within the determined rate. Related to harvest decisions are decisions concerning regeneration. The level of investments in regeneration is among the most difficult questions.

The foremost goal behind managing a forest is to maximize benefits obtained from that particular forest. The key point to remember is that the benefits obtained from a forest are dependent upon the ownership of the forest. Therefore, the manager needs to think about the following questions when developing a management plan:

1. For whom am I planning and what are the owner's goals?
2. What resources are available to me? (capital, land, labor, etc.)
3. How can these resources be put to their best use?
4. What information is needed? (yield data, economic data)
5. How do present actions affect future production?
6. What are the environmental impacts of my proposed management plan?
7. How do my plans coincide with the goals of local and state governments?

The forest manager uses information such as growth, present timber inventory and future inventory predictions to determine cut. The cutting of timber can be viewed as one of the most important tools a manager has available in order to achieve specified management goals. But, it must be kept in mind that harvesting has many implications for all aspects of forestry like:

- Markets for timber---will there be any?
- Growth of the forest---will harvesting increase growth?
- Recreation---will harvesting increase or decrease?
- Aesthetics
Cut determination must be included in a management plan. Several questions concerning harvesting should be answered by the manager within a management plan:

- **when** to cut; determination of the appropriate rotation length for the stand will not guarantee its harvest if there is no market for the product.

- **how much** to cut; this is dependent on the allowable cut and the available growing stock. Intermediate thinnings must be considered also.

- **where** to cut; accessibility, insect and disease problems, location of the mill or other utilization site can play a big part in determining the location of the cut.

- **which way** to cut; dependent on even-aged or uneven-aged stand conditions and what kind of product is being harvested.

- **what** to cut.

These are operational or stand-level questions. To answer these questions on cut determination the manager must account for the following in writing a management plan:

1. Objectives of management
2. Markets for the product
   - internal sales
   - external sales
   and the type of markets or products demanded
   - whole tree chips
   - pulpwood
   - sawtimber
3. Silvicultural considerations
   - overmature timber
   - regeneration options
   - diseased stands
   - insect problems
   - fire salvage
4. Logging problems
   - transportation access
   - hauling distances
5. Harvesting continuity vs. convenience
6. Thinning vs. not thinning
7. Growth and inventory data
8. Budget limitations

One important thing to remember is that management plans should be periodically revised to reflect changing objectives, changing markets and technologies, and to include new information. A good management plan should reflect any uncertainty of future conditions and the ability to adjust plans based on how the future unfolds. For instance, changes in markets (new market demands like oriented strand board - OSB) or changes in transportation costs which might influence decisions as to whether to cut, should be included in a management plan update.
FOREST REGULATION

"The organization and control of growing stock for a sustained yield of forest products from a specific forest area has traditionally been called forest regulation" (Meyer et al. 1961). Forest regulation lies at the heart of forest management. It involves the use of the tools of management such as site, stocking, structure, growth and yield, it also involves the size and timing of timber cuts which will be described later. Since forest management operates in many agencies under the constraints of sustained yield and even flow lets examine these concepts more carefully.

Sustained Yield

The concept of sustained yield was developed in the early 19th century in Germany during a time when, generally, the forests of the country were in poor condition, and guidelines for their management were missing. During this period, the model of a normal forest was developed. The normal forest was an idealized model of a fully regulated forest and was advocated as the condition towards which all forest properties should be managed. In the past, sustained yield was more of a theory than a practice due to the fact there was little demand for public timber. As demand for public timber increased, the Forest Service sought recognition of its land-use planning and sustained yield policies. In 1960, Congress passed the Multiple Use - Sustained Yield Act which required National Forests to have renewable surface resources developed and administered for multiple use and sustained yield of products and services. The Society of American Foresters has defined sustained yield management as:

"Management of a forest property for continuous production with the aim of achieving, at the earliest practicable time, an approximate balance between net growth and harvest, either by annual or somewhat longer periods."

Today the concept of sustained yield is not only concerned with the continuity of growth and yield but also the continuity of goods and services from the forest. Managing a forest for sustained yield requires that a sufficient growing stock be maintained. The periodic yields obtained from sustained yield must be calculated so that this growing stock is not depleted.

Not every forest can be managed on a sustained yield basis. Some areas of the U.S. are being seriously overcut while others are being undercut. While the growth and cut over a massive forest area may balance out, this is not sustained yield. Sustained yield can only be achieved via in-depth planning for very specific areas. There are a number of arguments for acceptance of the sustained principle. Many reasons are essentially external to the forest itself, and are based on economic, social, and administrative factors:

- Yearly cut of approximately equal volume, size, quality, and value of timber implies a stable business planning base and workload continuity.
- Current growth (harvested) and income not larger than necessary.
- Balance between yearly expenditures and receipts (liquidity).
- High degree of safety from fire, insects, and diseases.

A key question for sustained yield management is the level at which yield should be sustained.
Four key factors influence this level of sustainable yield:

a. Utilization standard--upper stem height can be varied.
b. Technology--full-tree harvesting.
c. Rotation--economic vs. biological.
d. Management intensity--overmaturity must be minimized.

Another important question deals with the time period over which currently unbalanced timber inventories should be converted to sustained yield, i.e., how fast full regulation is to be achieved. Specific questions are:

a. Over what time period should the conversion to sustained yield be accomplished?
b. Should economic considerations enter the decision on the length of the conversion period and the size of cut?
c. Should larger cuts be allowed during the conversion period or should even-flow constraints be imposed?

**Even Flow**

Sustained yield and even flow are frequently misinterpreted as being synonymous. However, there are subtle differences between the two policies. Even flow cannot be practiced apart from sustained yield. However, sustained yield can be practiced separately from even-flow.

Even flow regulation requires that management plans establish a periodic allowable cutting rate with the objective of providing an "even flow" of national forest timber in order to encourage the stabilization of communities and opportunities for employment.

**Nondeclining even flow** implies an even flow set at a level that could be sustained after full regulation of the growing stock has been achieved. The rationale behind the even-flow concept is community and employment stability. Throughout the twentieth century, Forest Service literature has emphasized the need to stabilize dependent communities with approximately equal timber harvests every year. The advantages of even flow are in some cases questioned such as community stability as a consequence of even-flow management.

Some of the major problems with the even-flow management concept are:

a. Compliance with this concept allows enormous growth losses (during conversion to even flow management) and makes no allowance for the capital cost of holding inventory.

b. The opportunities for economic growth are reduced because accumulated capital cannot be put to use as quickly.

c. With even flow management, entire economic fluctuations must be absorbed by timber prices. This does not promote stability of income, employment or markets.

Who was the culprit behind the spiraling cost of timber during the late 70's? Industry or the Forest Service?
Conversion to Sustained Yield

When forest inventories are unbalanced and a sustained yield objective exists for the forest enterprise, a key question that needs to be answered is how fast do we want to reach a fully regulated, sustained-yield operation? This question cannot be answered without looking at the various implications for different conversion speeds. If surplus volumes currently exist, one strategy might be to liquidate the surplus as quickly as possible. If market prices happen to be good and the total surplus could be sold without depressing prices, the generation of quick cash deposited into an interest-earning account or other investment might be a strategy that from a purely financial point of view could not be beaten. However, even a free market will tend to promote more of a gradual liquidation of surplus growing stock if the volume harvested in a specific time period impacts the landowners per-unit timber prices. To compare different conversion schedules, we could compare the discounted cashflows associated with various conversion schedules using the appropriate alternative rate of return. We need to be cautious in interpreting such simulated results as they reflect specific assumptions about future and present management costs and prices, and the discount rate. Many other strategies could be designed totally independent of any specific regulation method including the option to simply cut all surplus immediately independent of any regulation calculations.

ROTATION DETERMINATION

Rotation has been defined by the SAF as "the period of years required to establish and grow timber crops to a required specific condition of maturity." What is a specified condition of maturity? It is up to the manager to determine the conditions under which the stand(s) in question will be harvested. The conditions might be age, diameter, maximum yield or maximum profit.

Several formulas have been developed to aid the manager in rotation determination. Unfortunately, these formulas do not incorporate all of the factors which influence a manager's decision. In addition, some of the formulas were meant for use on a newly established forest not necessarily one which is already 30 years old. The point which should be stressed is that these formulas do not represent an absolute but rather an approximation which when accompanied by other factors help the manager to establish a rotation age.

Some of the factors which influence such decisions are:

1. The type of products demanded by the public
2. The production capacity of the forest
3. Insect, disease or disaster problems
4. Financial considerations, e.g., not enough timber available to merit harvest or the financial need of the owner to liquidate his/her holdings.

Rotation age can be approximated through the use of several formulas. Generally, it can be said that there are two types of formulas—those which determine a biological rotation age and those which determine an economic rotation age.
Maximum Volume Rotations

1. Maximum mean annual increment (MAI)

\[ \text{Maximum MAI} = \text{Maximum} \left( \frac{\text{Yield}}{\text{Age}} \right) \]

The maximum mean annual increment indicates the age at which average annual growth is the greatest and therefore for fully stocked stands it indicates the rotation of maximum volume production. This point of maximum MAI is intersected by the periodic annual increment (PAI) curve. PAI values are determined by dividing the increment for each period by the length of the period.

\[ \text{PAI} = \frac{\text{Yield}}{\text{Age}} \]

Periodic annual increment is a measure of a stand's performance or in other words it is an indicator of the current stand growth. One thing to keep in mind is that as long as the PAI is rising, MAI has not reached its maximum and, therefore, volume growth has not been optimized (Table 1).

<table>
<thead>
<tr>
<th>Age</th>
<th>Yield</th>
<th>MAI (Yield/age)</th>
<th>PAI (Yield/age)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>1,248</td>
<td>624</td>
<td>143</td>
</tr>
<tr>
<td>30</td>
<td>2,681</td>
<td>1,340</td>
<td>125</td>
</tr>
<tr>
<td>40</td>
<td>3,929</td>
<td>1,815</td>
<td>101</td>
</tr>
<tr>
<td>50</td>
<td>4,942</td>
<td>2,471</td>
<td>82</td>
</tr>
<tr>
<td>60</td>
<td>5,759</td>
<td>2,880</td>
<td>66</td>
</tr>
<tr>
<td>70</td>
<td>6,424</td>
<td>3,212</td>
<td>55</td>
</tr>
<tr>
<td>80</td>
<td>6,972</td>
<td>3,486</td>
<td>46</td>
</tr>
<tr>
<td>90</td>
<td>7,431</td>
<td>3,715</td>
<td></td>
</tr>
</tbody>
</table>

Economic Rotations

Forest Rent

Forest rent is a means of rotation determination which is very similar to the MAI rotation determination. It is an attempt to improve the concept of maximizing MAI by considering the average annual value increment rather than the average annual growth increment. In other words, it recognizes that all timber volumes do not have the same per unit value. The forest rent rotation is one where net income or value is maximized per unit of area instead of yield. The rotation age where forest rent is maximized is generally close to the age where MAI reaches its maximum.

\[ \text{Forest Rent} = \frac{\text{net value}}{\text{age}} = \frac{\text{revenue - cost}}{\text{age}} \]
Unfortunately, the forest rent theory is economically invalid. Forest rent does consider costs such as for planting and thinning and it considers revenues received from harvesting but it does not account for the time value of money. In other words, it treats costs or revenues occurring in year 0 the same as costs or revenues occurring in year 50.

As stated above, forest rent can be seen to represent annual net return from the operation of a fully regulated forest property. Capitalizing forest rent will give an estimate of the value of the land and timber together. In other words, by capitalizing forest rent, we are estimating the value of capital which would generate the forest rent.

For example: interest rate = 12% forest rent = $1875/acre @ 40 years

\[
\text{capitalized value} = \frac{1875}{0.12} = 156.25/\text{acre}
\]

**Financial Maturity**

The financial maturity rotation is a measure of the opportunity cost of investing in standing timber as opposed to putting your money in a bank account. Using this method of determining rotation you harvest the stand when stand value growth rate is less than or equal to alternative rate of return (i). Numerically the rotation would be when:

\[
\frac{(M_{A+t} - M_A)}{M} = i \quad \text{(alternative rate of return)}
\]

where \( t = \text{age interval} \)
\( M = \text{value (}$) \)
\( A = \text{age} \)

The ratio \( \frac{(M_{A+t} - M_A)}{M} \) \( \sim m \) can be approximated by using

where \( m \) is our estimate of the value growth rate.

\[
\frac{M_{A+t}}{M_A} = (1+m)^t
\]

or

\[
m = \sqrt[t]{\frac{M_{A+t}}{M_A}} - 1
\]

for example:

\[
i = 0.10 \text{ or } 10\%
\]
Stand Age (t)  |  M = value ($)  |  $\frac{t}{M_{A+1}} - 1 = m$
---|---|---
20 | 3 | 2747*
30 | 34 | .1681
40 | 160 | .0801
50 | 350 | 

*\(m = \frac{34}{3} - 1 = 0.2747\)

Rules of thumb:

1) leave stand if \(m > i\) percent
2) cut stand if \(m < i\) percent

The rotation age in the example would be between 40 and 50 years.

One shortcoming of using this concept of financial maturity to determine rotation lengths is that it does not consider the value of the land; by harvesting the stand at a younger age one can get started on the next rotation sooner. This consideration is not reflected in the calculations described above.

**Soil Expectation Value**

Using this theory of rotation determination, the rotation is the age at which the discounted value of an infinite series of periodic net returns (difference between returns and costs at rotation) reaches its maximum. The results of this calculation represent the value of bare land given all of the associated costs. Choosing the maximum SEV value yields the best economic rotation value for that stand given the assumptions behind the SEV formula.

\[
SEV = \frac{N}{(1+i)^{R-1}}
\]

where \(N\) = the net income from one rotation \(r\) in year \(r\) terms
\(i\) = discount rate
\(R\) = rotation age

The formula can also be written as:

\[
SEV = \frac{NPW}{(1+i)^t} + NPW
\]

As stated above, the results of the SEV calculation is the value of bare soil. In many cases, the management situation in forestry is such that we are never dealing with bare land. Instead when a manager is determining the rotation age the growing stock and the soil are being considered together. The soil expectation value does have a place in comparing various forest properties to determine the best value, but in rotation determination it cannot be used alone. It is used in combination with the simple financial maturity concept to estimate the value of the bare land for the second and subsequent rotations.
The annual equivalent of SEV is soil rent (SR). Soil rent can be viewed as starting today or starting one year from now but in both cases maximizing soil rent will give you the same rotation as when maximizing SEV.

\[
SR = \frac{(SEV)i}{(1+i)} \quad \text{first payment is immediately}
\]

\[
SR = (SEV)i \quad \text{first payment is one year from now}
\]

A hypothetical example follows to illustrate SEV and SR (Table 2).

**Financial maturity vs. soil expectation**

To illustrate what difference it might make to a landowner whether he chooses a financial maturity rotation versus a maximum soil expectation rotation, let’s look at the following graphs (Figure 1).

\[
\frac{\text{value growth}}{\text{value}} = \text{alternative rate of return} \ (i)
\]

\[
\frac{dM}{dt} = i \quad \frac{dM}{dt} = M \times i
\]

where \(M = \text{value} \ ($)\) is the financial maturity criterion. Note that this criterion only considers the opportunity cost of money and not land cost.

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![Figure 1. Influences of various factors on economic rotations.](image)
let \( a = \text{annual land cost} \)

\[ \text{let } a = \text{land cost} (\text{opportunity cost of land which is incorporated into the maximum soil expectation formulation in addition to the opportunity cost of money}) \]

S.E.V. = soil expectation value

F.M. = financial maturity

Table 2. Rotation age determination using soil expectation value—Example i = 10%

<table>
<thead>
<tr>
<th>Trial Rotation (years)</th>
<th>Initial Costs at year 0 (planting site prep)</th>
<th>Initial Costs at R(^1)</th>
<th>Annual Costs at R(^2)</th>
<th>Annual Costs at R(^3)</th>
<th>Total Costs at R</th>
<th>Total Revenue at R</th>
<th>Net Revenue SEV</th>
<th>SR</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>25</td>
<td>436.23</td>
<td>822.45</td>
<td>1258.68</td>
<td>1000</td>
<td>-259</td>
<td>-15.7</td>
<td>-</td>
</tr>
<tr>
<td>40</td>
<td>25</td>
<td>1131.23</td>
<td>2212.95</td>
<td>3344.43</td>
<td>3300</td>
<td>-44</td>
<td>-1.0</td>
<td>-</td>
</tr>
<tr>
<td>50</td>
<td>25</td>
<td>2934.75</td>
<td>5819.50</td>
<td>8754.25</td>
<td>9000</td>
<td>246</td>
<td>2.1</td>
<td>0.19</td>
</tr>
<tr>
<td>60</td>
<td>25</td>
<td>7612.00</td>
<td>15174.00</td>
<td>22786.00</td>
<td>23500</td>
<td>714</td>
<td>2.4</td>
<td>0.20</td>
</tr>
<tr>
<td>70</td>
<td>25</td>
<td>19743.75</td>
<td>39437.50</td>
<td>59181.25</td>
<td>63000</td>
<td>3819</td>
<td>4.8*</td>
<td>0.44*</td>
</tr>
<tr>
<td>80</td>
<td>25</td>
<td>51210.00</td>
<td>102370.00</td>
<td>153580.00</td>
<td>153160</td>
<td>420</td>
<td>0.2</td>
<td>0.02</td>
</tr>
<tr>
<td>90</td>
<td>25</td>
<td>132825.00</td>
<td>265600.00</td>
<td>398425.00</td>
<td>300000</td>
<td>-98425</td>
<td>-18.5</td>
<td>-</td>
</tr>
</tbody>
</table>

\(^1\) using compounding factor \( F = P(1+i)^n \)

\(^2\) using a series compounding factor \( F = A \cdot \frac{(1+i)^n-1}{i} \)

<table>
<thead>
<tr>
<th>Age</th>
<th>Forest Rent</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>(1000-25-30*5)/30 = 27.5</td>
</tr>
<tr>
<td>40</td>
<td>(3300-25-40*5)/40 = 76.8</td>
</tr>
<tr>
<td>50</td>
<td>(9000-25-50*5)/50 = 174.5</td>
</tr>
<tr>
<td>60</td>
<td>(23500-25-60*5)/60 = 386.25</td>
</tr>
<tr>
<td>70</td>
<td>= 894.64</td>
</tr>
<tr>
<td>80</td>
<td>= 1909.19</td>
</tr>
<tr>
<td>90</td>
<td>= 3328.05</td>
</tr>
</tbody>
</table>

There are three factors which affect the magnitude of the difference in the optimum rotation age between the maximum soil expectation criterion and the financial maturity criterion:

- interest rate
- shape of value growth curve
- land cost.

