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Forest Management Planning For Timber Production: A Goal Programming Approach

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FOREST MANAGEMENT PLANNING FOR TIMBER PRODUCTION: A GOAL PROGRAMMING APPROACH

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ABSTRACT

Forest management for timber production, under either public or private ownership, may require the simultaneous maximization of product output and revenue from harvests, maximization of product output and income from current reforestation investment and the minimization of reforestation expenditure. Not only are these objectives incommensurate, but some of them are incompatible as well. One way to handle such a management situation would be to set goals (targets) for all objectives and then try to minimize the deviations from these goals. Goal programming-an extension of linear programming-provides a technique for such an approach.

This dissertation presents a two-stage goal programming model which could be used for preparing and revising management plans for timber production. The questions to which this model provides answers include: where, when and how much to cut, and how to reforest the land after a harvest.

In the first stage, a "Long Range" reforestation plan is developed. In determining the extent of reforestation under different species and methods of regeneration (seeding or planting), the model takes into consideration: 1) the future, total, sustained yield product output requirements from the management unit, 2) revenue expectations from reforestation investments; 3) available forest land and reforestation budget, and 4) the expected costs, returns and product output of different reforestation alternatives. In the second stage, a "Short Range" harvest schedule is prepared. In determining the sequence in which individual compartments are taken up for harvest and subsequent reforestation, the expected volume and value of growing stock in different compartments during the next five to ten years, and the annual area limit on harvest set by the Long Range plan are taken into consideration. Techniques for reducing the size of the goal programming formulation to manageable proportions are also discussed. The *modus operandi* of the model is demonstrated through a hypothetical but realistic example.

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CHAPTER ONE

INTRODUCTION

PURPOSE OF STUDY AND MAJOR APPROACH

The objective of this study has been to develop a mathematical model for the allocation of capital and land among available timber production alternatives. Goal programming, an operations research technique, has been used to develop a planning method for public forests, designed to minimize the aggregate deviation of expected management achievements from the stated objectives.

The study has been motivated by the management situation prevailing in India: public ownership of nearly 95% of the forest resource, very low productivity from forest lands with high potential, a widening gap between the supply of and the demand for wood products, and an increased availability of capital for raising plantations of fast growing species under "Five Year Plans" (Rustagi 1972). This increased availability of capital for large scale reforestation has not resulted in rational and efficient allocation of capital among different states-forests are owned by the states in India and not by the federal government as in the United States-and forest divisions. Nor has it produced efficient forest management planning at the divisional level. Two issues are involved: First, in what manner should the capital be allocated among different states and finally among divisions? Secondly, how must the forest management activities of harvesting, tending and reforestation at the division level be planned to best meet the sum total of the management objectives?

FOREST LAND USE CONFLICTS

Forest lands are managed for many purposes, with one use, frequently timber production, often dominant on a particular area (Davis 1966). There are three alternative approaches for the management of a resource which can provide more than one product or service. It may be used for a single purpose, to the exclusion of others. This is noi a common practice in forest land use, although examples of this kind are found in the management of municipal watersheds (Davis 1966) and in the recreational or preservational emphasis of the national parks. At the other extreme, the forest resource may be used for multiple purposes in the literal sense, no single use being dominant. Instances of this kind of use are also uncommon, though an example of misuse of this approach can be found in the forest areas in India which are close to habitation. There, intensive forestry for timber production is often attempted simultaneously with unrestricted grazing, to the detriment of both. However, the most common land use in forestry is one in which, besides a dominant use, other uses are permitted at a restricted level. This is typical of forestry areas where timber production is the dominant use. With comparatively small adjustments, these forests also provide some grazing, wildlife and recreation benefits.

The focus of this study is on forest management for timber production. This, however, does not imply that timber production should be the principal management objective on all forest lands found suitable for the purpose. The extent of forest areas really suitable for timber production and available for the purpose should be determined after first taking into account the competing claims of the other forest land uses. Timber production should then be limited to the residual area. This point is made fo clarify the limits of the current study and to draw attention to an important interrelated problem of land use which will not be covered here.

FOREST MANAGEMENT FOR TIMBER PRODUCTION

Forest management has been defined by the Society of American Foresters (1958) as "The application of business methods and technical forestry principles to the operation of a forest property." Management primarily for timber production involves scheduling of harvest and reforestation in a spatial and temporal context. The harvest schedule provides estimates of timber volumes and values which will be available during the next five to ten years. The reforestation plan, on the other hand, indicates the amount of long range productivity. Integration of both under some form of sustained yield would provide continuity of production.

Most of the existing forest management methods are too heavily biased towards the scheduling of harvests and have dealt with the reforestation aspect only superficially. Investments in reforestation are heavy and, in the case of public forests, are possible only at the cost of some other social or economic activities. Therefore, there is an urgent need to improve the efficiency of investments in reforestation.

As the number of reforestation alternatives increases, the problem of rational selection of reforestation alternatives becomes more complex, a fact which increases the attractiveness of more formal analysis. This study is concerned with the development of a mathematical programming approach to the scheduling of current harvests according to needs, in a way compatible with sustained yield management and reforestation goals, subject to future requirements and current budgetary restrictions.

OPERATIONS RESEARCH APPLICATIONS IN FOREST MANAGEMENT PLANNING

Before formulating a new mathematical model to aid in forest management planning, a description of the management situation and the inadequacies of the existing operations research models and techniques is needed. This is essential for two reasons: First, to ensure that the proposed model conforms to the management situation for which it is being developed and second, to ensure that it is a definite improvement over models developed earlier. Most of the studies undertaken in the past have the drawback that, instead of looking for and applying the best approach consistent with a problem, management situations have been overly simplified and modified to fit a model. The result has been that either the problem was reduced to a suboptimization of some aspects of forest management, such as regulation of cut, harvesting or logging, or the scope of application was restricted to make the model applicable to a specific management situation.

A brief description of the forest management situation in India is presented here. The Indian forest management situation has been chosen as a point of reference because of the public ownership of the forest resource, complexities in management and the familiarity of the author with the forest management situation there.

Forest Management Situation in India

The basic forest management unit in India is a division, an area of from 50,000 to 200,000 hectares, depending on the location of the forest tract with respect to the centers of consumption and also on the value of the species. These units are divided into blocks, which are further subdivided into compartments delineated by permanent natural or artificially cleared boundaries. The compartments, not necessarily equal in area, are fairly uniform so far as site, age class distribution, composition and stocking are concerned. Their number in each unit may vary from a few hundred to over one thousand.

These forests are owned and operated by the state governments, and are managed under principles of sustained yield. There are few possibilities of significant changes in the forest area in the foreseeable future. The management objectives for these forests may be broadly classified as follows:

First, the state governments want the productivity from these forests increased. Currently, the forests are producing only a fraction of both their short range and long range potential. Not only do the governments want the present output increased but at the same time, they are interested in increasing and maintaining future productivity to reduce the existing gap between the supply of and demand for various wood products.

Second, as the forestry sector is one of major revenue-producing sources, the state governments want to maximize the current gross income from harvests, and to minimize the level of expenditure on forest management. Because the level of current expenditure determines the level of reforestation investment-which in turn would determine the level of future output from these forests-there is a conflict with the first set of management objectives.

Third, the state governments want to maximize possible product output and money income from the reforestation investment. Here, also, there is a conflict of goals, as the increased level of investment in the fixed land resource may produce more output, but the rate of monetary return on the investment may be expected to go down.

Thus, when only timber producing activities of forest management in public-owned forests of India are taken into account, one can see the multiplicity of management objectives and their incompatibility.