The formulas described above should not be thought to give absolute answers. Instead, the determination of a rotation age should incorporate economic, silvicultural and consumer demand factors. Let's examine a couple of management situations to see why.

Suppose you just inherited a 100 acre, 40 year old red pine plantation from your generous grandmother, what should you set your rotation age at? The answer to this question depends on your situation.

- If you recently graduated from college and have a lot of loans to pay back—you may want to liquidate your plantation immediately.
- If you recently had your second child, you may want to hold onto the plantation until the kids reach college age.
- There has been a high demand for pole timber so while the mill is still offering a high price you decide to get our of the forestry business and invest in money market certificates.
This situations may seem a bit unrealistic but realize that small private landowners do not always have the same goals as, say, a public landowner. The landowners' goals play as important a part in rotation determination as do biological and economic factors.

Now suppose you are the regional planner for the Forest Service. In this situation you will not deal with rotation age on a stand by stand basis, instead, you develop guidelines to follow for general stand types. In developing these guidelines you may look at past harvests, desired product type, consumer demand and the economic feasibility of harvesting. For large landowners a set of heuristics or rules of thumb can play an important part in rotation age determination.

Rotation length cannot be determined by just one factor, instead, a combination of factors should be considered before synthesizing a rotation age. In addition to the ages resulting from the numerical formulas, economic, silvicultural, pathological and entomological factors should be reviewed before a final decision is made.

The Role of Models in Planning

The last two decades have shown a proliferation of models for growth and yield estimation, for analyzing management alternatives from planting choices to thinning practices, for harvest scheduling including transportation considerations, and for project analysis. The growing capabilities of microcomputers and the user friendliness they emphasize are having a dramatic affect on model development and usage.

The purpose of models and modelling in forest management is to generate information that supports decision making at various levels of management. The generation of information is becoming increasingly important due to competition for scarce resources (including funding) and because of increased public sector awareness of natural resource issues. Also, decisions taken early in the life of a stand or forest property can affect many future management decisions. Thus, information is often needed for all stages of stand development and more importantly, information from the various stages needs to be linked for effective decision-making throughout stand rotations.

Models take many forms depending upon the specific problem they are intended to address, where in the managing organization the problem is addressed, and the kinds of data that are available to make and use models. Model form also depends on the expertise of the modelers.

The Normal Forest Model

Both sustained yield and even flow policies employ the concept of a fully regulated forest. What we need to know now is exactly what is a fully regulated forest. During the early part of the 19th century the model of a "normal" forest was developed as an idealized model of the fully regulated forest. Then the common management practice was to clearcut in adjacent stands. In order that a stand at the given rotation age was represented in every year it became necessary to represent stands from age 1 to the rotation age in the forest on a continuous time period basis. The total volume of all of the represented stands is considered the normal growing stock. In a normal forest with full stocking the site is assumed to be utilized completely with maximum growth maintained constantly throughout each year.
There are a few essential requirements of a normal forest that need to be understood:

1. Age and size classes must be represented in such proportion and be growing consistently at such rates that an approximately equal annual or periodic yield of products of desired size and quality be obtained.

2. Forest should be normal in terms of:
   - Growth
   - Rotation
   - Age-class distribution over equal areas
   - Growing stock
   - Cut (to provide sustained yield)

3. Assumptions involved with a normal forest
   - Linear growth
   - Equal site quality
   - Full stocking with only one species
   - No intermediate yields usually

Figures 2 and 3 illustrate normal growing stock and acreage distribution.
MEASUREMENT OF GROWING STOCK

A goal of most forest managers is to achieve a regulated forest which will satisfy management objectives. The only means of determining if the stocking of the forest is at the desirable level is to measure the volume of the growing stock and compare it to a known standard. What is used as a standard? In most cases normal yield tables are used for the comparison. With this question in mind, let's examine some of the procedures which can be used to determine regulated growing stock.

A Special Case

Remember that, in the normal forest, growth is assumed to be linear over the entire time horizon (Figure 4).

Figure 4. Growing Stock - Normal Forest.

Assume: rotation (R) = 8

\[ C_i = \text{growth of age class } i \]
Total annual growth of a regulated forest \( Y_R \) = \( Y_8 = \sum_{i=1}^{8} C_i \)

Notice that the sum of all growth \( C_i \) is also equal to \( V_8 \) or the growing stock in the 8th age class.

\[ \sum_{i=1}^{8} C_i = V_8 \]

Therefore, the annual cut of a regulated forest is also equal to the volume in the oldest age class or the total annual growth.

\[ Y_R = V_R \]

How do we measure growing stock with this special case—the normal forest? We could use the trapezoidal method as before (using dashed straight line in figure 4). Growing stock in this case can be measured even easier by the area of a triangle—since the normal forest assumes linear growth.

Remember that \( A = 1/2 \) BH

therefore,

\[
\text{total growing stock } G_R = \frac{1}{2} (8) (V_8) = \frac{8}{2} V_8 \text{ and}
\]

\[ 8V_8 = 2G_R \]

i.e., in one rotation the total amount cut amounts to 2 times the total growing stock volume.

**Measurement of Growing Stock—Von Mantel’s Method**

Von Mantel’s formula has been widely used in making quick estimates of growing stock from forests having some regularity in age-class distribution (Figure 5). It is a formula based on the observation that the growing stock of a fully regulated forest can be roughly estimated by a right triangle (even though growth is not linear as in the normal forest model).

Therefore, \( G_R = \frac{R}{2} V_R \)

using the previous example:

\[ G_R = \frac{70}{2} \times 77 = 2695 \text{ cords on 70 acres} \]

or \( 17325 \) cords on \( 450 \) acres

The accuracy of this formula is dependent on how close the normal forest concept fits the actual stand. The problem with this method is that it assumes measurable yield is linear beginning at Year 0 even though this is usually not the case. An adjustment factor can be applied to Von Mantel’s formula to account for the fact that significant volume yields do not occur at Year 0.
Von Mantel’s Method (triangle approx.)
- use of an adjustment to account for ages with zero volume

Using the previous example: \(a = 20\) because the yield table records no significant volume below age 20.

\[
G_R = \frac{70-20}{2} \quad 77 = 1925 \text{ on 70 acres}
\]

or 12,375 cords on 450 acres.

The Von Mantel formula generally:

- overestimates growing stock in cubic feet terms
- underestimates growing stock in board feet terms
- is independent of the yield table and is therefore very approximate.

![Diagram](image)

[Note: \(v_R = v_R^*\)

volume of oldest age class,
also growth or yield of
fully regulated forest.]

\[
G_R = \frac{R}{2} v_R
\]

adjustment factor, \(a\)

\[
G_R = \frac{R-a}{2} v_R
\]

Figure 5. Von Mantel Growing Stock Estimation
Yield Table Summation

Yield table summation is another method used to estimate growing stock. It is based on the assumption that the yield between any two ages increases linearly. Therefore, this formula will tend to overestimate some volumes while it will tend to underestimate others. Observe figure 6 below and see how the yield between any two age classes is approximated by a straight line. Growing stock is determined by summing the area of the trapezoids created by the straight lines between age classes.

![Diagram showing yield table summation](image)

**Figure 6.** Yield table summation (trapezoid method).

The summation of trapezoids can be written as:

\[ G_R = \left( \frac{V_0 + V_1}{2} \right) I + \left( \frac{V_1 + V_2}{2} \right) I + \ldots + \left( \frac{V_{n-1} + V_n}{2} \right) I \]

which is further simplified to:

\[ G_R = I \left( \frac{V_0 + V_1 + V_2 + V_3 + \ldots + V_n}{2} \right) \]

and again to:

\[ G_R = I \left( V_1 + V_2 + \ldots + \frac{V_n}{2} \right) \text{ because } V_0 = 0 \text{ (no measurable volume at time 0)} \]
where:

\[ G_R = \text{growing stock volume on } R \text{ acres of a fully regulated or normal forest} \]
\[ R = \text{rotation age and number of acres} \]
\[ I = \text{increment between age classes (age class interval)} \]
\[ V_n = \text{yield table volumes on a per acre basis for age class } n \]

If the stand is not fully stocked, a stocking percent should be directly applied to the derived growing stock.

**Yield Table Summation - Example**

Normal yield table for aspen (Table 3) SI = 80
Rotation \( R = 70 \)
450 acres
\[
G_{70} = 10 \left( V_{20} + V_{30} + \ldots + \frac{V_{70}}{2} \right)
\]
\[
= 10 \left( 0 + 7 + 31 + 52 + 67 + \frac{77}{2} \right)
\]
\[
= 1955 \text{ cords on 70 acres}
\]

On 450 acres normal growing stock equals

\[
\frac{450}{70} \times 1955 = 12,568 \text{ cords}
\]
Table 3. Normal yield table for quaking aspen; all trees 0.6 inches d.b.h. and larger (Brown and Gevorkiantz 1934)

<table>
<thead>
<tr>
<th>Site Index 80</th>
<th>Dominant</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
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<td>dbh</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>years</td>
<td>feet</td>
</tr>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>tree</td>
<td>tons</td>
</tr>
<tr>
<td></td>
<td>per acre</td>
<td></td>
</tr>
<tr>
<td></td>
<td>tree</td>
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<td></td>
<td>fresh</td>
<td></td>
</tr>
<tr>
<td></td>
<td>wt</td>
<td></td>
</tr>
</tbody>
</table>

| 20 | 44 | 3.3 | 1490 | 88 | 53 |
| 30 | 59 | 4.8 | 880  | 110| 89 |
| 40 | 71 | 6.3 | 600  | 129| 125| 31 | 5  |
| 50 | 80 | 8.1 | 400  | 143| 160| 52 | 25 |
| 60 | 88 | 10.3| 265  | 153| 191| 67 | 44 | 26 |
| 70 | 94 | 12.8| 185  | 161| 212| 77 | 58 | 46 |

<table>
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<th>Mean</th>
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</tr>
<tr>
<td></td>
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</tbody>
</table>

| 20 | 38 | 2.9 | 1800 | 83 | 46 |
| 30 | 52 | 4.2 | 1065 | 102| 76 |
| 40 | 62 | 5.4 | 760  | 120| 105| 17 |
| 50 | 70 | 7.0 | 495  | 133| 138| 39 | 12 |
| 60 | 77 | 9.0 | 330  | 144| 163| 55 | 31 | 3 |
| 70 | 82 | 10.9| 235  | 151| 184| 65 | 45 | 31 |

<table>
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<th>Mean</th>
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<tr>
<td></td>
<td>years</td>
<td>feet</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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<td>fresh</td>
<td></td>
</tr>
<tr>
<td></td>
<td>wt</td>
<td></td>
</tr>
</tbody>
</table>

| 20 | 33 | 2.3 | 2300 | 76 | 37 |
| 30 | 44 | 3.5 | 1400 | 94 | 62 |
| 40 | 53 | 4.3 | 980  | 110| 86 | 2  |
| 50 | 60 | 5.9 | 645  | 122| 107| 23 |
| 60 | 66 | 7.6 | 422  | 133| 130| 40 | 16 |
| 70 | 70 | 9.3 | 295  | 139| 145| 49 | 29 | 10 |

<table>
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<th>Mean</th>
</tr>
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<td>dbh</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>years</td>
<td>feet</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>tree</td>
<td>tons</td>
</tr>
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<td>fresh</td>
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</tr>
<tr>
<td></td>
<td>wt</td>
<td></td>
</tr>
</tbody>
</table>

| 20 | 28 | 1.9 | 3200 | 60 | 25 |
| 30 | 37 | 2.7 | 1910 | 75 | 40 |
| 40 | 44 | 3.5 | 1300 | 88 | 56 |
| 50 | 50 | 4.6 | 856  | 98 | 75 | 3  |
| 60 | 55 | 5.8 | 580  | 105| 88 | 18 |
| 70 | 58 | 7.1 | 400  | 109| 95 | 27 | 9  |

<table>
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<th>Dominant</th>
<th>Mean</th>
</tr>
</thead>
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<td>dbh</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>years</td>
<td>feet</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>tree</td>
<td>tons</td>
</tr>
<tr>
<td></td>
<td>per acre</td>
<td></td>
</tr>
<tr>
<td></td>
<td>tree</td>
<td></td>
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<td>fresh</td>
<td></td>
</tr>
<tr>
<td></td>
<td>wt</td>
<td></td>
</tr>
</tbody>
</table>

1Top diameters are inside bark.
2Cords and cunits are without bark.

Measurement of Growing Stock - Integration

Calculus can also be used in growing stock determinations. In this case, integration is very similar to the yield table summation method described earlier in that we are estimating the area under a curve. Integration is better in this instance because it can section off the area under the curve into a infinite number of extremely narrow trapezoids.
Example: silver maple, site index 70

Bd Ft Volume/acre = -4588 + 318.7 (age) - 1.765 (age²)

\[ G_R = \int_{A_0}^{A_R} \frac{Vol/acre}{A_0} = \text{area under curve between } A_0 \text{ and } A_R \text{ or 0 and 70} \]

\[ = -4588(\text{age}) + \frac{318.7}{2} (\text{age}^2) - \frac{1.765}{3} (\text{age}^3) \int_{A_0}^{A_R} \]

\[ G_R = 0 \int_0^{70} \frac{Vol/acre}{A_0} = 257,856 \text{ bd ft on 70 acres} \]

Relationship between growing stock and yield

As we stated earlier, in a fully regulated forest a relationship exists between the annual growth or yield (which could be harvested as an annual cut if the forest is regulated) of mature timber and total growth stock.

This relationship is stated as:

Annual Cut (AC) = volume present in the oldest age class

It can also be stated as:

\[ AC = \text{total annual growth of entire forest (excluding intermediate cuts)} \]

The relationship stated above is used in a formula developed by Hundeshagen as a means for estimating actual growth from a normal yield table. Hundeshagen's formula assumes that the ratio of estimated actual growth to estimated actual growing stock is proportional to the ratio of growth in a regulated forest and growing stock of a regulated forest.

\[ \frac{Y_s}{G_s} = \frac{Y_R}{G_R} \]

where:

\[ Y_s = \text{estimated actual growth or yield of a forest} \]
\[ Y_R = \text{regulated growth or yield of a forest} \]
\[ G_s = \text{estimated actual growing stock (or standing timber)} \]
\[ G_R = \text{regulated growing stock or what you are trying to achieve} \]

By restating the above as:

\[ Y_s = \frac{Y_R}{G_R} G_s \]
We see that actual growth of the forest can be estimated essentially through the use of a yield table. The ratio of $Y_R$ to $G_R$ is the ratio of growth (yield) to growing stock in a fully regulated forest which is applied to the actual forest growing stock to give us the actual growth (yield). This is also equal to the volume in the oldest age multiplied by the stocking percent.