The same situation could be found in publicly-owned forests in other parts of the world, with varying emphases on different management objectives.

Operations Research and Forest Management

Forest management planning for timber production has been practiced in India for more than a century. Management plans were prepared and revised periodically long before the development of computers and operations research techniques. These plans, based on regeneration by natural means, served their purpose very well. However, there has been an increased interest of late in the diversification of product output and in the maximization of product output and monetary returns from reforestation investments. This has led to a search for fast-growing species and better silvicultural methods. Rational selection of reforestation alternatives, in the light of future expectations and limits on the availability of land and capital, is difficult without formal analytic methods.

Mathematical models have been employed in forest management for many years, but the particular tools and the concepts of operations research are relatively new to the field. Operations research is not in itself a separate discipline, but rather a scientific attitude towards management phenomena (Kaufman 1963).

Apart from the fact that operations research techniques help in arriving at an optimal or better planning strategy, there are two other significant advantages resulting from their application which are not obvious. First, they require critical examination and explicit definition of all issues bearing on the problem. This includes assessment of the management objectives, the limitations within which the solution has to remain and the alternatives which are available. This phase of problem analysis increases the chance that the right problem is being solved. Second, after the problem is solved and an optimal solution is obtained, there are many aspects of the entire problem, including the solution, which could be further examined and the information so obtained used in further improving on the solution. These include:

a. Is the solution stable, *i.e.,* do small changes in the assumptions cause only small changes in the solution? If not, the problem should be re-examined and, if necessary, more precise information should be obtained to ensure stability of the otpimal solution.

b. Have the limitations been set realistically? Is it possible to improve on the solution by relaxation of some of these limitations? Which are they and what would be the effect on the overall solution of relaxing these limitations?

This feed-back is an essential feature of the systems approach. Conventional management planning methods lack these features.

Linear programming and simulation are the two major operations research techniques that have been used in forest management planning (Wardle 1966, Clutter *et al.* 1968, Navon 1971, Bare 1971, Bella 1971, Gibson *et al.* 1971, Gould & O'Regan 1967, Myers 1968). Dynamic programming has received some attention (Hool 1966, Schreuder 1968), but because of inherent computational difficulties and/or difficulties in formulating each specific model, dynamic programming has not approached the wide popularity enjoyed by linear programming. Non-linear programming, network theory, queuing theory and decision theory have been used to a very limited extent in forestry and practically none of these applications bear directly on forest management planning for timber production. Bare (1971) provides an excellent summary of the operations research applications to the problems of forest management.

With linear programming, the main problem is of handling multiple, incommensurate and often incompatible objectives, because it can handle only a single-valued objective function. Further a linear programming formulation has to be feasible to start with. In a complex management situation there is no way to know, *a priori,* that this is so.

With dynamic programming, apart from multiple objectives and infeasibility situations, problem size is also of significance. The problem size, in dynamic programming, increases exponentially with the increase in the number of state variables and linearly with the number of stages. Besides, there may be problems in defining state variables and in developing interrelationships between variables, constraints and management objectives.

The drawbacks of using simulation are obvious. It can handle only a few explicitly defined alternatives and there is no way to systematically locate a global optimum.

Considering the present state of the arts of dynamic programming and simulation, there appears to be no way to modify or improve upon them to handle the management situation discussed earlier in this chapter. If a way could be found to incorporate a multiple objective function and to proceed from an infeasible formulation, linear programming would be the most promising alternative for the current study because very large problems, involving thousands of variables and constraints, can be handled by computer programs. Even larger ones could be handled through decomposition by exploiting special problem structure. A mathematical model using a linear programming algorithm would thus have wide application.

Goal programming, which is an extension of linear programming, has both the capabilities required for dealing with the management problem under study. It can handle multiple objectives which may even be incompatible and/or incommensurate and it converts every problem into feasible form. In the following chapter, a presentation of the general goal programming model is followed by its adaptation to the given forest management situation.

CHAPTER TWO

FOREST MANAGEMENT PLANNING BY GOAL PROGRAMMING

In this chapter a general formulation of the goal programming model is followed by its adaptation to management planning for timber production. Issues such as rotation, financial criteria for ranking investments in reforestation, and the interest rate for discounting costs and returns, will also be discussed because of their effect on planning.

GOAL PROGRAMMING—ITS EVOLUTION AND CHARACTERISTICS

In forest management situations, as has already been pointed out, there is often more than one objective. The standard Linear Programming model is inadequate in such situations. Kapoor (1970) has presented a linear formulation of the multiobjective model as:

$$\begin{aligned} &\text{Extremize} \quad && Z = Q\,\underline{x} \\ &\text{subject to} \quad && A\,\underline{x} \leq \text{ or } \geq \underline{b} \qquad (1) \\ & && \underline{x} \geq \underline{0} \end{aligned}$$

where Q represents a pxn matrix of coefficients for the p objectives, A is an mxn matrix of technological relationships, x is an n-dimensional vector of decision variables, and b is an m-dimensional vector of resource or requirement levels.

In this formulation, the objective function is multidimensional and cannot be solved as such. However, strategies have been developed for reducing a multidimensional objective function to a single dimension, thus facilitating solution of the problem. For example, by premultiplying Q x by a p-vector of weights w, it is possible to reduce Z to a function linear in x, and in that case to reduce (1) to a regular linear programming formulation. The vector w may be composed either of the monetary values assigned to each unit of different objective function values or of the utility values, because dollar values do not always reflect the decision maker's estimate of the relative values of different objectives.

The main criticism of this approach lies in the implicit assumption that so long as Z is optimized a zero level of achievement for some of the objective function elements would be acceptable. This would certainly not be true in the case of product output from public forests. For example, if pulpwood production is more heavily weighted than sawlog production, the model could shift the entire production to pulpwood because that would maximize Z. By specifying a minimal acceptable level of production of sawlogs, or by providing both upper and lower bounds within which the achievement would be acceptable, it is possible to ensure participation for all desirable objectives at a positive level. However, in order to ensure feasibility, the lower bounds for the objectives to be maximized and upper bounds for the objectives to be minimized may be set at a too conservative level.

Another way for handling multi-objective problems would be to eliminate all except one of the objective functions from Z and to include these in the constraint set. This can be achieved by first determining the minimum and/or maximum level of acceptable achievement for everyone of the objectives to be included in the constraint set. With only one objective function left in Z, the multiobjective linear formulation reduces to linear programming, which can then be solved. The shadow prices of the objectives not optimized will indicate the rate and the limit of trade-off between the optimized objective and the others. The process can be repeated so that everyone of the objective functions is optimized in turn and then a final decision taken about the objective to be optimized and a more practical range set for the remaining objectives to be incorporated with the constraints.

Even though this approach appears logical, there may be some practical problems. First, there may be difficulties in assigning proper levels of performance for the objectives included in the constraint set. If these are too restrictive, the problem may be rendered infeasible. In order to ensure feasibility, the conditions of acceptable performance for the remaining objectives may be set to levels that do not reflect the decision maker's desires. Second, in the final analysis, it may not be simple to decide which of the several objectives should be optimized. This may be critical, as optimization of different objectives may result in different strategies, thus rendering their comparative evaluation difficult.

In the above two unidimensional formulations of the multi-objective model, some of the activities may end up at zero or at an unacceptably high level, depending on whether they were being maximized or minimized. Or, in order to ensure feasibility, their acceptable level of performance may be fixed at a level too low or high to be really helpful in decision making. In most production processes, whether for marketable or non-marketable goods and services, the decision maker can set targets (or goals) for all objectives which he would like to achieve. Whether these goals are based on the current level of performance, on the total potential, or on the expected requirements, is immaterial to the concept of goal setting. To take the specific example of forest management for timber production in public forests, these goals may reflect expectations with regard to the level of current product output, income from current harvest, the level of expenditure on reforestation, the level of employment in forest management related activities, the level of future output resulting from current reforestations, and the level of monetary returns from the two main factors of production, *i.e.,* land and capital. Once the goal for each management objective is given, the actual achievement of these objectives in relation to the goals becomes a measure of performance. This would require considerable thought in goal setting.

Another approach for handling the optimization of multi-objective management situations uses this concept of goals but, instead of optimizing the management objectives singly or in aggregate, it attempts to minimize the dissatisfaction resulting from incomplete realization of these goals. Instead of allowing only some of the goals to be satisfied, this dissatisfaction can be distributed among all objectives according to their relative importance to the decision maker.

This approach of minimizing the difference between goal targets and their actual achievement was developed by Charnes, Cooper and Fergusen (1955) as an extension of linear programming. The term goal programming was first used by Charnes & Cooper (1961). The general goal programming model can be represented as:

$$\begin{aligned} &\text{Minimize} && Z = \underline{w}^{+}\,\underline{d}^{+} + \underline{w}^{-}\,\underline{d}^{-} \\ &\text{subject to} && Q\underline{x} - \underline{d}^{+} + \underline{d}^{-} = \underline{h} \end{aligned} \qquad (2)$$

$$A\,\underline{x} \leq \text{or} \geq \underline{b}$$

$$\underline{x},\, \underline{d}^{+},\, \underline{d}^{-} \geq \underline{0}$$

where d^{+} and d^{-} represent the vectors of surplus and slack variables, w^{+} and w^{-} are vectors that represent the decision maker's value judgement of the penalties for each unit of deviation for over-achievement, and under-achievement respectively, from the stated goals, h is the vector of goals which the decision maker desires to achieve, and Q, A, x and b have the same interpretation as in (1). As the formulation is basically that of linear programming and as d^{+} and d^{-} are linearly dependent, the simplex algorithm would ensure that at most only one of the two deviational variables (d_j^{+} or d_j^{-}) corresponding to the jth goal would occur in the solution at a positive level.

The vectors w^{+} and w^{-} provide the decision maker with a powerful but flexible tool to reflect the degree of dissatisfaction resulting from over- and/or under-achievement of different goals. Unless both are undesirable, only one of the w^{+} and w^{-} elements corresponding to that goal may be at positive level. Though generally these elements would be non-negative, they need not be so restricted. When it is desirable and possible to exceed a goal without adversely affecting other goals, a negative weight would ensure that over-achievement is encouraged. In order to ensure that over-achievement of a goal does not interfere with the achievement of all other goals, the corresponding w^{+} element should be very small relative to others so that it receives lowest priority.

The vectors w^{+} and w^{-} could be used not only to reflect the relative value of each goal to the decision maker, but also for ranking different goals, if the decision maker desires to rank some goals ahead of others. The object of ranking is that, instead of considering all goals simultaneously, the goals of the higher rank are considered first after meeting all constraints. The goals of the next lower rank are considered only when no further improvement is possible in all goals of the higher rank. The achieved levels of the goals of higher ranks are automatically converted into constraints for the lower ranking goals. Several strategies exist which provide this ranking of goals for incorporation into the simplex algorithm (Charnes & Cooper 1961, Lee 1972, Field 1972). Because ranking does not permit trade-off from goals of higher rank to that of lower rank, it should be used with care. The larger the number of such ranks, the more rigid the resulting problem becomes, thus diminishing the advantage of goal programming. A relative weighting of the goals, without ranking, would be a useful and informative alternative to ranking.

The linear programming formulation consists of a unidimensional objective function and a set of constraints. The goal programming formulation, on the other hand, consists of an artificially-created unidimensional objective function and a set of multidimensional goals, and may also include a set of constraints. The difference between the constraints and goals is not of kind but only of degree. As observed by Ijiri (1965):

> ... The difference between the term *goals* and the term constraints is that the former represents the manager's (decision maker's) desires, whereas the latter represents the environment of his oRerations. However, in mathematical formulation, the only difference between the two is that *the constraints must be satisfied before any attempt* is *made to meet the goals.*

Though goal programming, being an extension of linear programming, can be termed an optimization technique, it goes beyond optimization. **In** linear programming, the numerical value of the objective function provides a measure for sensitivity analysis. **In** goal programming, on the other hand, no such inference can be drawn from the value of the objective function. A change in the priority structure as reflected in the vectors w^+ and w^- may provide significantly different objective function values, but it would be incorrect to infer that the program with a lower objective function value is necessarily better than the others. Once a decision about the level of goals and their relative priorities has been taken, goal programming attempts to achieve each goal to the maximum possible extent so that the aggregate of the weighted deviations is minimized. This inherent capability of goal programming to try to meet multiple goals according to a predefined priority structure comes very close to "satisficing". **In** fact, if all goals can be met, goal programming has little advantage over linear programming, and unless care is exercised in defining the vectors w^+ and w^-, goal programming may even provide an inferior solution.

The merit of goal programming lies in its translation of goals into what can be achieved. The goal programming analysis provides the decision maker with an opportunity to reassess his goals in absolute terms as well as relative to other goals. This should, in turn, enable the decision maker to redefine all goals and priorities because, as a result of the earlier analysis, he has an understanding of the interrelationship between different goals which was not obvious before. The formulation of goals and planning for their achievement is a dynamic process. It is unlikely that only one goal programming run would satisfy the decision maker.

In the formulation discussed so far, the objective function has been assumed to be linear in d^{+} and d^{-}. However, the penalty for over/under achievement need not be linear and may increase exponentially or in a step-wise manner. The resulting non-linear objective function could be handled in two ways: by piecewise, separable linear programming, for which techniques are available (Hadley 1964), or according to the following simple transformation: If h_j is the jth goal, the penalty for under-achievement (w_j^-) of which increases exponentially with d_j^-, let

$$H_j > hl_j > \dots > hi_j > \dots > hm_j > 0; \ (i=1, \dots ,m)$$

Formulate m extra goal equations with hi_j $(i=1, \dots ,m)$ as the right hand side. Incorporate these equations in the main model.

Similarly, if w_j^- is the corresponding weight, let

$$wi_j^- = (P)^i \, (w_j^-); \ (i=1, \dots ,m), \text{ and } P > 0.$$

Add $+i(wi_j^- di_j^-)$ to the objective function. The effect of these transformations will be that the weight for under-achievement of the jth goal will increase in an approximate exponential manner. By assigning a proper value to P, the rate of increase in the weight could be controlled. However, the number of the rows and columns in the model will increase by m and 2m, respectively, as a result of these transformations.