This brings up the point that Hundeshagen's formula does have certain problems because of its direct application of yield table data:

1. comparability of data (normal yield table vs. actual stand)
2. utilization standards
3. effect of understocking (approach towards normality)

Application of Hundeshagen's formula:

Given: species = Aspen
    site index = 80
    rotation = 70
    $G_o = 1500$
    $G_R = 1955$ cords/70 acres (from yield table summation)
    $Y_R = $ gross yield in cords to a 4 inch top

Find: Estimated actual growth or yield of this stand

Solution:

$$Y_a = \frac{Y_R}{G_R} \cdot G_o$$

$$Y_a = \frac{59}{1955} \cdot 1500$$

$$Y_a = 59$$

To obtain the stocking percent divide the estimated actual yield by the yield of a regulated forest.

$$\frac{Y_a}{Y_R} = \frac{59}{77} \times 100 = 77\% \text{ stocked}$$

or you can use the growing stock

$$\frac{G_o}{G_R} = \frac{1500}{1955} = 77\%$$

Hundeshagen's formula does provide a fast approximation of harvestable growth but it is dependent on the use of yield tables. Also, Hundeshagen's formula makes the assumptions of no thinning, equal site quality and sufficient stocking to merit comparison between regulated and actual stands.
Example

Yield Table

<table>
<thead>
<tr>
<th>Age</th>
<th>Volume/Ac (green tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>53</td>
</tr>
<tr>
<td>30</td>
<td>89</td>
</tr>
<tr>
<td>40</td>
<td>125</td>
</tr>
<tr>
<td>50</td>
<td>160</td>
</tr>
<tr>
<td>60</td>
<td>191</td>
</tr>
<tr>
<td>70</td>
<td>212</td>
</tr>
</tbody>
</table>

Stand Characteristics

<table>
<thead>
<tr>
<th>Age</th>
<th>Acres</th>
<th>Vol/acre</th>
<th>Actual annual growth/acre (tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stand 1</td>
<td>40</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>60</td>
<td>100</td>
<td>150</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
<td>250</td>
<td>20</td>
</tr>
</tbody>
</table>

R = 50 years

Calculate:

1. What is the actual growing stock of the forest?

Soln: \[ G_a = (\text{vol/acre} \cdot \# \text{ of acres}) \]

\[ 100(50) + 150(100) + 20(250) = 25000 \text{ tons on 400 acres} \]

2. What is the regulated growing stock volume of the forest?

Note: use yield table summation

Soln: \[ G_R = I \left(V_i + V_2 + \ldots + V_n/2\right) \]

\[ G_R = 10 \left(53 + 89 + 125 + 160/2\right) \]

\[ = 3470 \text{ tons/50 acres} \]

\[ = 27760 \text{ tons/400 acres} \]

3. Determine the regulated growing stock volume of the forest using Von Mantel's method with and without adjustment.

Soln: \[ G_R = \frac{R}{2} Y_R \quad \text{With} \]

\[ G_R = \frac{R-a}{2} Y_R \quad \text{Without} \]
\[
\frac{50 \cdot 160}{2} \quad = \quad \frac{50 \cdot 10}{2}
\]

\[
= \quad 4000 \text{ tons/50 acres} \quad = \quad 3200 \text{ tons/50 acres}
\]

\[
= \quad 32,000 \text{ tons/400 acres} \quad = \quad 25,600 \text{ tons/400 acres}
\]

4. What is the annual yield of the forest according to Hundeshagen’s model?

Soln: \[Y_a = \frac{G_a}{G_R} \cdot Y_R\]

\[
= \frac{25000}{27760} \cdot 160
\]

\[
= 144 \text{ tons/50 acres}
\]

\[
= 1152 \text{ tons/400 acres}
\]

5. Determine the stocking percent of the forest.

Soln: Stocking % = \[\frac{G_a}{G_R} \times 100\]

\[
= \frac{25000}{27760} \times 100
\]

\[
= 90\% \text{ stocking}
\]

6. What is the actual total growth of the forest?

Soln: actual annual growth/ac x acres in each stand

\[
2(50) + 1(100) + 5(250) = 1450 \text{ tons/year}
\]

**Uneven-Age Management**

In regulating the cut in uneven-age stands, the concept of rotation age is replaced with the concept of the cutting cycle. The cutting cycle refers to the number of years between removal of volumes from any given parcel of uneven-age timber. In a balanced uneven-age forest the total area can be divided into as many blocks as there are years in the cutting cycle. Stand volume removals would take place every year in one of these management blocks. This is illustrated in figure 7 below.
The intensity of the cut within a parcel or subdivision is determined by a number of possible methods. One procedure that has been used frequently is the Austrian formula. Assume that regulated growing stock volume $G_R$ of the forest above is 30 cords/acre, actual growing stock volume $G_P$ is 35 cords/acre, current annual increment is 1 cord/acre, and the adjustment factor in the Austrian formula is 10 years. Then:

$$AC \text{ per acre} = 1 + \frac{35 - 30}{10} = 1.5 \text{ cords/acre}$$

If the forest is regulated, total growth would be removed each year from the parcel that is currently up for cutting, i.e., for a cutting cycle of 1 year, every year 240 cords would be removed from the 160 acre parcel or an average of 1.5 cords/acre. In the case of an 8-year cutting cycle, 240 cords would be removed from 20 acres or 12 cords/acre. The important thing to note is that the intensity of cutting increases with the increase of the cutting cycle while the interval between visits for any given parcel decreases.

**DETERMINATION OF ALLOWABLE CUT**

A number of characteristics, especially long time horizons and associated uncertainty, make forest planning one of the most difficult and challenging undertakings in forestry. Vastly better tools are available today to forest planners than only a few decades ago. Simplistic formula methods for calculation of allowable timber cuts have been replaced with sophisticated simulation procedures, allowing comparison of alternative management activities before actual implementation, and with optimization models that can provide optimal management schedules over time. Despite the enormous inroads that have been made to improve forest planning through the use of sophisticated optimization tools such as Linear Programming (LP), increased data collection efforts especially
for stand inventories and ready access to powerful computers, plans developed today are possibly not that much better than plans developed the "old-fashioned" way following classical European "Forsteinrichtung" procedures that emphasized the development of silviculturally, ecologically and economically sound stand management prescriptions with proper adjustments to reflect necessary compromises dictated by market conditions, environmental disasters, and social circumstances.

Determination of the Cut

The determination of the cut is probably the most important forest management decision. The cut has far-reaching consequences for the total forest enterprise, both its biological and economic components. However, the existence of multiple objectives implies that there is no exact solution.

The accuracy needed in the determination of the cut varies with the timber supply and demand situation. The allowable cut is typically calculated for a specific period, utilizing the most current inventory information, and is revised periodically. Allowable cut is composed of both final and intermediate cuts.

Major considerations concerning the cut are:

- Total volume that should be cut.
- Cutting sequence of stands.
- Species, size, and quality.
- Spatial arrangement of cuts.
- Future management options

The answer to these questions will depend on:

- Objectives of management.
- Markets.
- Silvicultural needs.
- Logging problems.
- Degree of harvest continuity desired.

The one feature of forests that we should not forget is that the crop seldom requires immediate removal and that storage is possible. Managers can take advantage of this.

There are many different approaches to the determination of the cut. All are based on the common regulatory principle that, if the actual volume of the forest is equal to the desired volume and distribution, then the actual yield on a sustained yield basis may be equivalent to the actual growth (Meyer et al. 1961). If the actual volume is below the desired level, the cut is kept below growth to provide for the accumulation of additional growing stock. Obviously, the reverse is true when the reserve is larger than desired.

Several general approaches to cut determination exist:

1. Area control.
2. Volume control.
3. Combined area and volume control.
4. Modern operations research techniques.
It should be emphasized that timber regulation problems are solved more and more by using operations research techniques such as linear programming and simulation. An example of the first is Timber RAM (Resources Allocation Model) developed by the U.S. Forest Service (Navon 1971). An example of the second is ECHO (Economic Harvest Optimization), a model developed by Walker (1971). These models often are more difficult to use because they require knowledge of operations research methods by forest managers and access to a computer. Such techniques also typically require more inventory information than the first three approaches.

It is important, therefore, to be familiar with some of the simpler cut determination models which can provide useful solutions if properly applied and interpreted. If not properly applied, these models can lead to less than desirable conditions of growing stock and growth. It is the intent here to introduce these models (1 to 3 above) and to provide illustrative examples. These examples will serve to highlight advantages and disadvantages of various methods, and point to some of the major factors that should be considered in their selection. A computer model will be introduced to facilitate speedy calculations and examination of various strategies and initial conditions.

**Area Control**

The principle of area control is very simple. This method determines the allowable cut in terms of volume on the basis of acres assigned for cutting. Specifically the area cut per year equals the total acres divided by rotation. Since volume must occupy area and area available directly determines volume, cutting in this manner is quite logical.

As an example consider the following situation. A 1,600 acre tract of forest has been inventoryed. It was found that the entire area is well stocked with red pine. Three distinct, even-aged compartments (stands) are present. The manager decides that the area would be best utilized if it were regulated at the earliest possible time. Projected market conditions are such that any cutting schedule used during rotation one will not alter the supply-demand relationship. Area control techniques seem to be appropriate in this situation. A rotation age of 80 years will be assumed. Experience shows that a stocking level (in relation to normal yield table values) of 90 percent can be maintained once the forest is regulated.

The information obtained from the inventory is shown in the following diagram. The necessary step-by-step calculations follow using the yield table (Table 4).
Table 4. Yield per acre (ft\(^3\)) by age and site index of fully-stocked, even-aged red pine stands in Minnesota.*

<table>
<thead>
<tr>
<th>Stand age</th>
<th>Site index</th>
<th>45</th>
<th>55</th>
<th>65</th>
<th>75</th>
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</thead>
<tbody>
<tr>
<td>30</td>
<td></td>
<td>888</td>
<td>1,283</td>
<td>1,743</td>
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<td>6,214</td>
<td>8,442</td>
<td>10,976</td>
</tr>
<tr>
<td>140</td>
<td></td>
<td>4,449</td>
<td>6,428</td>
<td>8,732</td>
<td>11,353</td>
</tr>
<tr>
<td>150</td>
<td></td>
<td>4,581</td>
<td>6,619</td>
<td>8,992</td>
<td>11,691</td>
</tr>
</tbody>
</table>

* Values found from the equation: \[
\text{Yield} = 6.4088 \cdot S^{1.8342} e^{-0.534/A}
\]

where: \(S\) = site index

\(A\) = age

Base data are from Table 10, Eyre, F. H. and P. Zehngraff. 1948. "Red Pine Management in Minnesota." USDA Cir. No. 778, 70 pp. Yield is total cubic feet per acre excluding bark of trees 5 inches dbh and larger, to a top diameter of 4 inches inside bark.

I. Acres per age class under regulation assuming equal site productivity = acres/rotation range = 1,600/80 = 20 acres.

The procedure must be modified when different sites and stocking levels are present to adjust for differences in productivity. The aim is to get areas of equal productivity rather than equal surface area. The question that must be answered is: how much acreage should be cut annually to insure uniform volume production after rotation one?

II. **Yield per acre at 80 years**

<table>
<thead>
<tr>
<th>Stand</th>
<th>Yield per acre</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.</td>
<td>6,280 ft(^3)</td>
</tr>
<tr>
<td>B.</td>
<td>3,199 ft(^3)</td>
</tr>
<tr>
<td>C.</td>
<td>8,165 ft(^3)</td>
</tr>
</tbody>
</table>

III. Average productivity weighted by acres:

\[
\text{Average} = \frac{(6,280 \times 700) + (3,199 \times 300) + (8,165 \times 600)}{1,600} = 6,409 \text{ ft}^3.
\]

IV. Areas of equal productivity (acres cut per year):

A. \((6,409/6,280) \times 20 = 20.4\) acres.
B. \((6,409/3,199) \times 20 = 40.1\) acres.
C. \((6,409/8,165) \times 20 = 15.7\) acres.
V. Cutting time per stand:

A. $700/20.4 = 34.3$ years
B. $300/40.1 = 7.5$ years
C. $600/15.7 = 38.2$ years

The order in which the stands will be cut must now be known. For simplicity we will assume that stands will be cut from oldest to youngest, i.e., A, C, B.

VI. Average age at harvest:

A. $80 + 34.3/2 = 97$ years.
B. $40 + 34.3 + 38.2/2 = 113$ years.
C. $60 + 34.3 + 38.2 + 7.5/2 = 116$ years.

VII. Volume harvested (per year) in rotation one:

A. $7,187 \times 20.4 \times 0.90 = 131.95$ M ft$^3$
B. $10,222 \times 15.7 \times 0.85 = 136.41$ M ft$^3$
C. $4,062 \times 40.1 \times 0.80 = 130.31$ M ft$^3$

VIII. Volume harvested (per year) in future rotations:

A. $6,280 \times 20.4 \times 0.90 = 115.30$ M ft$^3$
B. $3,199 \times 40.1 \times 0.90 = 115.45$ M ft$^3$

There are a number of advantages and disadvantages the forest manager should be aware of when considering area control. Davis and Johnson (1987) lists the following:

- The volume cut is the average volume per unit of area multiplied by the area cut.
- Area control applied to an irregular forest and strictly followed yields irregular cuts in volume, size, and quality of timber.
- After one rotation, the forest will be completely regulated.
- An approximately uniform annual cut in rotation one cannot be obtained from an irregular forest by strict area control.
- The procedure is simple and direct.
- Areas to be cut are identified with areas on the ground (good for silvicultural considerations).
- It is particularly suited to forests composed of even-aged stands.
- If the forest is largely mature, the method may cause great losses from holding stands too long.
- Volumes (unit of production) are not explicitly considered.

---

$^1$Yield per acre at average harvest age times IV (area of equal productivity) times stocking percent.
Volume Control

In volume control the cut is determined by the conditions of the existing growing stock and often the growth of the growing stock. It should be noted that:

- Most volume control methods provide an approximate estimate which is applied for a short period of time and then reevaluated.
- Many of the methods are equally applicable to uneven-aged and even-aged stands (in fact all those not dependent on yield tables).
- In all cases a cut figure in terms of volume is determined and as many acres as necessary are cut.

A brief synopsis of the various formulas follows. For more detailed information, see Davis and Johnson (1987) or Meyer et al. (1961).

**Von Mantel's and Hundeshagen's**

- Both are very simple to apply.
- Neither consider whether present growing stock is desirable.
- They should only be applied in well-regulated stands because the simplifying assumptions do not necessarily apply well for a broad range of forest conditions.
- Von Mantel's assumes linear increase in growing stock with age.

1. **Von Mantel Formula**

   a) Von Mantel formula is applicable if age class distribution is approximately normal.
   b) Irregularity can exist in density of stocking.
   c) This formula will give satisfactory results if the above conditions exist.
   d) Best results are obtained if cubic measure is used.

   \[
   Y_a = \text{actual yield or allowable cut} = \frac{\text{actual growing stock volume}}{R/2}
   \]

   \[
   R = \text{rotation age}
   \]

   \[
   G_a = \text{actual volume of growing stock}
   \]

   \[
   Y_a = \frac{G_a}{R/2} \quad \text{or} \quad \frac{2G_a}{R-a}
   \]

   where \( a = \text{adjustment period} \).

2. **Hundeshagen Formula**

   a) Needs same condition as Von Mantel formula--normal age class distribution.
   b) In addition requires yield table for its application.
   c) The formula is essentially a scheme for estimating growth from a yield table.
   d) Hundeshagen's formula assumes that growth or yield in an actual forest, approximately regular in distribution, bears the same relation to its total growing stock as growth in a fully stocked regulated forest, as represented by normal yield tables, bears to its growing stock.

   Expressed as a proportion:

   \[
   \frac{Y_a}{G_a} = \frac{Y_R}{G_R}
   \]
\[ Y_a = \text{actual yield} \]
\[ G_a = \text{actual growing stock} \]
\[ Y_R = \text{growth or yield in a fully stocked forest} \]
\[ G_R = \text{growing stock in a fully stocked forest} \]

Consideration of the growth of the growing stock is incorporated in a number of volume regulation models. Generally, these models are superior to the ones which ignore growth. It should be understood, however, that the determination of the growth is one of the most difficult measurements in forestry practice. A discussion of the measurement of growth can be found in Davis and Johnson (1987) and Husch, Miller and Beers (1972).

Examples of allowable cut formulas which modify increment with growing stock information are:

3. **Austrian**

\[ AC = I + \frac{G_a - G_R}{a} \]

- \(I\) = current annual increment
- \(a\) = number of years in adjustment period.
- Reduce or increase the cut to build up or reduce average growing stock level.
- Better than Von Mantel and Hundeshagen in irregular conditions (age).
- Best when growing stock consists of even-aged second growth stands.
- Assume balanced stocking.

4. **Chapman's**

\[ AC = I_e + \frac{G_a - G_R}{R} \]

- \(I_e\) = MAI at rotation age and average density of stocking. \(G_a, G_R, \text{and } R\) as before.

5. **The "Modified" Barnes Method and Tabular Check**

Barnes (1951) described a new method of volume regulation that was based on the calculation of allowable cut in such a manner that the total inventory would be cut once over one rotation. Since annual allowable cut is closely related to average age at harvest, it follows that if an estimate can be made of average cutting age during rotation one, the actual yield obtainable at that age should furnish a good estimate of allowable cut (Barnes 1951).

To calculate allowable cut, the following steps are required:

1) Compute average weighted (by acres) age of growing stock over all stands (AG).
2) Determine average cutting age.
   - If a forest has a "normal" distribution of age classes then average age of growing stock is \(R/2\).
   - As an approximation to actual average cutting age we use: \(RA = AG + R/2\).
3) Compute average weighted (by acres) stocking over all stands.
4) \(AC = (\text{normal volume/acre at } RA \text{ for average SI}) \times \text{stocking} \times A/R\).
We will call this allowable cut the "modified" Barnes estimate. (Barnes describes a slightly more cumbersome estimate.) In the procedure recommended by Barnes, this allowable cut "guess" becomes the starting point of an iterative process designed to refine the "guess" and derive a better estimate of allowable cut. With this estimate the sum of the individual cutting times of all stands in the inventory equals rotation age. This iterative process to be described next is known as the Tabular Check or Barnes Method.