Figure 1 represents the relationship between the goal attainment level (h_j - d_j^-) and the corresponding cumulative total weighted deviation for the jth goal. P = 0 corresponds to the linear relationship between the deviation d_j^- and the total penalty cost for deviation from the stated goal. Any positive value of P corresponds to a non-linear relationship between the deviation from a goal and the total

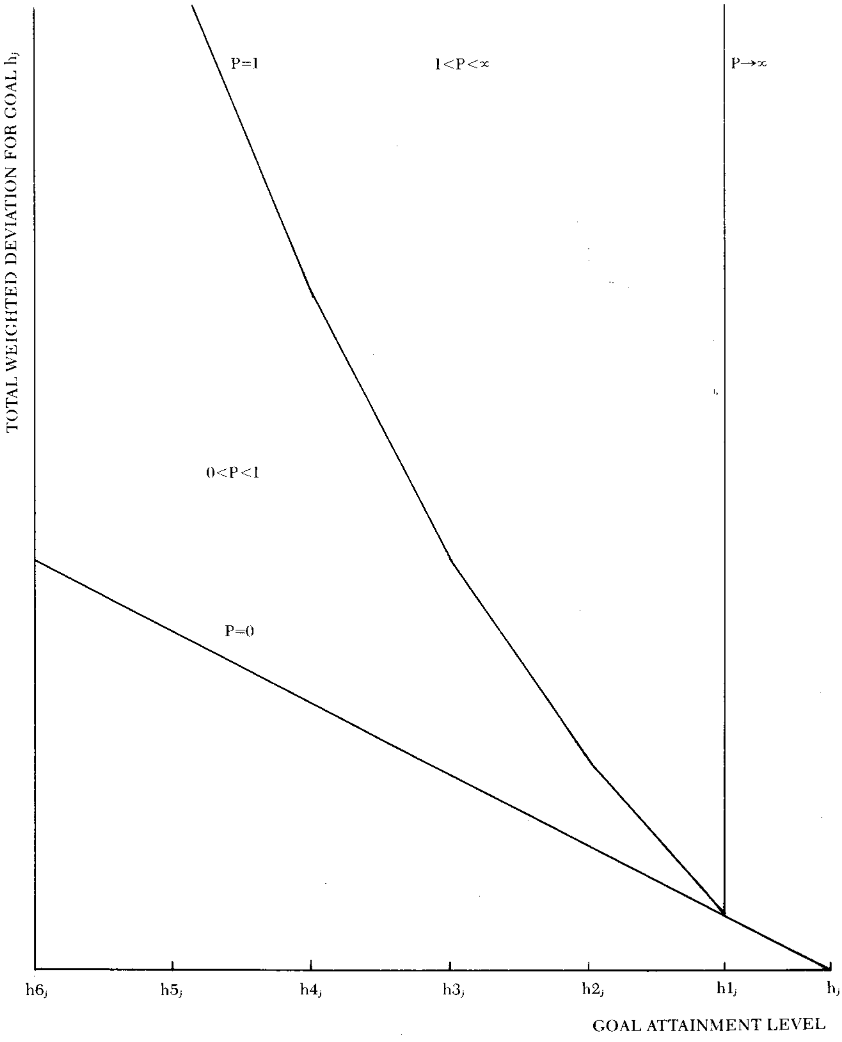

FIGURE 1. Total weighted deviation for under-achieving a goal with non-linear weights.

penalty for that deviation. When $P = \infty$, the goal reduces to a constraint.

LITERATURE REVIEW

Goal programming is not a new technique. The basic elements of the method were introduced by Charnes, Cooper & Fergusen (1955). Their problem, which dealt with the determination of salary levels of executives over a range of seven categories, with the constraint that an executive of higher category could not be paid less compensation than one in the lower category, had linear constraints with a non-linear objective function. No weights or priorities were used. The term "Goal Programming" was first used by Charnes & Cooper (1961) in their two-volume publication "Management Models and Industrial Applications of Linear Programming." In that they also showed how maximization or minimization of some of the objectives could be combined with the minimization of deviations from the goals. They also discussed weighting and pre-emptive ordering of goals.

Ijiri (1965) presents perhaps the most extensive treatment of the theory of goal programming and its comparison with the generalized inverse approach. The fundamental difference between the two is that in goal programming the objective function is:

$$\text{Minimize} \qquad Z = \sum_i w_i \left| h_i - \underline{c}_i \, \underline{x} \right| \tag{3}$$

whereas in the generalized inverse approach it is:

$$\text{Minimize} \qquad Z = \sum_i \sqrt{w_i \, (h_i - \underline{c}_i \, \underline{x})^2} \tag{4}$$

where h_i, w_i and c_i represent the ith goal, the weight associated with the ith goal and the corresponding vector of technological coefficients for the ith goal, respectively.

A recent publication by Lee (1972) incorporates and expands the initial work by Charnes & Cooper and Ijiri. Lee has also prepared a FORTRAN computer program for handling goal programming problems of up to 125 variables (including deviational variables) and 60 rows. Its principal advantage over standard LP packages is in a builtin scheme for ordinal ranking among goals. No weights need be assigned explicitly to ensure ranking.

Charnes, Cooper and others have made the maximum contribution to the scarce but growing literature on goal programming. Almost all of their applications relate to manpower planning for the U.S. Navy (Charnes *et al.* 1968 a, 1969). Charnes *et al.* (1971) formulated a goal programming model for manpower planning with an embedded input-output analysis. The only recorded application by Charnes *et al.* (1968 b & c) outside manpower planning relates to advertising media planning.

Lee (1971), Lee, Lerro & McGinnis (1971), and Lee and Clayton (1972) have also presented goal programming applications as aids to managerial decision making. The application by Lee (1971) is very simple and hypothetical, and more of an outline to the basic concepts of the procedure. In association with Lerro & McGinnis (1971), Lee applied goal programming to the selection of efficient portfolios for commercial banks. Lee & Clayton (1972) developed a goal programming formulation to determine personnel need for academic institutions.

Courtney *et al.* (1972) applied goal programming to deal with the problem of population location in metropolitan areas. The usefulness of this approach to urban planning, real estate development and designing of transportation systems is demonstrated through an application in Texas University student housing.

Contini (1968) developed a procedure for handling uncertainty in a goal programming formulation, where the goals and subgoals (or decision variables) are related by a linear system of stochastic equations. The objective function in this case involves maximization of the probability that a realization, in terms of target achievability, lies in a confidence region of predetermined size.

Even though goal programming appears to be better suited for handling problems related to forest management than linear programming, and in spite of the fact that goal programming is not a new technique, there appears to have been no published application of goal programming to the problems of forestry or timber processing. This lack of interest in goal programming appears to be more on account of the lack of awareness rather than because of demonstrated inadequacy of this approach. Field (1973) appears to be the first to expose goal programming in the forestry literature as a decision making tool in forest management. His illustration, though hypothetical and simple, demonstrates the flexibility and versatility of the goal programming approach. His example relates to the management of a private forest for multiple objectives including productive and recreational uses. His own contribution to the goal programming literature is a simple method for assigning weights to ensure ordinal ranking between different goals while using standard LP packages.

APPLICATION OF GOAL PROGRAMMING FOR TIMBER MANAGEMENT PLANNING

Underlying Assumptions

Models are abstractions of reality. The translation of a complex biological-economic problem into a mathematical model often requires substantial simplifications. So long as these simplifying assumptions do not stray far from reality, their effect on the outcome of a study may be only marginal. A clarification of the underlying assumptions will define the scope of the applicability of this study.

A forest is a complex entity resulting from the interaction of many biophysical factors. Some of these, such as soil and atmospheric conditions, are fixed and cannot be altered significantly. However, man can control the composition and stocking of a forest stand and the quantity and the size of the product from it. The assumptions being made here relate both to the operational environment and to the manner in which human intervention might be used.

The productive capacity of a forest varies with the site, which represents the sum total of all environmental factors. Though the changes in the site and consequently in the productive capacity are gradual, this variation in the productive potential is recognized by division of the forest lands into broad site classes for the purpose of forest management. The extent and location of each site class is assumed to be clearly known. Site class I is assumed to be the best, site class II the next best, and so on.