It involves:

a) The estimation of a "true" cutting time for each stand given an initial trial harvest level.

b) The summation of the individual cutting times of each stand for the given harvest level.

c) An adjustment if the trial harvest level yields a sum of cutting times unequal to rotation.

We will outline these steps in the following:

Estimation of "true" cutting time for a stand:

1) Set trial-cut level (from modified Barnes).
2) Calculate initial estimate of cutting time for stand.
   \[ \text{yield at current stand age} \over \text{trial cut} = NY_i \]
3) Calculate average age at harvest
   \[ \text{current age} + \frac{NY_i}{2} \]
   \[ = AG_i \]

where: \( i = 1, 2, 3, ... \) indicates the step reached in the iteration.

4) Calculate yield at average harvest age \( AG_i \).
5) Recalculate years to cut from stand
   \[ \text{yield at age} AG_i \over \text{trial cut} = NY_{i+1} \]

6) If \( (AG_i - AG_{i+1} \leq 0.01) \) start at step 1 for next stand where 0.01 is an arbitrary stopping level which defines accuracy of the cutting time. Use a starting age for next stand: stand age \( + NY_{i+1} \).

7) Otherwise go back to step 3.

A graphical illustration of this procedure is shown in Figure 8. We, therefore, approach a "true" cutting time by using increasingly accurate estimates of volume at average harvest age. With a large number of stands a computer solution is necessary.
Figure 8. Cutting time iteration.

Note: Interpolation in the yield table (Table 4)

To determine volume at age 62.98 for site index 65, use straight-line interpolation or substitute age into yield function:

\[ V_{62.98} = V_{60} + \frac{(\text{actual age} - 60)}{70-60} (V_{70} - V_{60}) \]

\[ = 4,860 + \frac{62.98 - 60}{10} (5,627 - 4,860) \]

\[ = 5,088 \text{ ft}^3 \]

or

\[ V_{62.98} = 6.4088 \times 1.8342 e^{1.534/4} \]

\[ = 5,101 \text{ ft}^3 \text{ using } S = 65 \]

\[ A = 62.98 \]

Once this procedure has been carried out for each stand using the initial trial level for allowable cut, an estimate is obtained of the sum of cutting times over all stands. If the sum of cutting times is not equal to the rotation, a new level for the allowable cut is set and a new cutting time iteration, stand by stand, is started with the new cutting level. Obviously, if the sum of cutting times is greater than rotation age, our next guess should be larger than the initial and correspondingly smaller if the sum of cutting times is less than rotation age.
This iteration is continued until the difference between the sum of cutting times over all stands and rotation age is negligible. To find a cutting level which will ultimately make this difference equal or close to zero, an efficient iteration technique such as Newton-Raphson or interval halving should be used (Figures 9, 10).

Figure 9. Newton-Raphson iteration of determining allowable cut with the Tabular Check.
Volume Control (Illustration)

- Same data as area control example.
- Need to calculate:
  a) Actual growing stock volume $G_x$.
  b) Regulated growing stock volume $G_R$.
  c) Yield for regulated growing stock condition $Y_R$.
  d) Current annual increment (CAI).
  e) Mean annual increment at rotation age (MAI_R).
  f) Average age of current growing stock weighted by acres $A_w$.
  g) Average stocking level at present weighted by acres $S_w$.
  h) Average weighted site index $SI_w$ (weighted by acres).

(1) Actual growing stock volume $G_x$:
$$G_x = 6,280 \times 0.90 \times 700 + 1,483 \times 300 \times 0.80 + 6,319 \times 0.85 \times 600 = 7,535,010 \text{ ft}^3.$$ 

(2) Regulated growing stock volume $G_R$ (yield table summation)
- Need to calculate average weighted site index $SI_w$
  $$SI_w = (65 \times 700 + 75 \times 600 + 45 \times 300)/1,600 = 65$$
  $$G_R = G_80 = 10(1.743 + 2.910 + 3.959 + 4.860 + 5.627 + \frac{6.280}{2}) = 222,390 \text{ ft}^3 \text{ on 80 acres}$$
222,390 \ \frac{1,600}{80} = 4,447,800 \text{ ft}^2 \text{ on 1,600 acres.}

Often managers have evidence that their stands are not growing at the level indicated in the yield table requiring an adjustment of \( G_R \) obtained from a yield table. Assume that the growth of the inventory is at 90 percent of the yield table, then desired growing stock volume after regulation would be:

\[
G_R = 4,447,800 \times 0.9 = 4,003,020
\]

(3) Yield for regulated growing stock

\[
Y_R = Y_{80} = 6.280 \times \frac{1,600}{80} \times 0.90 = 113,040 \text{ ft}^2.
\]

(4) Current annual increment.
- Calculate derivative of yield function for each stand in its current condition and sum over all stands.

Red pine yield:

\[
Y = 6.4088SI^{1.8342} e^{-61.534/\text{age}}
\]

\[
\text{CAI} = \frac{\text{dy}}{d \text{Age}} = \frac{394.359 SI^{1.8342} e^{-61.534/\text{Age}}}{\text{Age}^2}
\]

Giving CAI for fully stocked stands on a per acre basis

<table>
<thead>
<tr>
<th>Stand</th>
<th>Age</th>
<th>CAI</th>
<th>CAI x acres x stocking</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.</td>
<td>80</td>
<td>60,382</td>
<td>60,382 x 700 x 0.90</td>
</tr>
<tr>
<td>B.</td>
<td>40</td>
<td>57,016</td>
<td>57,016 x 300 x 0.80</td>
</tr>
<tr>
<td>C.</td>
<td>60</td>
<td>108,001</td>
<td>108,001 x 600 x 0.85</td>
</tr>
</tbody>
</table>

Total 106,805 ft\(^3\)

Alternative method: Calculate CAI for average age-site stocking combination.

a) Average weighted age: \( A_w \)

\[
A_w = (80 \times 700 + 60 \times 600 + 40 \times 300)/1,600 = 65 \text{ years.}
\]

b) Average weighted site index \( S_w \)

\[
S_w = (0.90 \times 700 + 0.80 \times 300 + 0.85 \times 600)/1,600 = 0.86
\]

c) Average weighted site index \( S_w \)

CAI for \( A_w, S_w, \) and \( S_w \) would be misleading because of severe nonlinearity of growth curve, but surely is less work.
CAI (A_w, S_w, SI_w) = (394,359 x 65^1.8342 x e^{61.534/65})/65^2 x 0.86 =
76.59 x 0.86 = 66.06 ft^3/acre or a total of 105,696 ft^3.

Note that the first method is preferred especially when widely differing stands are being considered.

(5) Mean annual increment at rotation age (and average SI):

\[ MAI_R = \frac{\text{yield at age 80 for SI}_w = 65}{80} = \frac{6,280}{80} = 78.5 \text{ ft}^3/\text{acre}. \]

To find appropriate a value for the current forest multiply by acres and S_w:

\[ MAI_R = 78.5 \times 1,600 \times 0.86 = 108,330 \text{ ft}^3 \]

which estimates the sum of all increments for all stands as if they were harvested at rotation age.

**Summary of information:**

\[ G_a = 7,535,010 \text{ ft}^3 \text{ SI}_w = 65 \]
\[ G_R = 4,003,020 \text{ ft}^3 \text{ S}_w = 0.86 \]
\[ Y_R = 113,040 \text{ ft}^3 \text{ A}_w = 65 \]
\[ CAI = 106,805 \text{ ft}^3 \]
\[ MAI_R = 108,330 \text{ ft}^3 \]

**Von Mantel**

\[ AC = \frac{2}{R} \quad G_a = \frac{2}{80} (7,535,010) = 1.88,375 \text{ ft}^3. \]

or

\[ AC = \frac{2}{R-a} G_a = \frac{2}{80-30} (7,535,010) = 301,400 \text{ ft}^3. \]

**Hundeshagen**

\[ AC = \frac{Y_R}{G_R} G_a = \frac{113,040}{4,003,020} 7,535,010 = 212,779 \text{ ft}^3. \]

**Austrian Formula**

\[ AC = CAI + \frac{G_a - G_R}{a} = 106,805 + \frac{7,535,010 - 4,003,020}{30} \text{ assuming 30-year adjustment period.} \]

**Chapman's Formula**

\[ AC = MAI_R + \frac{G_a - G_R}{R} \]

\[ AC = 108,330 + \frac{7,535,010 - 4,003,020}{80} = 152,480 \text{ ft}^3. \]
Modified Barnes Formula

\[ AC = \text{yield at average cutting age times average weighted density}. \]

Average cutting age \( RA = A_w + R/2 = 65 + 80/2 = 105 \)
yield at age 105
(and average \( SI_w = 65 = 7542.4 \)

\[ AC = 7,542.4 \times 0.86 \times \frac{1.600}{80} = 130,106 \text{ ft}^3. \]

**TABULAR CHECK**

The following three tables illustrate all the calculations necessary in the Tabular Check or Barnes Method (Tables 5-7). Note that the initial trial cut for the harvest time iteration is based on the calculation of allowable cut according to the Modified Barnes Method, i.e., 130 M ft\(^3\). The sum of the cutting times being greater than the rotation, a new trial harvest level is calculated (138 M ft\(^3\)), yielding a sum of cutting times smaller than the rotation. The next and final trial cut of 134 M ft\(^3\), obtained using a Newton-Raphson iteration, stops the procedure because the sum of cutting times closely approximates the rotation.

At this point we have generated six solutions to the volume control problem (Table 8). It is apparent that the results of the various approaches differ substantially, from 130,106 ft\(^3\) for the Modified Barnes method to 224,538 ft\(^3\) for the Austrian method.
### Table 5: Tabular check, first iteration.

<table>
<thead>
<tr>
<th>Stand</th>
<th>Site Index</th>
<th>Stocking Percent</th>
<th>Present Age</th>
<th>Present Volume (Total)</th>
<th>Average Age at Harvest</th>
<th>Average Volume at Harvest</th>
<th>Cutting Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Acres</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>65</td>
<td>.90</td>
<td>80</td>
<td>6.280 x 0.90 x 700</td>
<td>80 + (3956 / 130) / 2 = 96.2</td>
<td>7.01 x 0.90 x 700 = 4474</td>
<td><strong>4474 / 130</strong> = 34.4</td>
</tr>
<tr>
<td></td>
<td>700</td>
<td></td>
<td></td>
<td></td>
<td>80 + 34.4 / 2 = 97.2</td>
<td>7.196 x 0.90 x 700 = 4533</td>
<td>4533 / 130 = 34.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>80 + 24.9 / 2 = 97.4</td>
<td>7.207 x 0.90 x 700 = 4540</td>
<td>4540 / 130 = 35.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>700</td>
<td></td>
<td></td>
<td>35</td>
</tr>
<tr>
<td>C</td>
<td>75</td>
<td>.85</td>
<td>60 + 35 = 95</td>
<td>4.120 x 0.85 x 600</td>
<td>95 + (4702 / 130) / 2 = 113.1</td>
<td>10.226 x 0.85 x 600 = 5215</td>
<td><strong>5215 / 130</strong> = 40.1</td>
</tr>
<tr>
<td></td>
<td>600</td>
<td></td>
<td></td>
<td></td>
<td>95 + 40.1 / 2 = 115.1</td>
<td>10.322 x 0.85 x 600 = 5264</td>
<td>5264 / 130 = 40.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>95 + 40.5 / 2 = 115.2</td>
<td>10.331 x 0.85 x 600 = 5269</td>
<td>5269 / 130 = 40.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>95</td>
<td></td>
<td></td>
<td>35 + 40.5 = 75.4</td>
</tr>
<tr>
<td>B</td>
<td>45</td>
<td>.80</td>
<td>40 + 15.4 = 115.4</td>
<td>4.061 x 0.80 x 300</td>
<td>115.4 + (572 / 130) / 2 = 119.1</td>
<td>4.119 x 0.80 x 300 = 988</td>
<td><strong>988 / 130</strong> = 7.6</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td></td>
<td></td>
<td></td>
<td>115.4 + 7.6 / 2 = 119.2</td>
<td>4.120 x 0.80 x 300 = 989</td>
<td>989 / 130 = 7.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>300</td>
<td></td>
<td></td>
<td>75.4 + 7.6 = 83</td>
</tr>
</tbody>
</table>
Table 6. Tabular check, second iteration.

<table>
<thead>
<tr>
<th>Stand</th>
<th>Site Index</th>
<th>Stocking Percent</th>
<th>Present Age</th>
<th>Present Volume (Total)</th>
<th>Average Age at Harvest</th>
<th>Average Volume at Harvest</th>
<th>Cutting Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>65</td>
<td>0.40</td>
<td>80</td>
<td>6.280 x 0.90 x 700</td>
<td>80 + \left(\frac{345}{138}\right)/2 = 94.3</td>
<td>7.058 x 0.90 x 700 = 4447</td>
<td>4501 / 138 = 32.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>700</td>
<td>3956</td>
<td>90 + \frac{32.7}{2} = 96.1</td>
<td>7.145 x 0.90 x 700 = 4501</td>
<td>4501 / 138 = 32.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>90 + \frac{32.6}{2} = 96.3</td>
<td>7.154 x 0.90 x 700 = 4506</td>
<td>4506 / 138 = 32.7</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>75</td>
<td>0.85</td>
<td>60</td>
<td>9.069 x 0.85 x 600</td>
<td>92.7 + \left(\frac{4662}{138}\right)/2 = 109.5</td>
<td>10.043 x 0.85 x 600 = 5122</td>
<td>5122 / 138 = 37.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>32.7 =</td>
<td>4626</td>
<td>92.7 + 31.1/2 = 111.3</td>
<td>10.134 x 0.85 x 600 = 5169</td>
<td>5169 / 138 = 37.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>600</td>
<td></td>
<td>92.7 + 37.5/2 = 111.4</td>
<td>10.143 x 0.85 x 600 = 5173</td>
<td>5173 / 138 = 37.5</td>
</tr>
<tr>
<td>B</td>
<td>45</td>
<td>0.80</td>
<td>40</td>
<td>3.949 x 0.80 x 300</td>
<td>110.2 + \left(\frac{460}{138}\right)/2 = 113.6</td>
<td>4.017 x 0.80 x 300 = 964</td>
<td>964 / 138 = 7.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>70.2 =</td>
<td>947.9</td>
<td>110.2 + 7/2 = 113.7</td>
<td>4.018 x 0.80 x 300 = 964</td>
<td>964 / 138 = 7.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>300</td>
<td></td>
<td></td>
<td></td>
<td>= 77.2</td>
</tr>
</tbody>
</table>

Table 7. Tabular check, final iteration.

<table>
<thead>
<tr>
<th>Stand</th>
<th>Site Index</th>
<th>Stocking Percent</th>
<th>Present Age</th>
<th>Present Volume (Total)</th>
<th>Average Age at Harvest</th>
<th>Average Volume at Harvest</th>
<th>Cutting Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>65</td>
<td>0.90</td>
<td>80</td>
<td>6.280 x 0.90 x 700</td>
<td>80 + \left(\frac{345}{134}\right)/2 = 94.8</td>
<td>7.079 x 0.90 x 700 = 4460</td>
<td>4460 / 134 = 33.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>700</td>
<td>3956</td>
<td>80 + 33.3/2 = 96.6</td>
<td>7.169 x 0.90 x 700 = 4577</td>
<td>4577 / 134 = 33.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>80 + 33.7/2 = 96.9</td>
<td>7.180 x 0.90 x 700 = 4523</td>
<td>4523 / 134 = 33.8</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>75</td>
<td>0.85</td>
<td>60</td>
<td>9.141 x 0.85 x 600</td>
<td>93.8 + \left(\frac{462}{134}\right)/2 = 111.2</td>
<td>10.132 x 0.85 x 600 = 5167</td>
<td>5167 / 134 = 38.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>33.8 =</td>
<td>4662</td>
<td>93.8 + 38.6/2 = 113.1</td>
<td>10.226 x 0.85 x 600 = 5215</td>
<td>5215 / 134 = 38.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>600</td>
<td></td>
<td>93.8 + 38.9/2 = 113.3</td>
<td>10.234 x 0.85 x 600 = 5220</td>
<td>5220 / 134 = 39.0</td>
</tr>
<tr>
<td>B</td>
<td>45</td>
<td>0.80</td>
<td>40</td>
<td>4.000 x 0.80 x 300</td>
<td>112.8 + \left(\frac{460}{134}\right)/2 = 116.4</td>
<td>4.069 x 0.80 x 300 = 976</td>
<td>976 / 134 = 7.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>72.8 =</td>
<td>960</td>
<td>112.8 + 7.3/2 = 116.4</td>
<td>4.070 x 0.80 x 300 = 977</td>
<td>977 / 134 = 7.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>300</td>
<td></td>
<td></td>
<td></td>
<td>= 80.1</td>
</tr>
</tbody>
</table>
A number of questions arise at this point: Which of the regulation formulas should be used? What is the long-term effect on inventory growth and growing stock of following each of the calculated cutting levels? To answer these and other questions a simulation program will be introduced that will facilitate the calculations of allowable cuts and their implementation while keeping track of the changing conditions of inventories due to cutting and growth accumulation. The program, furthermore, will be used to compare the regulation formulas described here over a 200-year projection period using an actual forest inventory.