The area of a forest management unit may be in hundreds of thousands of hectares and as management planning implies spatial and temporal ordering of specific stand treatment, it would be necessary to identify each of the stands without ambiguity. This can be achieved by dividing the forest into small units. Fortunately this division exists in most of the intensively managed forests in the form of blocks and compartments with permanent boundaries. The total number of compartments would not affect the model, except that the total size of the problem would increase with the number of compartments involved.

The compartments may vary in area but they are assumed to be located in one site class and to be fairly uniform so far as the composition, age, and stocking are concerned. The assumptions are required for prediction of stand parameters such as stand height, average diameter, number of trees per hectare and the rate of growth. As precise techniques for projecting stand parameters and growth of uneven-aged and irregularly stocked stands do not exist, we are compelled to confine our analysis to even-aged stands.

The production time in forestry is very long and many of the decisions made now will have consequences far into the future. This need for looking far ahead requires a basic assumption that the forest area is not likely to be withdrawn from timber production. As producers of a basic and renewable resource *(viz.,* timber), publicly and industrially owned forests may be safely assumed to remain under timber production on a continuous basis. This assumption can be easily relaxed to imply that a forest area will remain under timber production at least till the reforestations, which are being planned now, are merchantable.

The above and other assumptions on which the planning model is based may be summarized as follows:

a. The forest is to remain permanently under timber production.
b. The forest has been divided into broad site classes.
c. The forest has been divided into compartments which may be variable in area but are uniform with regard to the site class, age, composition and stocking.
d. The final harvest will be by clear-cutting.
e. The stands will be regenerated artificially.
f. The type, intensity and frequency of thinnings have been determined independently.
g. It is the end products (such as sawlogs, plywood and pulpwood) which determine the species composition in reforestation, pro-

vided it is acceptable on ecological and other environmental grounds.

h. A list of reforestation alternatives exists for each site class, and information regarding establishment costs, rotation, total product output and the returns from thinning and final harvest are known.

1. The expected yield from thinnings and final harvest is known for each compartment for each of the next five to ten years. The expected money returns from these harvests are also known.

It can be seen that the information needed for the goal programming analysis is not unique. Many of these assumptions are required in forest management decision-making situations using other techniques.

Management Objectives as Goals

Management objectives provide a rationale for the selection of the best possible course of action from among many that may be available. If the objectives are several and incompatible, merely specifying that objectives A, Band C be maximized and the objectives X, Y and Z be minimized, would not be enough. In that case it may be necessary to specify attainment levels for most or all of the objectives. These attainment levels (or goals) would provide the criteria for judging the overall performance of the enterprise and at the same time provide direction to the management operations. In this section, the objectives of managing a forest property for timber production are analyzed to facilitate their formulation into goals and their incorporation in the goal programming model.

Capital, in the form of equipment, material and manpower is used with the land to grow timber, which in turn provides income to the owner. Depending on the type of ownership and its extent, forest management objectives for timber production may include the amount of annual (or periodic) timber harvest, revenue from these harvests, expenditures on all aspects of forest management, product output and money income from the current reforestation investments, and other concerns such as the utilization of manpower, equipment and material. The operation of a forest property affects the current flow of income and also influences the flow of timber products and income in the future. It is not possible to plan forest management on a short term basis without consciously or otherwise affecting the long-run *How* of timber products and income. A production period of several decades is a characteristic feature of forest management and is indicative of the need to look far beyond the present to ensure that current management operations are compatible with future expectations. Accordingly, some obvious objectives such as product output, current revenue, reforestation investments and returns are viewed in this light.

Timber (and fuelwood) is the primary product from the forests of India, as is true of the forest areas specifically set aside for timber production in other parts of the world. **In** forests managed primarily for timber production, the level of output from harvests during a planning period and the expected output from planned reforestations could be one set of management objectives to be pursued. Given a situation where more than one product is desired, the simultaneous maximization of their output on a fixed land base may be impossible. For proper guidance in managerial decision making in such a situation, it may be necessary to specify goals for some or all of these products. Some are produced in limited quantities even when not planned, such as the limited production of pulpwood (or fuelwood) from thinnings and final harvest while producing sawlogs. Depending on the production objectives, goals must be specified for products actually desired.

These product goals would be needed for two different periods: the immediate planning period and the distant future when the reforestations planned now would mature. Future production goals would affect the current reforestation strategy, *i.e.,* the alternatives to be used in reforestation and the area under each.

Income objectives may also be of interest. As in the case of production goals, two time periods would be involved, one relating to income from harvesting of the existing stands and the other concerning returns from the reforestation investment. As future income would be a direct consequence of reforestation investment, it would be appropriate to consider it as a return on the capital investment and the land. Once an investment has been made, marginal economic principles should determine when to harvest a stand. Whether to harvest a stand at a particular time or not should be a question based on the rate of increase in the value of the stand and the land. If ΔR represents the increase in the value $R(t)$ of a stand growing on a land of value V, and if p is the opportunity cost of capital, the marginal rule dictates that:

$$\text{if } \triangle R < [R(t)+V]\,p; \quad \text{harvest the stand,}$$
$$\text{if } \triangle R > \{R(t)+V\}\,p; \quad \text{hold for at least one year,} \qquad (5)$$
$$\text{if } \triangle R' = \{R(t)+V\}\,p; \quad \text{the stand may be harvested or allowed to grow for another year.}$$

The main difficulty with this approach lies in objectively determining the value of land, as it is rarely freely traded. Assuming that the land will remain under timber production, for the above test of maturity, the expected land value should be computed using Faustmann's formula and the alternative use of the land after harvest.

An absolute, single decision rule of this kind is rarely used in practice, because of requirements such that a specific area or volume must be harvested each year. Given these conditions of operation, the financial decision rule for maximizing income from harvesting existing stands would have to be suitably modified. This modification might take one of many forms. We may maximize total income from harvest, subject to constraints on area and/or volume; or we may maximize the volume or value growth of the remaining stands subject to restrictions mentioned earlier.

Another set of goals may relate to the expenditure on forest management operations. These may be broadly grouped under three categories:

a. annual administrative and protection costs;
b. annual harvesting costs; and
c. annual reforestation costs.

Annual administrative costs can be assumed to be independent of the intensity of forest management and are so treated in this study. Similarly, harvesting costs are costs incurred to provide immediate income and, therefore, are not subjected to rigorous budgetary restrictions commonly associated with other expenditures.

Reforestation costs usually form the major part of the annual expenditure budget. This is really an investment and should be viewed as such. This investment will affect the future production level and the rate of financial return from this investment on the forest land through the associated establishment costs, expected output, and money returns from each of the reforestation alternatives.

Before the mathematical formulation of different goals for the goal programming model is taken up, certain questions have to be answered. These have bearing on the goals whether they be related to product output, profit, or expenditure. These include:

a. the rotation to be used,
b. the financial criteria for evaluating profitability of different reforestation investments,
c. the interest rate to be used for discounting costs and returns in reforestation.

These aspects will be taken up in some detail as the proper selection of reforestation alternatives is the key issue of this study.

Criteria in the Selection of Reforestation Alternatives

In an earlier section of this chapter, an assumption was made about numerous reforestation alternatives. More than one species may be suitable for each product *(i.e.,* sawlogs, plywood and pulpwood). Each of these species may have a different rotation, establishment costs, total product output and income. Some species may provide more than one product output. In addition to sawlogs or plywood, the small-sized material from thinnings and lops-and-tops from final harvest usually provides a sizable amount of pulpwood or fuelwood.