<table>
<thead>
<tr>
<th>Table 2. Summary: volume control results.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stand</td>
</tr>
<tr>
<td>A</td>
</tr>
<tr>
<td>B</td>
</tr>
<tr>
<td>C</td>
</tr>
</tbody>
</table>

\[ S_{AV} = 65; S_{AW} = 0.86; A_{W} = 65 \]
\[ G_{AV} = 7,535,010 \]
\[ G_{A} = 4,003,020 \]
\[ Y_{AV} = 113,040 \]
\[ CAI = 106,805 \]
\[ MAI = 108,330 \]

Von Mantel AC = 188,375 or 301,400 with a = 30
Hundeshagen AC = 212,779
Austrian AC = 224,538
Chapman AC = 152,480
Modified Barnes AC = 130,106
Tabular Check AC = 134,000
All volume units in ft³

<table>
<thead>
<tr>
<th>Table 3. Yield per acre (ft³) by age and site index of fully stocked, even-aged, pure aspen stands in the Lake States.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stand</td>
</tr>
<tr>
<td>A</td>
</tr>
<tr>
<td>B</td>
</tr>
<tr>
<td>C</td>
</tr>
<tr>
<td>D</td>
</tr>
<tr>
<td>E</td>
</tr>
<tr>
<td>F</td>
</tr>
<tr>
<td>G</td>
</tr>
<tr>
<td>H</td>
</tr>
</tbody>
</table>

1Values found from the equation:
\[ \text{Yield} = 8.9836 S^{1.5494} e^{-0.675 A} \]
where: S = site index
A = age

Base data are from Table 154, Brown, R. M. and S. R. Gervorkiantz, 1934, "Volume, Yield, and Stand Tables for Tree Species in the Lake States." University of Minnesota Agricultural Experiment Station Technical Bulletin 39, 208 pp.
Yield is total cubic feet per acre excluding bark for all trees 10 inches dbh and larger.
ALLOWABLE CUT SIMULATION

Simulation models have been used extensively in forest management to estimate maximum harvest levels that can be maintained over time. These models are concerned with determining how much timber can be harvested and tend to ignore the problem of scheduling specific stands for treatment; they either assume a simple scheduling rule or require one as a model input. The key to the model must be in the way it ranks stands or stand treatments. Simple rules like oldest stands first, do not take into account important economic factors like distance to market, or relationships between existing timber supplies and timber demand. At times, it might be important to weigh heavily the impact of actions on future growth and mortality, but under other circumstances it might be best to follow a simple greedy algorithm and minimize the initial harvest plus transport costs. Developing a method of prioritizing alternatives is the major difficulty in developing a simulation model for timber management scheduling. Good heuristic rules have not been identified for the timber management scheduling problem. The prioritizing method must be responsive to the changing conditions of the forest over time. It must be sensitive to the relative levels of timber demand and supply and how these relative levels change over time. Specifically, it must be capable of determining when management needs to gear up and invest heavily in regeneration activities, and when management can cut back and rely on existing inventories. To be responsive in this sense, it seems that some sort of adjusting mechanism or tuning process is essential for prioritizing alternatives within the simulation process. Supply and demand relationships are difficult to describe, and are definitely dependent on the schedule implemented.

Simulation models used for determining allowable cut levels, use the fixed-time step method of modelling. They mimic management by actually harvesting and growing stands over time. Each period they rank stands and harvest until the current estimate of the allowable/desirable cut is reached. This approach has several inherent problems. First, forests contain multiple products. There is not one simple harvest level to achieve each period. Harvesting an individual stand usually produces timber for several products. Meeting cut levels for all products simultaneously can be difficult. Another problem with the fixed-time step method is in recognizing the many options available for individual stands, as well as the long-term impact of those actions. The situation is not always so simple as deciding whether or not to harvest. Thinning as well as clearcuts are possible. Furthermore, full tree chipping, traditional roundwood operations, and chip and sort systems are all considered clearcuts, yet each yields significantly different products and total volumes.

Using the Allowable Cut Evaluation Simulator (ACES)

Microcomputer algorithms have been developed to simplify the task of enumerating the various methods for determining an allowable cut. Access to these algorithms or models does not diminish the decision makers need to understand the conceptual basis of allowable cut calculations and the importance of the data inputs required for application of these tools.

One recently developed program is the Allowable Cut Evaluation Simulator (ACES) described in Rose and Burk (1986). This program can be run on a microcomputer or the University's Cyber mainframe computer. Input requirements are limited to stand data and various run parameters. Beyond this, ACES is a menu-driven microcomputer program written for the IBM personal computer and IBM compatibles in Microsoft FORTRAN. The program allows the user to quickly calculate allowable cuts using one of six volume control methods or area control with adjustment for site productivity. Input data required for the program consist of (1) stand data describing current inventories of the cover type for which allowable cuts are to be calculated and (2) a number of run parameters. Stand data or stand parameter inputs created via keyboard input may be
permanently saved before logging off to facilitate future analysis with similar data and to reduce the time and effort for data entry. Most input statements are checked by the program for correctness. An error message will appear on the screen if the user enters an unacceptable input value. The user at this point can correct the data entry error and proceed with the analysis.

The user's manual (Rose and Burk 1986) serves several functions:

1. to describe how ACES is used for allowable cut calculations.
2. to illustrate the various output options of the program through examples.
3. to facilitate data preparation for allowable cut analysis and to support classroom instruction and independent study.

Program Inputs

ACES can be used to organize and develop allowable cut schedules. Program inputs consist of the following information:

1) Stand data required for each stand includes acres, age, stocking either in volume units (cubic feet or cords) or as a stocking percent, and site index.

2) Run parameters including:
   - Abbreviated output: (Y or N)
   - Volume output units: (Cu Ft or Cords)
   - Ageclass width: Years
   - Species selected: 1 or 2
   - Rotation: Years
   - Min. cutting age: Years
   - Anticipated stocking after harvest: Percent
   - Interval to reevaluate allowable cut: Years
   - Number of times to evaluate allowable cut:
   - Cut determination method: 1=Tabular Check, 2=Modified Barnes
     3=Austrian, 4=Chapman, 5=Hundeshagen
     6=Von Mantel, 7=Area Control
   - Stocking: 1=Percent of normal, 2=Volume
   - Volume units: 1=Cubic Feet, 2=Cords
   - Stocking of young stands: Percent
   - Cutting priority: 1=Age, 2=Age and Site

These data are entered either from the keyboard or are loaded directly from previously created disk files. After data has been entered, it can be easily edited from within the program.

An option to save program input values (stand data as well as run parameters) is provided. After all input data has been entered and the appropriate calculations have been performed, ACES also writes information shown on the screen to a disk file which can be recalled at any time for printing.
Instructions for Using ACES

After inserting the disk with the ACES software into drive A or B, type <ACES> after the A> or B> prompt and then press the <ENTER> key. For hard disk users, the program is executed by typing <ACES> and pressing the <ENTER> key after going to the subdirectory on which ACES resides. This key is used to send typed information from the keyboard to the central processing unit of the microcomputer. (Do not type the < and > marks here or anywhere else where information entry is requested). The <ENTER> key must be pressed after typing in the appropriate response to the data entry prompts within the program.

Program Outputs

The following example illustrates the inputs required by ACES and the outputs generated by ACES from these stand and run parameters inputs:

Sample Case: Tabular Check Volume Control - Short Output

I. Inputs

<table>
<thead>
<tr>
<th>Stand</th>
<th>Acres</th>
<th>Age</th>
<th>Stocking (Volume or %)</th>
<th>Site Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1200.00</td>
<td>15.</td>
<td>80.00</td>
<td>65.</td>
</tr>
<tr>
<td>2</td>
<td>1264.00</td>
<td>75.</td>
<td>23.80</td>
<td>65.</td>
</tr>
<tr>
<td>3</td>
<td>2766.00</td>
<td>35.</td>
<td>36.10</td>
<td>65.</td>
</tr>
<tr>
<td>4</td>
<td>14045.00</td>
<td>55.</td>
<td>33.30</td>
<td>65.</td>
</tr>
<tr>
<td>5</td>
<td>11000.00</td>
<td>65.</td>
<td>75.00</td>
<td>65.</td>
</tr>
<tr>
<td>6</td>
<td>5000.00</td>
<td>45.</td>
<td>50.00</td>
<td>70.</td>
</tr>
<tr>
<td>7</td>
<td>4002.00</td>
<td>55.</td>
<td>25.40</td>
<td>55.</td>
</tr>
<tr>
<td>8</td>
<td>1422.00</td>
<td>15.</td>
<td>59.70</td>
<td>45.</td>
</tr>
<tr>
<td>9</td>
<td>19003.00</td>
<td>25.</td>
<td>39.10</td>
<td>65.</td>
</tr>
<tr>
<td>10</td>
<td>4433.00</td>
<td>45.</td>
<td>35.30</td>
<td>55.</td>
</tr>
<tr>
<td>11</td>
<td>13849.00</td>
<td>15.</td>
<td>59.20</td>
<td>65.</td>
</tr>
<tr>
<td>12</td>
<td>10100.00</td>
<td>65.</td>
<td>70.00</td>
<td>55.</td>
</tr>
<tr>
<td>13</td>
<td>1555.00</td>
<td>45.</td>
<td>59.40</td>
<td>55.</td>
</tr>
<tr>
<td>14</td>
<td>2971.00</td>
<td>25.</td>
<td>55.30</td>
<td>65.</td>
</tr>
<tr>
<td>15</td>
<td>5993.00</td>
<td>75.</td>
<td>57.80</td>
<td>65.</td>
</tr>
<tr>
<td>16</td>
<td>2849.00</td>
<td>15.</td>
<td>76.30</td>
<td>55.</td>
</tr>
<tr>
<td>17</td>
<td>9925.00</td>
<td>55.</td>
<td>50.00</td>
<td>65.</td>
</tr>
<tr>
<td>18</td>
<td>6673.00</td>
<td>5.</td>
<td>50.00</td>
<td>55.</td>
</tr>
<tr>
<td>19</td>
<td>1385.00</td>
<td>65.</td>
<td>55.00</td>
<td>45.</td>
</tr>
</tbody>
</table>
SUMMARY OF RUN PARAMETERS

1. Abbreviated Output (Y or N): Y
2. Volume Output (1=Cu ft, 2=Cords): 2
3. Ageclass Width: 10. Years
4. Species Selected (1=Aspen, 2=Red Pine): 1
5. Rotation: 50. Years
6. Min. Cutting Age: 35. Years
7. Anticipated Stocking after Harvest: 90.00 Percent
8. Interval to Reevaluate Allowable Cut: 10 Years
9. Number of Times to Evaluate Allowable Cut: 3
10. Cut Determination Method (1-7): 1
11. Stocking: (1=Percent of normal, 2=Volume): 1
12. Stocking of Young Stands: 90.00 Percent
13. Cutting Priority (1=Age, 2=Age and Site): 1
Sample Case: Tabular Check Volume Control - Short Output
(continued)

II. Outputs

DISTRIBUTION OF GROWING STOCK IN YEAR 0.

<table>
<thead>
<tr>
<th>AGE (YEARS)</th>
<th>SITE (FT)</th>
<th>AREA (ACRES)</th>
<th>YIELD/ACRE</th>
<th>TOTAL YIELD (M CORDS)</th>
<th>ANNUAL GROWTH (CORDS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>65.</td>
<td>7257.</td>
<td>39.180</td>
<td>284.33</td>
<td>3110.4</td>
</tr>
<tr>
<td>70</td>
<td>59.</td>
<td>22485.</td>
<td>40.980</td>
<td>921.43</td>
<td>13420.</td>
</tr>
<tr>
<td>60</td>
<td>64.</td>
<td>27972.</td>
<td>20.812</td>
<td>582.14</td>
<td>11842.</td>
</tr>
<tr>
<td>50</td>
<td>62.</td>
<td>10988.</td>
<td>18.678</td>
<td>205.23</td>
<td>6236.3</td>
</tr>
<tr>
<td>40</td>
<td>65.</td>
<td>2766.</td>
<td>10.675</td>
<td>29.527</td>
<td>1483.2</td>
</tr>
<tr>
<td>30</td>
<td>65.</td>
<td>21974.</td>
<td>6.0435</td>
<td>132.80</td>
<td>13075.</td>
</tr>
<tr>
<td>20</td>
<td>62.</td>
<td>19320.</td>
<td>1.6431</td>
<td>31.745</td>
<td>8681.8</td>
</tr>
<tr>
<td>10</td>
<td>55.</td>
<td>6673.</td>
<td>.28544E-03</td>
<td>.19048E-02</td>
<td>4.6883</td>
</tr>
</tbody>
</table>

TOTAL 119435. 2187.2 57853.

DESIRABLE 1812.3 .10651E+06

ESTIMATES OF ALLOWABLE CUT

HUNDESHAGENS = 120133.000 CORDS
VONMANTELS = 97208.8400 CORDS
CHAPMANS = 64061.4900 CORDS
AUSTRIAN = 76595.7700 CORDS
MODIFIED BARNES = 77222.8500 CORDS

ALLOWABLE CUT ACCORDING TO METHOD 1
FOR YEARS 0. TO 9. = 78734. CORDS/YEAR
DISTRIBUTION OF GROWING STOCK IN YEAR 10.

<table>
<thead>
<tr>
<th>AGE (YEARS)</th>
<th>SITE (FT)</th>
<th>AREA (ACRES)</th>
<th>YIELD/ACRE</th>
<th>TOTAL YIELD (M CORDS)</th>
<th>ANNUAL GROWTH (CORDS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>55.</td>
<td>13455.</td>
<td>39.682</td>
<td>533.93</td>
<td>5840.8</td>
</tr>
<tr>
<td>70</td>
<td>64.</td>
<td>27972.</td>
<td>24.720</td>
<td>691.48</td>
<td>10071.</td>
</tr>
<tr>
<td>60</td>
<td>62.</td>
<td>10988.</td>
<td>23.949</td>
<td>263.16</td>
<td>5353.1</td>
</tr>
<tr>
<td>50</td>
<td>65.</td>
<td>2766.</td>
<td>15.778</td>
<td>43.641</td>
<td>1326.1</td>
</tr>
<tr>
<td>40</td>
<td>65.</td>
<td>21974.</td>
<td>12.210</td>
<td>268.30</td>
<td>13477.</td>
</tr>
<tr>
<td>30</td>
<td>62.</td>
<td>19320.</td>
<td>8.4783</td>
<td>163.80</td>
<td>16127.</td>
</tr>
<tr>
<td>20</td>
<td>55.</td>
<td>6673.</td>
<td>1.0440</td>
<td>6.9666</td>
<td>1905.3</td>
</tr>
<tr>
<td>10</td>
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<td>9140.</td>
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<td>617.34</td>
</tr>
<tr>
<td>0</td>
<td>65.</td>
<td>7147.</td>
<td>.00000</td>
<td>.00000</td>
<td>.00000</td>
</tr>
</tbody>
</table>

TOTAL 119435. 1972.0 54717.

DESIRABLE 1812.3 .10131E+06

ACRES CUT IN PERIOD = 16287

ESTIMATES OF ALLOWABLE CUT

- HUNDESHAGENS = 108313.100 CORDS
- VONMANTELS = 87644.4800 CORDS
- CHAPMANS = 63573.8100 CORDS
- AUSTRIAN = 62700.3900 CORDS
- MODIFIED BARNES = 82320.7300 CORDS

ALLOWABLE CUT ACCORDING TO METHOD 1
FOR YEARS 10. TO 19. = 78211. CORDS/YEAR
DISTRIBUTION OF GROWING STOCK IN YEAR 20.

<table>
<thead>
<tr>
<th>AGE (YEARS)</th>
<th>SITE (FT)</th>
<th>AREA (ACRES)</th>
<th>YIELD/ACRE (COrDS)</th>
<th>TOTAL YIELD (M COrDS)</th>
<th>ANNUAL GROWTH (COrDS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>63.</td>
<td>18825.</td>
<td>29.454</td>
<td>554.47</td>
<td>6065.6</td>
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<tr>
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<td>62.</td>
<td>10988.</td>
<td>28.448</td>
<td>312.58</td>
<td>4552.5</td>
</tr>
<tr>
<td>60</td>
<td>65.</td>
<td>2766.</td>
<td>20.231</td>
<td>55.958</td>
<td>1138.3</td>
</tr>
<tr>
<td>50</td>
<td>65.</td>
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<td>18.046</td>
<td>396.54</td>
<td>12050.</td>
</tr>
<tr>
<td>40</td>
<td>62.</td>
<td>19320.</td>
<td>17.129</td>
<td>330.93</td>
<td>16623.</td>
</tr>
<tr>
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<td>55.</td>
<td>6673.</td>
<td>5.3869</td>
<td>35.947</td>
<td>3539.1</td>
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<tr>
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<td>9140.</td>
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<tr>
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<td>15981.</td>
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<td>3599.5</td>
</tr>
<tr>
<td>0</td>
<td>61.</td>
<td>13768.</td>
<td>.00000</td>
<td>.00000</td>
<td>.00000</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td>119435.</td>
<td></td>
<td>1739.4</td>
<td>56053.</td>
</tr>
<tr>
<td>DESIRABLE</td>
<td></td>
<td></td>
<td></td>
<td>1812.3</td>
<td>93504.</td>
</tr>
<tr>
<td>ACRES CUT IN PERIOD =</td>
<td>22602</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

ESTIMATES OF ALLOWABLE CUT

- HUndeshagens = 95537.8800 CORDS
- Vonmantels = 77307.0400 CORDS
- Chapmans = 66318.0200 CORDS
- Austrian = 52406.6100 CORDS
- Modified Barnes = 86454.9500 CORDS

ALLOWABLE CUT ACCORDING TO METHOD 1
FOR YEARS 20. TO 29. = 79075. CORDS/YEAR
DISTRIBUTION OF GROWING STOCK IN YEAR 30.

<table>
<thead>
<tr>
<th>AGE (YEARS)</th>
<th>SITE (FT)</th>
<th>AREA (ACRES)</th>
<th>YIELD/ACRE</th>
<th>TOTAL YIELD (M CORDS)</th>
<th>ANNUAL GROWTH (CORDS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>55.</td>
<td>5880.</td>
<td>23.166</td>
<td>136.23</td>
<td>1490.2</td>
</tr>
<tr>
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<td>65.</td>
<td>2766.</td>
<td>24.031</td>
<td>66.469</td>
<td>968.07</td>
</tr>
<tr>
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<td>65.</td>
<td>21974.</td>
<td>23.140</td>
<td>508.47</td>
<td>10343.</td>
</tr>
<tr>
<td>50</td>
<td>62.</td>
<td>19320.</td>
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<td>489.11</td>
<td>14863.</td>
</tr>
<tr>
<td>40</td>
<td>55.</td>
<td>6673.</td>
<td>10.883</td>
<td>72.623</td>
<td>3648.0</td>
</tr>
<tr>
<td>30</td>
<td>65.</td>
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<td>152.68</td>
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<td>15981.</td>
<td>6.5270</td>
<td>104.31</td>
<td>15068.</td>
</tr>
<tr>
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<td>.49567</td>
<td>13.903</td>
<td>5929.3</td>
</tr>
<tr>
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<td>67.</td>
<td>9651.</td>
<td>.00000</td>
<td>.00000</td>
<td>.00000</td>
</tr>
</tbody>
</table>

TOTAL 119435.  
DESIRABLE 1812.3  
ACRES CUT IN PERIOD = 23933

The outputs from such simulation runs need to be carefully analyzed and be compared to other regulation alternatives. Plotting of key information such as growth, growing stock volumes, allowable cuts, acres cut, and age-class distributions can facilitate the interpretation of results.

**Model Application Example**

Application of the model to a real inventory situation will be illustrated in the following. The purpose is to show differences in the various control methods and to point out potential shortcomings in the models.
Description of data

Aspen inventory data for the Bear Island State Forest, situated northeast of Ely, Minnesota, in Lake and St. Louis counties, were obtained from the Department of Natural Resources 1978 Phase II inventory. This inventory consists of 320 individual aspen stands. Stands were chosen to illustrate the present condition of aspen on many state-owned lands and the need for regulatory management techniques. Figure 11 shows the very irregular nature of the age class distribution of the present inventory. About 77 percent of the total 10,020 acres are between 40 and 69 years old. Five percent of the acreage is in stands 70 years and older, leaving only 18 percent in ages 1 to 39 years. The ages, acres, volumes, and site indexes of these stands were supplied as input into the regulation simulation model.

![Graph showing ten-year age classes]

Figure 11. Initial age-class distribution of aspen covertype, Bear Island State Forest, Minnesota.

Procedure

Six volume regulation methods were applied to the aspen inventory over a 200-year simulation period. Annual allowable cuts were recalculated at ten-year intervals. Three model outputs were of special interest for comparison of the regulation approaches: a) allowable cut levels, b) growing stock levels, and c) age-class distributions. Initial stand conditions and input parameters were identical for each method. The input specifications were as follows:
Number of stands = 320.
Age at which harvestable yield first appears = 15 years.
Rotation age = 50 years.
Minimum cutting age = 40 years.
Length of adjustment period (Austrian formula) = 20 years.
Interval at which allowable cut is reevaluated = 10 years.
Number of times allowable cut is reevaluated = 20.
Stocking for young stands = .55.
Anticipated stocking percent under management = 80 percent.
A stand growth model for aspen based on the attached yield table (Table 10) by Brown and Gevorkiantz (1934).

Discussion and Results

To summarize the more interesting results, a graphing and plotting package developed at the College of Forestry was used to draw graphs of allowable cut and current growing stock and histograms of age class distributions.

Under each of the regulation approaches, nearly regulated conditions were obtained after about 80 years. Allowable cut levels stabilized at about 6,000 cords and show relatively small differences after growing stocks became more fully regulated (Figures 12 and 13). Hundeshagen and Von Mantel are distinctly different in that initial allowable cuts are much higher than for the other procedures, resulting in initial overcutting and a subsequent rapid drop in allowable cut levels for about 20 years. A possible explanation is the lack of any consideration for growth of the inventory in determining allowable cut. The Austrian formula also shows a considerable decline in allowable cut initially despite its incorporation of growth into the formula. Since current periodic growth is relatively small for the largely overmature inventory, it did not greatly influence the allowable cut initially. On the other hand, Chapman's model, which uses mean annual increment at rotation age, shows no drop in allowable cut over time.

Generally, all control procedures appear to do a favorable job in achieving full regulation. On the other hand, the initial fluctuations of the Von Mantel, Hundeshagen, and Austrian formulas make these models possibly unacceptable in this and other situations. One reason of the acceptable long-term behavior of these models is the periodic reevaluation of allowable cuts which the original control methods had not foreseen. With the speed and flexibility of a computer model, frequent updates not only are easily made, but also improve the performance of otherwise inflexible models. A second reason why some of the more inflexible models such as Hundeshagen and Von Mantel appear reasonably acceptable over the long-term in terms of achieving full regulation is the use of normal yield table data for growth projection with only a possibility of adjusting the percent of normal growth that would be achieved by a stand. More precise approaches to growth projection could be incorporated in to the model to obtain more realistic results in this respect. However, the method used in this model more closely reflects the procedure which many forestry enterprises use today to project future stand conditions.
Growing stock (Figures 14 and 15) in all cases shows a decline in about the first 20-40 years of the simulation and, then, a general increase to stable, long-term equilibrium conditions. Differences between growing stock levels are substantial. Von Mantel and Hundeshagen result in substantial overcutting initially and a subsequent long and slow build-up to sustainable yield levels. Von Mantel reaches stable growing stock levels far below all other approaches. Since it maintains
similar allowable cut levels, this implies that younger age classes must be cut to maintain the cutting level. This result is illustrated in the next set of figures.

Figure 14. Growing stock for Bear Island State Forest.

Figure 15. Growing stock for Bear Island State Forest.

Age-class distributions were obtained for each 10-year interval. Figures 16 and 17 show the age-class distributions for year 0 (initial condition), year 10, and every 30 years thereafter for the Tabular Check method.
Figure 16. Age-class distribution, Bear Island State Forest.
Figure 17. Age-class distribution, Bear Island State Forest.
The effects of the regulation procedure on regulating the severely unbalanced forest within a reasonable short time period is apparent. The distributions are similar for all the other methods except for Von Mantel and Hundeshagen. For the former, cutting into younger age classes occurs to maintain allowable cut levels similar to the other methods from a lower growing stock volume.²

Summary of ACES

We have shown that the application of volume control procedures to inventory data over long planning periods is essential to gain insight into the long-term sustainable yield of our forest inventory.

The simple formula approaches to timber regulation, specifically Hundeshagen and Von Mantel, have been widely criticized as being inadequate because of the inherent assumptions of a normal forest. More modern forest planning models such as Timber RAM (Navon 1971), a linear programming approach, or ECHO (Walker 1971), an economic harvest optimization model, have been introduced to replace old formula approaches.

There are at least three reasons why the formula approaches still have merit:

1. They provide simple, fast estimates of allowable cut; some of the modern regulation models are very complex and frequently are not understood by the forest on the ground.

2. If current harvest levels are known to be far below allowable cuts, the optimization of cutting levels might be less critical; it is important, however, to gain an understanding of the long-run sustainable yield of an inventory after full regulation has been obtained.

3. Formula approaches work satisfactorily in achieving full regulation if allowable cuts according to the various formulas are recalculated at reasonable intervals, e.g., 10 years.

The selection of a specific regulation model depends primarily on the objectives of the forest enterprise. Equally important, however, is the knowledge of how implementation of calculated allowable cuts will change future forest inventories in terms of growing stock, growth, and age-class distributions.

This question can be answered for a specific inventory by simulating allowable cut calculations and implementation over time. It is apparent from our simulations using the Bear Island aspen inventory that the regulation models with the most restrictive or simplifying assumptions, i.e., Von Mantel, Hundeshagen, and Austrian, led to severe fluctuations in the allowable cut which could be unacceptable to the manager for a number of reasons. If we followed Von Mantel, we would have a cut the first decade of 50 percent above sustainable yield levels, followed by a drop two decades later to two-thirds of sustainable yield levels.

All models over the long-run led to stable conditions. It is impossible, however, to predict the behavior of the models, especially the more restrictive ones, for different initial inventory conditions. The simplicity of the formula approaches to allowable cut calculations was one of the most important reasons for their use. With the availability of computer programs like the one presented here, it is possible to first examine how various regulation models will affect growth, growing stock, and cutting levels before selecting a specific approach. More importantly, with the

²The average scaled cutting volume of aspen over the last 5 years has been 1,135 cords.
availability of this program, there is little reason to not use the superior Tabular Check procedure for calculating the allowable cut.

Our example illustrated for example that current harvests for aspen in the Bear Island State Forest are far below cuts desirable for achievement of regulated forest conditions. If full regulation within a reasonable time period is an objective, increased harvest would be in the interest of the supervising agency and would contribute to the solution of silvicultural problems posed by an overmature aspen inventory. Calculation of reliable, long-run sustainable yields has also become more critical recently because new and substantial future demands for timber are becoming apparent. While current demand for aspen is still below desirable cutting levels, recent developments could bring about substantial increases in the demand for aspen and other hardwoods. Several timber companies have announced plans for or have begun construction of waferboard plants which will increase utilization of the hardwood resource. Demand increases will be substantial and provide a great opportunity for forest managers to speed up the job of regulating unbalanced timber inventories. The availability of this powerful simulation program should facilitate this job greatly.

ALLOWABLE CUT EFFECT (ACE)

In the previous section we discussed methods of determining allowable cut. This section illustrates how today's allowable cut can be increased by accounting for future volume contributed by newly planted stock. This effect is known as the allowable cut effect or ACE and it can be defined as the immediate increase in today's allowable cut attributable to expected future increases in yields. Do not confuse ACE with ACES. The latter is an acronym for the regulation simulator described above and has nothing to do with ACE. The ACE can result from any management practice that increases average growth rates.

Conditions for ACE

1. Must calculate and actually harvest allowable cut
2. Must be based on volume regulation techniques not area control
3. Allowable cut must be dependent on the rate of growth of trees in management unit
4. Must be a reserve of merchantable timber available.

Example of ACE

Red pine inventory
- site index 65
- rotation 100 years
10,000 acres of average age 140 (8,000 ft³/acre)
2,000 acres of average age 30 (7,325 ft³/acre)

Hanzlik Formula

This method of allowable cut calculation is suitable for stands made up of old growth and immature timber. It was originally developed to initiate management in unregulated Douglas-fir stands in the PNW.

\[ AC = \frac{V_m}{R} + I \]
where
\[ R = \text{rotation} \]
\[ V_m = \text{volume of mature merchantable timber} (> R \text{ years old}) \]
\[ I = \text{MAI of immature stands at rotation age} \]

The cut is made up of two parts:

1. old growth volume spread equally over R years
2. growth of immature stands.

Let's use the previous three stands for example. Assuming stand A is mature, stands B and C are immature and there is no change in stocking.

\[ \frac{V_m}{R} = \frac{(6280 \times 0.90 \times 700)}{80} = 49,455 \]

\[ I = \text{MAI at rotation for stands B and C} \]
\[ = \frac{3199}{80} \times 0.80 = 31.99 \text{ ft}^3/\text{acre for B} \]
\[ = \frac{8165}{80} \times 0.85 = 86.75 \text{ ft}^3/\text{acre for C} \]

Sum of MAI = 31.99 x 300 + 86.75 x 600 = 61,647

\[ \text{AC} = 49,455 + 61,647 = 111,102 \text{ ft}^3/\text{year} \]

This formula is applicable to situations where you have mature timber, a large area of young material, and a smaller representation of intermediate ages.

\[ \text{AC} = \frac{V_m}{R} + \text{MAI}(R) \quad \text{(Hanzlik Formula)} \]
\[ = \frac{8000}{100} \times 10,000 + \frac{7325}{100} \times 2000 \]
\[ = 946,600 \text{ ft}^3 \]

If an additional 5,000 acres of red pine are planted on the same site, the AC would increase by:

\[ \frac{7325}{100} \times 5000 = 366,250 \text{ ft}^3 \text{ or } 73.25 \text{ ft}^3/\text{ac} \]

When a cash flow analysis is carried out for the plantation investment and the increase in allowable cut is included as a benefit of the plantation, the IRR increases above the one obtained without including the ACE. This can be seen below:

<table>
<thead>
<tr>
<th>Cashflow Analysis Without ACE</th>
<th>Year</th>
<th>Activity</th>
<th>$/acre</th>
</tr>
</thead>
<tbody>
<tr>
<td>Costs</td>
<td>1</td>
<td>land purchase</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>planting</td>
<td>75</td>
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<tr>
<td></td>
<td>1-100</td>
<td>administration</td>
<td>1</td>
</tr>
<tr>
<td>Benefits</td>
<td>100</td>
<td>stumpage</td>
<td>2563.75</td>
</tr>
</tbody>
</table>


Cashflow Analysis With ACE

<table>
<thead>
<tr>
<th>Year</th>
<th>Activity</th>
<th>$/acre</th>
</tr>
</thead>
<tbody>
<tr>
<td>Costs</td>
<td>1 land purchase</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>1 planting</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>1-100 administration</td>
<td>1</td>
</tr>
<tr>
<td>Benefits</td>
<td>100 stumpage</td>
<td>2563.75</td>
</tr>
<tr>
<td></td>
<td>1-100 ACE</td>
<td>25.64</td>
</tr>
</tbody>
</table>

ACE = 73.25 ft$^3$/acre x $0.35/ft^3 = $25.64/acre

The IRR's show an apparent increase in the desirability of investment. The discrepancy described above is what has been described extensively as the "allowable cut effect (ACE)" (Schweitzer, Sassaman, and Schallau 1972; Lundgren 1973). ACE is the increase in today's allowable cut due to future expected increases in growth. If, for example, a large plantation is being established today, the expected future growth of this plantation can be captured in today's allowable cut if enough old-growth timber is available. Thus, increases in the allowable cut are being justified by the implementation of plantation projects. A problem arises when the cash flow due to the increase in allowable cut is used to justify the financial attractiveness of the plantation project. The ACE would make the plantation project more attractive than the same plantation project without the ACE. Naturally, the cash flow attributable to ACE could be generated without planting trees since it is based simply on the increased harvest of available mature timber. The cash flow from that increased harvest is, therefore, not attributable to the plantation directly but rather is tied to existing administrative constraints that would forbid the increased harvest today unless provisions for increased future growth through plantation establishment or other measures were made. ACE thus can be considered a quantitative measure of the opportunity costs of existing administrative constraints.

The counter argument to the above logic is that ACE measures the cost of administrative restrictions. In most instances, restrictions on the size of cut cannot be changed, therefore, the only way to increase allowable cut would be by providing for future production through growth increasing measures.

ACE and Cash Flow Analysis

One of the questions that frequently arises in the analysis of forestry projects is how to treat initial cash flows generated from the harvest of an existing stand where a plantation project is to be considered. Should the positive cash flow generated from the harvest at the beginning of a Christmas tree plantation establishment be added to the plantation project or should that cash flow be ignored? Obviously, the inclusion of an early positive cash flow will make the plantation project relatively more attractive in financial terms and might lead to the conclusion that the plantation project should be undertaken. What if the plantation project without the initial harvest of old-growth appears financially unattractive (i.e., the with and without principle)? To resolve these two conflicting recommendations for plantation investment, we need to explore what causes this apparent discrepancy.