Some species may be raised by more than one method. Direct sowing and entire transplanting are common examples. Some species do well with planting of stumps (roots & shoot cuttings), examples of which in India include: *teak* (Tectona grandis, Linn.), *semal* (Bombax ceiba, Linn.) and *tun* (Cedrella toona, Roxb.). Because of different costs and returns associated with diffrent species, methods of regeneration, and a wide range of possible initial stocking, the decision to prefer one over others is primarily one of economics and not of silviculture. Another assumption of regeneration of cutover stands by artificial means provides this flexibility in the choice of species.

So far as the budget goal is concerned, each reforestation alternative affects the manager's choice primarily in two ways: through a) its establishment costs and, b) its rotation length. There may be other factors besides the two mentioned above, such as manpower, equipment and material requirements. Whereas these factors may be limiting only in specific situations, the establishment cost and rotation, when combined with fixed land and sustained production, would affect the reforestation investment, expected product output and the expected money return at maturity. In view of the all-encompassing effect of rotation on managerial decision making, broad implications of rotation in relation to management planning are examined here.

Rotation. Under sustained yield management, the rotation affects the level of annual investment in reforestation. Though this investment could be lowered substantially by adopting longer rotations, the cost of these long rotations, as reflected in reduced mean annual increment and money returns, may be far greater than hypothetical benefits from lower annual investment. With a long rotation, the ratio of annual turnover to the total investment tied up in land and growing stock is lower and it may be possible to get a better return by investing that amount annually on a smaller land base and adopting optimal rotations. However, in order to ensure complete utilization of the available capital and land, those reforestation alternatives which have lower establishment costs or longer optimal rotations should also be considered, particularly when the level of annual reforestation investment is expected to be critical in the management planning. The management of a forest property is concerned with the maximization of the total returns on the combined investment of capital and land, and it is not always possible to determine *a priori* whether the land or capital is going to be most limiting in the planning of management operations. Inclusion of alternatives which have lower establishment costs or longer optimal rotation would ensure that the possibility of a limiting budgetary situation has been covered. Establishment costs of each alternative and the associated optimal rotation are used here in formulating budgetary and sustained output goals and constraints respectively.

What constitutes an optimal rotation cannot be resolved easily. Depending on whether the owner is interested in maximizing product output or profit, it could be either the rotation of maximum volume production or the financial rotation. The former is usually longer than the latter. Economists generally disfavor the rotation of maximum volume production because it provides a lower monetary return on the investment of capital and land than the financial rotation (Gaffney 1960, Pearse 1967). This argument focuses on returns to the private land owners and ignores the fact that there may be other monetary returns resulting from the availability of the timber. Benefits from timber growing do not end with the production of stumpage, and the contribution of the stumpage to the general economy is widely recognized. Hair (1963) has reported that in the U.S.A., each dollar in stumpage contributed $25.00 to the Gross National Product in 1958. In the case of the private forests, the indirect return would not accrue to the owner, and in that situation the financial maturity criterion would alone be valid.

The determination of the rotation of maximum volume production is relatively easy because it requires only the estimation of volume output at different points in time. Determination of financial rotation, on the other hand, is more complex and uncertain. Besides the volume estimate, estimates are also needed for the stumpage prices, which are usually determined residually by subtracting transportation and logging costs from the market price expected to exist at the time of harvest. There are several criteria for financial maturity, which may result in very different estimates of an optimum economic rotation. Gaffney (1960) and Bentley & Teeguarden (1965) provide surveys of the literature on this topic. Gaffney concludes that Faustmann's Bodenrente (soil rent) provides the only correct method for computing financial maturity.

For this study, a financial rotation which maximizes the expected land rent (or the expected soil value, as both imply the same rotation) is suggested. Both rotations-of maximum volume production and of financial maturity-could be used as two different reforestation alternatives as they would have different output and financial returns.

Financial Criteria for Evaluating Profitability of Reforestation Investments.

Three different criteria may be used in forestry for comparing the financial performance of investment alternatives. These are:

Internal rate of return

Present net worth

Benefit-cost ratio

If the question is only of accepting or rejecting an investment proposal, anyone of three could be used, because an internal rate of return greater than the interest rate corresponds to a positive soil expectation value and to a benefit-cost ratio of greater than 1. However, when a selection is to be made from among several alternatives, different criteria may provide different rankings. Further, the inclusion or exclusion of the land value may at times give different results.

Though the internal rate of return provides a measure which is independent of the investment level, it cannot be used for comparing investment in reforestation because of the assumption of capital fixity. If two alternatives maturing at different ages are compared, the internal rate of return approach implies that the entire return from the earlier maturing alternative can be re-invested during the remaining period at the rate earned earlier by that investment. In the timber growing context this implies that only capital is scarce and the land, whether free or at cost, is available to completely utilize the available capital.

Another criticism of the internal rate of return approach stems from the fact that when alternatives with different establishment costs are compared, the method fails to provide a satisfactory criterion.

Lastly, the rate of return criterion is very sensitive to the land value used in the analysis. Unfortunately it is not possible to fix land value objectively, as in most timber production situations land does not change hands frequently enough to have an objective market value. A method for comparing alternatives in which land value is not considered explicitly would therefore be preferable.

In the present net worth approach, the underlying assumption is that the capital is not fixed but the land is. Given the cost of borrowing money, this method provides a measure of the return from land, if no land value has been used in the computations. The main drawback of this method lies in ignoring the effect of different maturity ages. If the present net worth is the same for two alternatives with different rotations, this criterion would not indicate any preference. However, the shorter rotation may be preferable, as the land would be released much earlier. Also like the internal rate of return, present net worth is sensitive to the land value and it would not be difficult to show contradiction in ranking due to this approach by using low and high land value.

However, it is possible to overcome both of these shortcomings by modifying the present net worth of a single rotation to the expected soil value or annualized land rent-which is the annual interest charge on the expected soil value as determined by Faustmann's formula.

Both the soil expectation value and the annualized land rent are due to Faustmann (1849) and are independent of the subjective land values. The annualized land rent, as a practical tool, has certain merits over the soil expectation value approach. First, it denotes the rate of annual return from the land in addition to the recovery of capital with interest. Second, the annual costs which were ignored earlier in the computation of present net worth, could be handled easily with the annualized land rent, because it amounts to deduction of a constant amount from the annualized land rent of all alternatives. **In** fact the annual costs could be pro-rated on the basis of the site classes, after computation of the annualized land rent, instead of spreading them evenly over the entire forest management unit.

The benefit-cost ratio, like the internal rate of return, measures the return on the invested capital and land. **It** is unsuitable for comparing alternatives which mature at different periods or which require different initial investments. Lower investments, due to the smaller denominator, tend to give a higher benefit-cost ratio, even though the magnitude of the return may be small. **It** is also sensitive to land values and the ranking may be contradictory when with-and without-land value ratios are compared.

From the foregoing discussion it can be seen that the annualized land rent approach is the best criterion for comparing investments in reforestation. However, a fixed land base, sustained yield management, and limited investment funds make it difficult to indicate which of the alternatives would be best in a particular situation. Different alternatives may have different reforestation costs, rotations, mean annual increment and annualized land rent, and the alternative which maximizes the mean annual increment may not provide the maximum annualized land rent and the minimum reforestation investment. The goal programming model is expected to provide answers to these problems in the context of a given reforestation budget, land area, production goals and the expectations of return from the land.

Interest Rate for Discounting. No factor affects forest management planning more markedly than the interest rate to be used for discounting costs and returns. The effect of the interest rate is felt in more ways than one. First, it affects the rotation of financial maturity.