In the Christmas tree example described above, the early cash flow due to harvest of mature timber on the site has nothing to do with the plantation project. If the harvest would take place regardless of whether or not the plantation was established, the additional cash flow should clearly not be attributed to the plantation project. The project should be analyzed without the ACE to determine whether it is financially attractive. Including ACE as a positive cash flow without proper consideration of the administrative circumstances might lead to implementation of a project that
without ACE would be financially disastrous. In most situations, ACE should not be included as a cash flow into the project. It is a separable component unrelated to the project activity itself. Only in cases in which administrative constraints prevent the harvest of the old timber unless the plantation project is implemented might ACE be included into the project as a cash flow.

Complexity of Forest Planning

Forest planning is a complex undertaking. In the US planning for public forests has reached probably the highest level of sophistication anywhere in the world, based on the amount of money spent in planning and the tools developed for this task. Despite all these efforts, forest plans have remained under attack by various interests groups as not being responsive to their needs. In defense of public forest planners, this is not surprising considering the complexity of planning a biological system over time where economic evaluation criteria are to be used for timber and nontimber products and services. In critic of past approaches, there has been too much reliance on the technical aspects of solving stand management scheduling models via linear programming using one of two model formulations (Johnson and Scheurman 1977). While LP is a powerful tool for optimization, it cannot effectively deal with large problems (required in forest planning) due to technical limitations of even large computers. We will discuss these problems in a later chapter. In our work, we have emphasized the development of easily understandable, highly transparent planning tools that make the analysis of development scenarios relatively simple. We also are putting major emphasis on the interpretation of model results that can help decision makers in understanding the ramifications of alternative policies. Our approach attempts to work like an expert system in that information gained from individual analyses becomes part of a knowledge base that can facilitate planning in the future.

Important Aspects of Forestry Problems

From a modelers viewpoint the most difficult process of modelling a problem is the process of "structuring the problem" or describing the key aspects of the problem in a mathematical form. For most forestry problems it is difficult to determine how much emphasis should be given to the various aspects of the problem. To get a good understanding of this modelling problem, one only needs to consider the many and interrelated aspects of most forestry problems that could be important:

1. Multiple forest products--the forest produces a wide range of products, both timber and nontimber. Usually it is difficult to analyze opportunities for producing one product without considering the other products.

2. Multiple stand locations--the location of stands in relation to the market is extremely important. The costs of accessing the stand and transporting the products to market are often a large proportion of the total production cost.

3. Multiple products in each stand--harvesting a stand can produce multiple products that are not necessarily shipped to the same market. Harvesting a stand for one product thus might help increase the supply of another product in another market.

4. Multiple markets--seldom is there one buyer to consider for a specific product from a specific stand. Price differences between markets are the significant factor affecting the allocation.

5. Substitutable stand outputs--at least some stand outputs can be used for several products. For example, a large log might be shipped to either a sawmill, a pulpmill, or a fuelwood market.
The end-use will depend on the differences in transport costs and delivered prices for the possible end-uses.

6. Nontimber product substitutes—for example, fuelwood users can usually utilize some other form of biomass or even coal.

7. Long production periods—it takes time for trees to grow. Long planning horizons are generally needed. Future timber supplies will depend on how much of the forest is harvested in the meantime. It is thus necessary to consider timber demands when evaluating future timber supplies.

8. Uncertain timber demands—the quantity of wood demanded by a mill is likely to depend on the cost of wood and the general state of the economy. Predicting future demand-price relationships for individual markets is extremely difficult.

9. Differences in stand characteristics—stands usually differ not only in age but also in terms of current species mixes, relative stocking levels and general site productivity potential.

10. Future production opportunities—forest management must be concerned not only with when to harvest existing stands but also with the long-term impact of immediate actions on future rotations. Specifically, each stand has a landholding cost that is due to future opportunities foregone (or postponed) by not harvesting and regenerating the stand today. This cost depends on the production potential and location of the site and the regeneration alternatives that are available. Decisions on regeneration are often extremely important because they involve immediate actions (investments) that can vary significantly in management intensity and cost.

11. Alternative management intensities for existing stands—thinning is one potential management tool. The number of thinning alternatives can be enormous for some stands, especially if multiple species are involved. Other tools are also generally available such as fertilization, weed control, and general timber stand improvement options.

12. Multiple harvest systems—harvest options can range from traditional roundwood operations to tree-length logging to full-tree chipping to chip-and-sort operations. Within some of these general harvesting methods there are also a range of plausible harvest equipment combinations.

13. Multiple ownerships—within a region, lands are seldom all under a single ownership or are managed for the same objective. Predicting landowner actions is a difficult task.

14. Changing land base—the amount of forest land changes over time. Marginal agricultural land might be converted to forest land or forest land might be converted to other land uses.

15. Growth and yield uncertainties—forestry deals with a biological process that is in itself difficult to predict. There are also potential catastrophic events of concern such as disease outbreaks, drought or fire. It is extremely simplifying to assume that all acres respond to treatment in an "average" manner.

16. Spatial interactions—the management of one stand is seldom independent of the management of nearby stands. For example, roadbuilding will often access several stands and some general management emphases, like timber production and wilderness, are often not compatible on adjacent acres.
17. Sequential decisions—forest management is a dynamic process. Only those decisions that require immediate action must be made today. Future actions can depend on how the future unfolds. Long-term impacts of immediate actions need to be considered in making decisions not only because forestry involves long production periods but also because actions taken today can influence the range of options that will be available for future decisions.

In developing models it is extremely important to consider how users will consider these aspects of the problem, either through multiple runs of the model or within the model itself. These practical considerations are easily forgotten as modelers probably tend to become involved with the many technical aspects of the model and tend to overlook the practical considerations. Obviously a real concern is whether the model is a too simplified representation of the problem.

MANAGEMENT PLANS

The development of management plans represents the combination of all of the information the manager has collected about the forest into one comprehensive plan of action. Depending upon the size of the forest this plan may range from a list of recommendations to a detailed description and plan for the forest. No matter how brief or comprehensive the plan may be it is always subject to change.

General

Planning is
   An orderly means ...
   Used by an organization ...
   To establish effective control
   Over its own future.

The characteristics of a good plan are:

(1) It should be logical.
    Begin with objectives,
    Establish the means of accomplishment of objectives.

(2) Good planning is comprehensive.
    Programs
    Services
    Organization and staffing
    Facilities
    Finance

(3) A good plan is flexible and action-oriented.

(4) A good plan extends into the future.

(5) A good plan is formal.

(6) Good planning involves people.
A good plan incorporates all relevant knowledge about the inventory being planned for, properly reflects the setting of the enterprise in the larger economic environment, and produces strategic as well as operational plan components that reflect the uncertainty in which management decisions are being made.

Forest Service Planning

In response to the RPA, the forest service is changing their planning methodology to incorporate quantitative planning models. A model can be thought of as a theoretical projection of a possible system of forest management. A model does not always require the use of a computer but in most cases the computer speeds up the process tremendously. The two most frequently used models in forestry are those which arrive at an optimal solution and those which try to approximate optimal solution or just try to find good solutions. The area and volume control programs described earlier fall into the latter category (usually simulation models) in that they provide answers to the specific resource conditions but they do not attempt to solve a specified objective function or goal. "Simulation takes a model of reality and produces a likeness of the behavior which is represented by the model." The recent trend in forestry has been towards the use of optimization models. Specifically, linear programming (LP) has come into use as an optimization technique for forest management planning.

The Forest Service Planning Process

There are basically three tiers of Forest Service planning which have evolved from the RPA and NFMA.

1) **RPA Assessment and Program** - The assessment is to be completed every 10 years and the program is to be completed every 5 years. Together these two documents are supposed to determine the productive capabilities of the National Forests and Grasslands. In addition, the program sets quantitative objectives for these resources and identifies opportunities for other owners.

2) **Regional Plans** - These are to serve as a link between the national RPA planning and the individual forest plans. Once the national program is complete the Chief of the Forest Service allocates a share of the national goals to each region. It is the region's responsibility to translate those regional goals down to the forests within that region.

3) **National Forest plans** - These plans serve as the direction for the actual management of the individual forests.

Each plan tries to identify local problems and address management alternatives to meet them. This is basically a top-down planning process with national and regional goals being transmitted downward to the forest level. There is also a complementary upward flow of information from the forest level to the national level where the information is eventually incorporated into the RPA Assessment and Program.

The regulations describe this flow of information and how it is to be completed and its direction of flow. Basically, the regulations concern themselves with the resolution of issues identified either at the national, regional or forest level. The regulations identify a planning process by which these issues are to be resolved and a series of management standards and guidelines to be applied to the alternatives which solve the issues.
The regulations can be separated into three sections:

1) introduction and purpose
2) planning process
3) management standards and guidelines.

The planning process makes up the largest portion of the regulations. This process is to take place at both the regional and forest level.

One of the biggest reforms from the NFMA was that Forest Service planning be interdisciplinary. Planning teams must be made up of members which have skills to identify recreation, range, timber, wildlife and fish and wilderness opportunities.

The planning process presented here must be conducted by interdisciplinary planning teams.

1) Identification of Issues
   - identified by team members
   - identified by public
   - identified by state government
   - identified by local government

The Regional Supervisor or the forest supervisor determines which issues will be dealt with in the plan.

2) Identification of Planning Criteria

   These are basically the standards for planning:
   - process of decision making (what data needs to be collected)
   - standards in evaluating alternatives

3) Data Collection
   Data quality varies among resources.

4) Analysis of the Management Situation
   Looks at the area’s ability to support the goods and services demanded by the public.

5) Formulation of Alternatives
   The planning team must develop management alternatives to reflect a range of possible output levels.

6) Estimated Effects of Alternatives

   Team must estimate
   - physical
   - biological
   - economic
   - social
   effects of each alternative and measure how each alternative responds to RPA goals.

7) Evaluation of Alternatives
   on the basis of physical, biological, social, economic and environmental effects.
8) Preferred Alternative Recommendation

9) Selection of Recommendation

10) Monitoring and Evaluation

The Forest Service has adopted an LP model, FORPLAN, as its chief planning tool. National forests across the entire U.S. are being forced to accept this new method of management. Since these models are becoming an important part of forest management it is important that you understand a little bit about LP and the assumptions behind it. An understanding of these things will help you gain a better understanding of the use of such quantitative models. These models are informational tools and they only provide as good information as the information provided as input.

The Forest Planning model FORPLAN is run on the forest level at step 5 of the planning process. Step 5 is the formulation of alternatives. FORPLAN is basically a resource allocation and scheduling model. FORPLAN does not in itself formulate alternatives instead it takes each alternative and evaluates the major source impacts and interactions and schedules the output of those resources over time in order to meet set goals (RPA goals).

We will discuss the basic idea behind FORPLAN since this type of quantitative planning model is in vogue with the Feds, state and industry. The FORPLAN model is a resource allocation and scheduling model which uses linear programming as a solution technique. Linear programming is not synonymous with computer programming--it is just a solution technique. As the problem becomes larger it is much easier to solve the problem on the computer.

Evaluation of National Planning Process

Timber management scheduling problems are large and complex. They deal with biological processes and require long planning horizons. Uncertainty surrounds nearly every element of the problem.

Vastly better tools are available today to forest planners than only a few decades ago. Simplistic formula methods for calculation of allowable timber cuts have been replaced with sophisticated simulation procedures, allowing comparison of alternative management activities before actual implementation, and with optimization models that can provide optimal management schedules over time.

National Forest planning in the U.S. has put all its stakes into one highly sophisticated linear programming (LP) package called FORPLAN (Johnson, Jones, and Kent 1980). While forerunners of this model such as the Timber Resources Allocation Model or Timber RAM (Navon 1971) were applied to single resources such as timber, FORPLAN was designed to tackle multiple-use aspects of National Forest management. A number of questions have been raised as to the adequacy of LP models such as Timber-RAM as a long-range planning tool (Chappelle, Mang, and Miley 1975). Recently, FORPLAN has been subject of several critical evaluations (Apple 1982, Rose 1984, Rose and Hoganson 1984). At the same time, many of the plans of individual National Forests have come under intense attack by public and private agencies and individuals.

The limitations of the modern LP approach to planning are not so much inherent in LP itself, but rather in the technical limitations imposed on planners by even our largest computers. It has required the need for a high level of aggregation of management classes. For public land management agencies, multiple use considerations required by law have increased the complexity
of the planning process and with it the degree of uncertainty and the need for more complex sensitivity analyses and flexibility for derived plans. Forest planners in the process of aggregation ignore information that is essential for operational planning. The aggregated models generate solutions that have several undesirable characteristics. They are difficult to translate into operational plans, and they produce solutions that are highly sensitive to changes in assumptions.

Technological limitations of even our largest computers and exponential increase in solution costs of increasing LP problems have forced planners to formulate models with highly aggregated data. Empirical evidence suggests, that solutions from highly aggregated models are more sensitive to changes in model assumptions. Thus, optimal solutions implemented in the short-run could easily turn out to be nonoptimal, but unfortunately are often also irreversible. It has also become apparent that it is difficult or impossible to derive operational plans from aggregated models that can be easily and effectively implemented by the forest practitioner. The high costs of generating optimal LP solutions have also stood in the way of dealing with questions of uncertainty through sensitivity analyses. Empirical evidence suggests that solutions from highly aggregated models are furthermore more sensitive to changes in model assumptions. These and other problems have motivated the search for alternative planning techniques. Forest planners in the process of aggregation ignore information that is essential for operational planning. The high costs of generating optimal LP solutions have also stood in the way of dealing with questions of uncertainty through sensitivity and post-optimality analyses. These and other problems have motivated the search for alternative planning techniques.

Components

A management plan usually contains information pertaining to the past and present condition of the forest along with future goals to be attained. A general outline of the information which might be included in a management plan is as follows:

I. Forest Land Description
   A. Ownership
   B. Size and location
   C. Past history of ownership
   D. Topography
      1. How does topography relate to logging?
      2. Will there be any hydrological concerns if logging occurs?
   E. Soil and geological characteristics
   F. Accessibility to current road network

II. Forest Description
    A. Covertype
    B. Age classes present
    C. Growing stock
    D. Site quality
    E. Growth
    F. Defect and mortality percentages
    G. Compartamental (stand) boundaries

III. Management Alternatives

IV. Economic Factors
    A. Economy of the local community
B. Demand for the product
C. Transportation costs

V. Prior Management Practices
   A. Description
   B. Weak spots
   C. Possible improvements

VI. Policy and Management Objectives
   A. Attain full regulation
   B. Incorporation of multiple uses
   C. Even flow

VII. Regulation/Forest Management Scheduling
    A. What method?
    B. Over what time period?
    C. How is it to be accomplished?
    D. Desired effects

VIII. Cultural Treatments -- TSI
      A. What?
      B. How?
      C. When?

IX. Silvicultural Perspective
    A. Logging methods
    B. Planting
    C. Release

X. Forest Protection

XI. Incorporation of Multiple Uses

XII. Revision of Plans

FOREST MANAGEMENT SCHEDULING MODELS

Models used to address forest-wide problems are generally called forest-wide scheduling problems. These models can best be thought of as simply economic analyses of specific forest management units (analysis areas) that are done simultaneously because of some interactions between the units in terms of shared resources or constraints on the forest as a whole. Separate economic analyses of the individual analysis areas are not appropriate by themselves because they do not have an acceptable method for incorporating the forest-wide interactions (concerns) into the analysis. For example, suppose a forest has an abundance of timber in the older age classes and very few acres in the younger age classes. An economic analysis done on each stand separately might indicate that most acres should be cut today, but this type of analysis lacks an acceptable way of coordinating activities across the forest to help achieve a more acceptable flow of timber over time. A closer look at forest scheduling models will show that forest-wide scheduling models use a method of
valuing (pricing out) these forest-wide concerns and actually use the same basic concepts that are used in an economic analysis of specific management alternatives for specific forest stands.

Most linear programming models applied in forestry use one of two basic forms that are commonly referred to as Model I or Model II (Johnson and Scheurman 1977).

Simulation models have been used extensively in forest planning to simulate forestry activities over time. Simulation models can handle a significant amount of detail and are generally appealing to users because they are generally easy to understand. A disadvantage of simulation models is that they do not solve problems, they simply mimic a system. Simulation models used for forest management scheduling are often referred to as binary search models because they are used to search for the value of only one decision variable. A good example would be a model used to estimate an allowable cut that can be achieved over a specified planning horizon. Essentially the simulation model is used to mimic different harvest levels and a search technique is used to narrow in on the allowable cut by using the simulation results to adjust upper and lower bounds on the estimate. The simulation model traces the forest through time period by period by harvesting each period until the specified harvest level is reached and then growing the entire forest forward to the next period. Assumptions are necessary in a model of this type regarding the sequencing of stands for harvest and the type of regeneration activities to implement after harvest. Intermediate harvests (thinning), multiple forest products, and mixed species stands are all difficult to handle in this type of framework. For example, when multiple products are present, it is difficult to simulate activities and satisfy harvest levels of several products simultaneously.