A higher discount rate results in an earlier financial maturity and may result in a higher annual reforestation investment on a sustained yield basis, because the area to be reforested annually would be larger with a shorter rotation. The shorter financial maturity rotation may also result in lower product output. Second, it affects the expected soil value or the annualized land rent. A higher discount rate results in a lower expected soil value or annualized land rent. Third, when alternatives which mature at different time periods are being compared, the discount rate may affect their relative ranks on the basis of their expected soil value or annualized land rent. A higher discount rate may favor an earlier-maturing alternative over a later-maturing one, but this ranking may be reversed if a lower discount rate is used. It is, therefore, important that the interest rate to be used for discounting in the economic analysis of the forest management operations is decided upon well before the analysis is attempted, and only after careful consideration of all its implications.

Though there is general consensus among economists that the discounting rate for public investments should be different from that in the private sector, the views regarding the direction which this shift should take are Widely divergent. Marglin (1963), on the one hand, recommends use of a lower interest rate for public investments than in the private sector. Baumol (1968), on the other hand, advocates a much higher discount rate in public investments than used in the private sector, to neutralize the effect of corporate tax on the net business income.

Without getting involved in the controversy of the discount rate to be used in public investments, we can safely state that the decision on the discount rate to be used in forestry will be taken at a high level, and the forest managers will rarely be called upon to take a decision on this matter. Though there may not be a controversy about the discount rate to be used in the private sector, the argument that for reforestation investments in the public sector the rate would be provided to the forest manager by some central decision making authority, and not determined by the forest manager himself, also holds in private forest management planning.

In the example presented in the next chapter, it is assumed that the forest manager has been provided with 5% as the rate to be used for discounting costs and income for computation of the nnancial maturity and annualized land rent from different reforestation alternatives.

Goal Programming Model

Two related but fundamentally different issues are involved in forest management planning for timber production:

a. Given the goals on future product expectations, reforestation investment, the expectations of return on this investment, and the sustained yield management constraint, what should be the rate of reforestation by different alternatives? This issue may be termed "Long Range" planning, because the output and income resulting from the current reforestation investments will be available only after a long waiting period.

b. Given the rate of reforestation, as determined by the Long Range plan, how should the harvesting, which is to precede the reforestation, be distributed in time and space? This may be termed "Short Range" planning as the decision involves actual stand treatment within the next five to ten years.

The difference between the two is not so much one of time as of the type of decisions required. The Long Range plan deals primarily with policy issues such as the quantity and quality of product mix expectations, the extent of reforestation investment needed for the realization of these expectations, and the expectations of monetary returns from the investment. Here one takes into account the forest growth potential and not necessarily the distribution and composition of existing stands. The Long Range planning also provides the maximum flexibility in management planning because a forest manager can do little, except wait, after reforestation has been carried out. Because of the far-reaching effects of the Long Range planning, the need for post-optimal analysis and parametric programming is far greater here than in the case of the Short Range planning.

The Short Range plan, on the other hand, deals with the actual stand treatment and the decisions which depend on the actual condition of the stands. Except for changes in the order in which individual stands are to be taken up for harvesting, a forest manager has little flexibility in Short Range planning. Though there might be significant variations in the product output and revenue from harvest because of these changes in the harvest scheduling on a year-to-year basis, their overall effect on the total outcome during a planning period of five to ten years may be only marginal.

Though both of these plans can be combined into a single model, the output of which will provide answers to policy questions and harvest scheduling simultaneously, no specific advantage would result from this. Indeed this may result in a problem whose size may become too large and the number of site classes, reforestation alternatives and the number of years in the planning period may have to be restricted in order to reduce the problem size to manageable proportions. Post-optimal analysis and the parametric programming, so essential to the Long Range plan, may have to be severely restricted. Therefore, the goal programming model developed in this study treats the forest management planning problem as two sequential problems, the output of the Long Range plan becoming the input for Short Range planning. The models developed in this chapter are based on this division of the forest management planning problem.

Long Range Plan. We are now ready to translate the multi-objective reforestation planning problem into a goal programming formulation. Let '$X_{m,a}$' be the decision variable representing the area of site class m (m = 1, . . ., M) to be reforested annually by alternative a (a = 1, . . ., A).

1. Timber Product Output Goals

$$\sum_m [\sum_a (X_{m,a} Y_{m,a})] - d1_b^+ + d1_b^- = Z_b \qquad (6)$$

where

$Y_{m,a}$ – is the unit area output of timber product b (b = 1, . . ., B) from alternative a.

Z_b – is the total product output goal for product b from the entire forest management unit.

$d1_b^+$ – is the surplus deviational variable corresponding to product b.

$d1_b^-$ – is the slack deviational variable corresponding to product b.

$\sum_a$ – is the summation over all reforestation alternatives a in site class m.

$\sum_m$ – is the summation over all site classes m.

There may be one such goal equation for each product output. For some, there may be both an upper and lower bound. It is not necessary that goals be set for each product output.

2. Reforestation Budget Goal

$$\sum_{m} \{\sum_{a} (X_{m,a} C_{m,a}) \} - d2^{+} + d2^{-} = E$$

$C_{m,a}$ – is the unit area reforestation cost for alternative a in site class m.

$d2^{+}$ – is the surplus deviational variable.

$d2^{-}$ – is the slack deviational variable.

E – is the annual reforestation budget goal.

It may be argued that the reforestation budget is more of a constraint and should be treated as such. However, in the long run, there is no real constraint and theoretically everything can be changed by policy decisions at some level. It would not be unreasonable to proceed on the assumption that in public ownership the area under each forest management unit is not going to change in the foreseeable future. The same cannot be said of the budget level, which can be expected to change as considered desirable by the appropriate decision-making authority.

Another advantage of treating the budget as a goal stems from the fact that the effect of variations in the budget level on product output or income from the land could be studied and the information used by the central decision makers not only for the total amount of investment in reforestation but for the efficient allocation of this amount among different management units as well.

A single equation is needed for this goal. If the budget level is going to change from year to year, these changes can be handled by parametric programming.

3. Expected Return from Land Goal.

$$\sum_{m} \sum_{a} \{(X_{m,a} W_{m,a} R_{m,a})\} - d3^{+} + d3^{-} = R$$

where

$W_{m,a}$ – is the annualized land rent by reforestation alternative a in site class m.

$R_{m,a}$ – is the rotation corresponding to reforestation alternative a in site class m.

R – is the income goal from the use of the forest land.

$d3^+$ – is the surplus deviational variable.

$d3^-$ – is the slack deviational variable.

Only one equation is needed in the model for this goal.

4. Sustained Output Constraints.

$$\Sigma\ (X_{m,a}\ R_{m,a}) \leq X_m \tag{9}$$

where

X_m – is the total area of the forest land of site class m in the management unit.

It would be reasonable to assume that the reforestation cost for a particular species and method of regeneration will not differ materially in different site classes, but the amount of total harvest, rotation and income therefrom may be expected to differ substantially. Thus, in order to avoid wide fluctuations in the reforestation budget with emphasis on equal annual product output and income, or conversely, in order to avoid fluctuations in income and product output from given level of reforestation budget, a separate constraint is provided for each site class.