Scheduling models use one of two methods for breaking the forest into units for analysis: contiguous analysis areas or noncontiguous analysis areas. Most applications, especially the earlier applications, have used the noncontiguous approach where the analysis areas are assumed to be homogeneous in terms of their biological characteristics, but the acres are scattered throughout the forest. In contrast, the contiguous analysis area approach groups stands by location but does not maintain homogeneity in terms of the biological characteristics. The contiguous approach has some advantages for dealing with spatial aspects of the problem, but problems are created because (1) many variables are often needed to describe the many combinations of management options that are possible within an analysis area when an analysis area contains several types of stands, and (2) integer variables (and integer programming methods) are generally needed to describe options for each analysis area because options generally must be applied to the entire analysis area if applied at all.

**Major Modelling Difficulties**

The modelling process involves three basic steps: data collection, model development, and application and interpretation of results. For data collection, it is important to recognize that most models are extremely data intensive. Data is required for all the important aspects of the problem. This usually includes information on the existing forest inventory; growth and yield projections including estimates for natural regeneration; and harvest, transport roadbuilding and regeneration costs.

In selecting a general model form, models have the general characteristics (weaknesses) of the form selected. For forest-wide or "scheduling" problems the two most common forms are linear programming models and simulation models. Linear programming (LP) models are desirable because they can find optimal solutions for the problem as formulated, but model size is a problem for many forestry applications. Simulation models are better suited for recognizing more complex relationships, but simulation models do not "solve" problems, they only mimic the situation.
The three most challenging aspects of modelling forestry problems to deal with are: (1) the spatial aspects of the problem, (2) uncertainty as it relates to the basic data and the sequential nature of decisions and (3) the large size of the problem. Spatial aspects of the problem are difficult for two reasons. First, because of the potential interactions between stands, alternatives for neighboring stands need to be considered simultaneously. This does not necessarily increase the size of problem, but it adds considerable complexity. Second, locational aspects as to specific markets for products harvested can add another, very large dimension to the problem and make the number of potential management options for some stands enormously large. For example, consider a stand for which there has been identified 10 possible management treatments (timings) that each involve harvests in three time periods. If each harvest produces 4 different products, hardwood and softwood sawlogs and hardwood and softwood pulp and each product can be shipped to one of four possible markets, then by adding market destination as a descriptor to define management alternatives, the number of alternatives increases from 10 to over 167 million! If one also wanted to consider the option of allowing sawlog material to be sold as pulp then the number of timing by shipping combinations increases to 640 million options. Using basic linear programming techniques this would mean that 640 million variables would be needed to describe the options available for just this one stand.

Considering that almost all data used in the modelling process has some associated uncertainty surrounding it, it should not be surprising that uncertainty is a problem. Uncertain futures and the need to keep options open are fairly well recognized, but uncertainty is a difficult to model because of the many aspects of uncertainty involved as well as the importance of the process by which the future unfold important (Hoganson and Rose 1987). Also, once one recognizes uncertainty one must also address ones attitude towards risk and the utility of the potential outcomes. For example, are landowners risk neutral and thus interested in maximizing expected return, or is the landowner more concerned about the consequences of a worst case outcome? In general, problems are generally large even when the future is assumed to be known. Current modelling methods can recognize some simplified aspects of uncertainty but even that usually requires a significant increase in both model size and complexity.

Model size is a problem because of the many aspects of the problem. Model formulations must often be simplified to keep formulations of practical size. A common problem is to develop a method for classifying the stands and aggregating the data to meet model size limitations. Balancing the emphasis given to each aspect of the problem is difficult with few guidelines available. Generally, the classification scheme is likely to significantly impact the ability of the model to be used to examine certain aspects of the problem. Unfortunately, the classification scheme used must be identified at the beginning of the modelling process when it is often not clear as to what questions are most important to address. After more is learned about the problem, one can always go back and make changes, but changes can be costly because of the work required in data collection and synthesis.

Another key aspect in model development and use is the understanding of exactly how the model will be used to help make decisions. For example, it is important to recognize which decisions are the pressing decisions that will need to be made before more information becomes available. In general, it is desirable to give more emphasis in the model to the immediate future with the idea that more analyses can be performed for decisions that are not needed today. Also, it is important to recognize initially that multiple model runs are the almost always needed to test model assumptions. To test some assumptions considerable savings might be possible by starting from an intermediate or even final solution for a prior set of assumptions. In some cases it might be possible to automate the process of performing a sensitivity analysis concerning assumptions. Also it is important to recognize that the final solution itself often contains an enormous amount of
useful information besides an "optimal" solution or schedule this is especially true with linear programming models which are probably the most widely used models in forestry.

DESCRIPTION OF AN INTEGRATED FOREST PLANNING MODEL

In 1987, a project, funded by the Minnesota Commission on Natural Resources (LCMR) was initiated. Its purpose was to develop alternative planning tools that could overcome some of the problems of traditional approaches and address some of the problems of forest planning described above. The prototype of an integrated forest planning package for use on microcomputers has been completed (Rose et al. 1989). Figure 1 depicts the major modules of the modelling system. The system is designed to automate and link the data synthesis and computer processing aspects of the planning process while allowing for user interaction and control. Each system component is capable of functioning as a stand-alone system to serve specific aspects of forest planning. An overriding objective in designing the system was to develop the capability of examining forest-wide concerns (objectives and constraints) without losing stand-level detail though data aggregation.

We have made every effort to make this software transparent and understandable to the user to avoid the problem that planning might be seen as a black box. Each module is documented with a user's manual. Additionally, on-screen help facilities are used to minimize the need for reference to the user's manual. A major effort was made to produce comprehensive and understandable model outputs.

The microcomputer-based system integrates two major planning modules, DTREES and DUALPLAN.

DTREES: A Stand-level Prescription Writer

The Decision TREE System (DTREES) system (Pelkki and Rose 1987, 1989) produces several management alternatives (prescriptions) for each stand. Each alternative is a sequence of management actions to apply over the planning horizon. The Report Writer/Prescription Editor modules provide management summary reports and an automated format for editing prescriptions. The prescriptions developed for each stand are used as input to DUALPLAN, a management scheduling model which selects an "optimal" prescription for each stand based on overall forest objectives and constraints. DTREES can function both as a "front-end" prescription writer to a management scheduling algorithm and as a management tool for evaluating specific options for an individual forest stand. It provides a list of alternative management sequences for each forest stand by simulating management activities and responses. Included in the DTREES system objectives are (1) use of a tree based growth projection system, (2) a modular systems design, (3) an understandable and user accessible silvicultural decision system, (4) avoidance of stand aggregation, and (5) a flexible inventory data interface which will accept current stand-level data bases.

The primary goal of DTREES is to provide a range of plausible alternative management prescriptions for individual forest stands. The system is designed to model any forest stand type in the Lake States. Prescription alternatives are based on established silvicultural guidelines. Ease and clarity of use were major considerations in developing DTREES. Alternatives developed by DTREES can be input into a regional or forest-wide planning model or evaluated independently stand by stand in terms of their contribution to financial, wildlife, recreation, and conservation objectives. Based on the results of either type of analysis, modifications can be made in DTREES in terms of the criteria used to develop the prescriptions and new alternatives can then be generated.
Deriving Economic Cashflows

Silvicultural alternatives, generated by DTREES, need to be translated into economic cashflows that reflect the underlying costs of carrying out activities such as site preparation, planting, thinning, harvesting, and transport. This translation is accomplished with a user-friendly program called HarDec (Arthaud et al. 1989). HarDec was created to compare harvesting systems to silvicultural prescriptions, obtain wood product volumes, determine harvesting costs, and calculate transportation costs. The program was designed to be user friendly and yet provide maximum flexibility.

DUALPLAN: A Model for Forest-wide Planning

Linear programming (LP) models have been used in forest management planning for almost thirty years. The major difficulty with LP models is that the problem cannot be described completely by a LP formulation of manageable size. This is usually recognized within the planning process and even LP models are used more like simulation models to help learn more about the real world problem by changing model assumptions and applying multiple runs. DUALPLAN is a computer model that has desirable characteristics of both an optimization model and a simulation model. DUALPLAN is based on a solution process (Hoganson and Rose 1984) that utilizes an understanding of the forestry problem; it recognizes some of the key yet simple relationships between an LP formulation of the problem and the economic interpretation of key model variables; it capitalizes on the fact that problems, as specified in a mathematical model, are usually defined more precisely than need be for most situations.

Most simulation models for forest management scheduling cannot be classified as economic models because so many assumptions are made concerning harvest priorities and management intensity. DUALPLAN is different in that it uses basic rules of economics to select management activities. Like other simulation models it mimics activities in an effort to learn more about the forest; however, a significant difference with DUALPLAN is the general method of simulation. DUALPLAN simulates activities analysis area by analysis area rather than period by period. In other words, it simulates the management of each analysis area for the entire planning horizon before moving on to the next analysis area. From a practical standpoint this is extremely important because it helps overcome most of the basic problems of simulation concerning multiple forest products, mixed species stands and intermediate harvests. By considering individual stands for the entire planning horizon, the model can look-ahead to consider the long-term impacts of actions aimed primarily at producing long-term benefits.

At least three characteristics of the forestry problem are utilized by DUALPLAN in the solution process. First, is the serial correlation or general relation that is almost certain to be present between the marginal costs of production for each product over time. Forest management involves relatively long production periods with harvests for most stands usually possible in several planning periods. Considering the way marginal costs of production are used to value management alternatives of individual stands, it is highly unlikely that one would find large shifts in the marginal costs between successive periods. If large shifts occurred, one would find it advantageous to shift large volumes of output either into or out of that period depending on the relative value of the product in that period compared to neighboring periods. With management options available to shift product flows between periods one can essentially think of the marginal costs for a product over time as essentially a single curve whose values must be serially correlated unless the product flow constraints shift dramatically between periods.
Another simple relationship used within DUALPLAN is the general ability to predict how management options would change as marginal costs of production (product prices) change. For example, for a given set of price estimates one can probably shift some output from one period to the next simply by increasing the relative value of the product in the period for which more output is desired. Similarly, if more output is desired for all periods one would simply need to raise prices to make it profitable to push the margin out to harvest more stands and to make desirable to implement more intensive management on some stands. Although these are very simple concepts, they give general direction as to how results might be improved in a way not considered in most mathematical solution techniques.

Another characteristic of the forestry problem utilized with the solution method used in DUALPLAN is the basic notion that forest-wide constraints do not necessarily need to be achieved precisely. For example, if one wants to produce an even flow of timber of 1000 units per period, an optimal solution for producing say 1000 units plus or minus 50 units is likely to be acceptable. The acceptable deviation is likely to vary by problem, but for the most part, precision of the data used in the analysis is lacking, so users are probably fooling themselves if they think that exact achievement of specified output levels is necessary.

DUALPLAN can be summarized as a simulation model that follows the following steps:

1. Identify which forest products have constrained product flows over time. For products with constrained output levels, estimate the desired output levels to be considered in this run of the model. For the products that are unconstrained, input assumed product values.

2. Estimate the marginal costs of production for the constrained products at the desired output level for each period.

3. Using the estimated marginal costs of production as prices, determine the optimal management strategy for each analysis area.

4. Tally the product (and input) flows for the forest to determine the total production level for the forest based on the estimate of the marginal cost of production.

5. Compare the forest-wide outputs to determine whether the levels are acceptable. If acceptable, report the solution found and stop. Otherwise go to step 6.

6. Use the results of the last solution found and an understanding of the problem to re-estimate the marginal costs of production for each constrained product in each period.

7. Return to step 3 and repeat the scheduling process.

For the unconstrained case, DUALPLAN can find, in a single pass through steps 1 to 5, the management plan that maximizes present net value of the forest. This should not be surprising as in this case one does not have a forest-wide problem; each analysis area can be analyzed independently without concern for forest-wide interactions. For the case where forest-wide concerns are present, the key to the approach is in the process of reestimating the marginal costs of production. Experience to date has shown that the process is not sensitive to the initial estimates of the marginal costs of production.

DUALPLAN can be described in terms of either a Model I or II format and can utilize either type of format in terms of management prescriptions used as input.
Model Applications and Extensions

The simulation approach has been applied in several studies concerning the timber supply situation in Minnesota. The concept was first applied in a short-term supply analysis that looked at the impact of mill expansions on timber procurement costs for specific mills (Rose et al. 1984). The most recent application focused on the impact of wood energy use on the timber supply costs of more traditional wood users (Hoganson 1987). Both short-term and long-term impacts were examined with focus on the values of the marginal costs of production (key dual variables). Approximately 40 different scenarios (model formulations) were considered with the model recognizing approximately 3000 different analysis areas.

Model size or computation time has not been a concern on any applications to date. Tests of the approach have been limited to several data sets, but success of the approach does not seem to depend on good initial estimates of the key dual variables (Hoganson 1987).

Applications to date have used an IBM mainframe computer with only limited concern given to computational efficiency. DUALPLAN is a recent effort to bring this general forest management scheduling method to the microcomputer. Considerable attention has been given to making the model "user friendly" but undoubtedly additions and modifications will likely be desirable as more experience is gained. A key to model use is its linkage with computer software aimed at producing the enormous amount of input information that is necessary for a forest-wide analysis.

A key aspect of the simulation approach is its ability to break the problem into smaller problems of more manageable and understandable size. This seems to be the general suggested direction for model improvements from the results of recent LP applications of forest management scheduling (Alston and Iverson, 1987). It is important to recognize the distinction between large models and complex models. The advantage of the simulation approach is that the overall model can still be relatively large without being very complex. Its primary limitation seems to be the need to limit the number of forest-level constraints. It is these constraints that make the model complex.

The modelling process could potentially be improved significantly by better incorporating an understanding of the forestry problem into not only the solution process but also into reformulations of the problem after initial results are obtained. The simulation approach has a real advantage in that intermediate solution results can be used to adjust the model formulation before completely solving the problem. As an example, consider the problem of valuing ending inventory. With a LP approach this is difficult because ending inventory volumes are sensitive to the prices assumed for ending inventory. With a simulation approach it is easy to use a simple rule like "value ending inventories using the marginal prices for the last planning period or a weight average of several of the last few planning periods."

A general strategy often used with optimization methods is to formulate the model so that all possible management options are considered in the mathematical formulation. For many forest management scheduling problems this strategy can lead to prohibitively large formulations. For example, consider the decision variables that are necessary to describe one contiguous analysis area with six management options-clearcut in any one of six periods. Assuming there is only one market, then only six decision variables are needed for this analysis area. However, if we assume that there are five possible products harvested in any clearcut and four potential markets for each product, then there are four to the fifth power possible shipping combinations for each of the six clearcut options. This means that either 6144 variables or 126 variables and 30 additional constraints would be needed in the model just to describe the six clearcut options for the one analysis area. Problems with model size can increase even more rapidly when several stands are
grouped together into a single contiguous analysis area. For example, if only five stands are grouped together with 100 management options available for each stand then there are 10 billion possible management options for the one analysis area.

The simulation approach has the potential of overcoming model size problems by using simple rules rather than complete enumeration of all possible combinations. For example, if multiple markets are considered in the LP formulation, the interpretation of the dual problem indicates that the products would be shipped to the "most profitable" market where the values of the dual variables would be used to measure profit. Rather than consider all combinations, the simulation model could follow the simple rule "ship products to the most profitable market" where procurement zones could be defined and adjusted as the marginal cost (price) estimates are adjusted during the solution process. This type of approach could likely utilize some of the recent developments with geographic information systems.

The sequential nature of the decision-making process is another aspect of the forest-wide problem that the simulation approach could plausible help address. Models become large and solution processes become more complex when stochastic elements are recognized within the modelling process. Very little attention has been given to the uncertainty problem and the issue of flexibility of immediate actions in terms of the options that will remain available for the uncertain future. Some work has been done on this problem using the simulation approach and it was found that it is very difficult to model the process of how uncertainty about the future actually unfolds (Hoganson and Rose 1987). Simple heuristics might be the most practical approach for modelling this aspect of the scheduling problem.

A simulation approach which actually interprets its own initial results to adjust the model formulation might be considered an "expert system." The "expert" would be a systems analyst who has a good understanding of forestry and economics and can learn more about the problem from intermediate results. Perhaps some of the new computer languages could be utilized for this type of model.

**SUMMARY**

New modelling and computer technologies will be extremely useful for forestry problems. Concepts of artificial intelligence and expert systems could be extremely useful in the modelling process. With expert systems it is likely that it will be possible to incorporate an understanding of the problem into the modelling process so that the problem will never need to be specified or enumerated completely. These ideas have been incorporated to some extent in the integrated planning model described above. Another area in particular that this concept should apply is in the aspect of recognizing spatial multiple markets and the combinatorial nature of those problems. New data base systems and Geographic information systems should also greatly enhance our abilities to work with large amounts of data and give more recognition to spatial problems.

Forestry problems are challenging problems to modelers because most problems are extremely large and complex. It is not surprising that the timber supply situation in Minnesota is still so difficult to understand or predict. More research is needed to tackle some of the more difficult aspects of the problem, but increased experience and new advances in computer and modelling technologies make the outlook very promising for models that will help significantly in gaining a better understanding of the resource management opportunities.
REFERENCES