5. Objective Function.

In all the goal equations, surplus and slack variables ($d1^+$, $d1^-$, *etc.*) are used to take care of over and under achievement of each goal. As pointed out earlier in this chapter, it is not necessary that for each goal both of the corresponding deviational variables should be included in the objective function. There may be goals for which over-achievement may be welcome (such as income from land and product output). The situation where under-achievement may be desirable is typified by the reforestation budget goal. Whether both or only one of the deviational variables is to be in the objective function will depend on the specific management situation. The general Long Range planning objective function used in the goal programming formulation is:

$$\left.\begin{array}{l} \text{MINIMIZE } \sum_{b} (w1_b^+\, d1_b^+ + w1_b^-\, d1_b^-) + w2^+\, d2^+ + \\ \qquad w2^- d2^{-+} w3^+\, d3^+ + w3^-\, d3^- \end{array}\right\} \tag{10}$$

where $w1^+$, $w1^-$, *etc.* are numerical weights assigned to the corresponding deviational variables. A higher weight would indicate that the decision maker (not necessarily the forest manager) imputes a greater penalty cost for deviating from that goal.

We can now have some idea about the size of the goal programming formulation. With A as the total number of reforestation alternatives over all site classes, and B as the number of product output categories such as sawlogs, quality veneer, plywood, matchwood, pulpwood and fuelwood, the total number of columns is not likely to exceed A + 2B + 4. This includes two deviational variables for each goal. The number of rows will be only M + B + 2, with M the total number of site classes into which the management unit has been divided. Assuming that the number of reforestation alternatives is not likely to exceed 20 for each site class, that the number of site classes as a rule is not going to exceed 5, and with 5 product categories, the goal programming formulation of the Long Range planning problem is not likely to have more than 114 columns by 12 rows.

Two assumptions are implicit in the above formulation:

1. Only the reforestation budget affects the Long Range planning outcome. Annual expenses for administration, protection, taxation, and so on, and the costs associated with harvesting and thinning do not affect the level of reforestation budget.
2. A given reforestation alternative will cost the same in a site class regardless of compartment location.

These assumptions are not unreasonable. In the short run of five to ten years, annual carrying charges may be assumed to be independent of the intensity of forest management. Further, in governmental budgeting, allocation of funds for reforestation is generally done separately, on the basis of the future product output needs, and may therefore be assumed to be independent of all other costs associated with forest management. The second assumption is a little stronger. In addition to accessibility, reforestation costs may vary with the ground and cover conditions. In the Short Range planning analysis, flexibility is being provided to increase and decrease the area to be harvested annually in each site class. By combining the higher reforestation costs with the reduction in area and vice versa, it is possible to ensure complete utilization of the annual reforestation budget.

To these we add another assumption that, in real money values, the costs and returns will not vary from year to year. This means that the planning strategy during the next five to ten years will vary, if at all, because of the changes in the reforestation budget. Unless there is a change in the vector of goals during the next five to ten years, the strategy developed by solving the above one-period formulation will remain valid for the entire planning period. As the solution to the problem of one year does not affect the decisions in the subsequent years, the solution to the goal programming formulation can be more efficiently obtained by solving several small one-period formulations than by solving one large multi-period formulation.

By post-optimal analysis and parametric programming, we can test the stability of the solution. This will also provide valuable feedback to the centralized planning authority, which may lead to a modified vector of goals and/or weights. The effect of relative weights on different product output and income can be examined and the trade-off values for favoring one against another determined. These points will be clarified in the example presented in the next chapter.

Short Range Plan. Once the total area to be reforested by each reforestation alternative has been determined in the Long Range plan analysis, we can compute the total area by site classes which is to be harvested annually during the next five to ten years. With this information and the biological and economic data about the existing stands, we are ready to formulate the harvest scheduling problem.

Let '$X_{n,m,i}$' represent the area of compartment n (n = 1, . . ., N), in site class m (m = 1, . . ., M) to be taken up for harvesting (and subsequent reforestation) in period i (i = 1, . . ., I). The goals, constraints and the objective function of the harvest scheduling problem can be formulated as follows:

1. Product Output Goals

$$\left.\begin{matrix}\sum_{m}\left[\sum_{n}\{X_{n,m,i}V_{n,s,b,i} + (X_{n,m} - \sum_{j} X_{n,m,j})\, T_{n,s,b,i}\}\right] \\ -d1^{+}_{b,i} + d1^{-}_{b,i}\end{matrix}\right\} = Q_{b,i} \qquad (11)$$

where

$V_{n,s,b,i}$ – is the volume of product b of the species s in compartment n, on a unit area basis, which is available in final harvest in period i. Here
s = 1, . . ., S (species)
b = 1, . . ., B (product category)

$T_{n,s,b,i}$ – is the thinning yield from compartment n, by product b of species s, on a unit area basis, if due in period i.

$X_{n,m}$ – is the total area of compartment n with its associated site class m. Only one site class is associated with each compartment.

$\sum_j X_{n,m,j}$ – is the summation of the area of compartment n, which is taken up for harvest between periods 1 and i.

$Q_{b,i}$ – is the output goal for product b in period i.

$d1_{b,i}$ – is the surplus variable corresponding to product b and period i.

$d1_{b,i}$ – is the slack variable corresponding to product b and period i.

Theoretically, there can be one such equation for each product b and for each period i. Actually, there may not be goals for each product, and for some of the products there may be both an upper and lower bound.

2. Current Income Goal

$$\sum_m \left[\sum_n \{X_{n,m,i}\, P_{n,i} + (X_{n,m} - \sum_j X_{n,m,j})\, P^{*}_{n,i}\} \right] - d2^{+}_{i} + d2^{-}_{i} = G_i \qquad (12)$$

where

$P_{n,i}$ – is the stumpage value from compartment n in period i, on a unit area basis, in the final harvest.

$P^{*}_{n,i}$ – is the stumpage value from thinning in compartment n, on a unit area basis, if due in period i.

G_i – is the income goal for period i.

$d2^{+}_{i}$ – is the surplus variable corresponding to the income goal in period i.

$d2^{-}_{i}$ – is the slack variable corresponding to the income goal in period i.

As in the case of product goals, the first component provides revenue from the final harvest and the second provides revenue from thinning. Unlike the Long Range planning formulation, the income here is the total revenue from timber harvest and is not differentiable into income from land and the money investment in this land.

There is one equation for each period.

3. Area Constraints.

Two categories of area constraints are required. The first ensures that the total area to be harvested in each site class and in each period does not deviate from the area arrived at after the Long Range planning analysis. The second ensures that the total area actually harvested during the planning period does not exceed the physical area of the compartment.

$$\sum_{n} X_{n,m,i} = X_{m,i} \tag{13}$$

where

$X_{m,i}$ – is the total area of site class m to be harvested in period i.

This ensures that the total area to be harvested in each period is equal to that provided by the Long Range planning analysis. There would be one constraint for each site class and each planning period.

The second set of area constraints guarantees that the total area to be harvested in a compartment during the planning period of five to ten years, does not exceed the area of that compartment.

$$\sum_{i} X_{n,m,i} \leq X_{n,m} \tag{14}$$

There would be one such constraint for each compartment.

4. Objective Function

The objective function in this goal programming formulation consists of the sum of the dot product of the two sets of deviational variable vectors *d1* and *d2* with their corresponding vectors of weights *w1* and *w2*. The general objective function formulation is:

MINIMIZE

$$w1^{+} \cdot d1^{+} + w1^{-} \cdot d1^{-} + w2^{+} \cdot d2^{+} + w2^{-} \cdot d2^{-} \tag{15}$$

As in the earlier formulation (10), it is not necessary that both deviational variables for each goal be in the objective function. As the objective is to maximize product output and income from harvests during the next five to ten years, only the negative deviations (*i.e.*, shortages) need be incorporated in the objective function. In fact it is not even necessary that this part of the analysis be handled by goal programming. With a constraint on the area to be harvested in each period, either product output or income may be maximized by linear programming (Littschwager & Tcheng 1967).

Whether the Short Range planning problem is to be formulated for goal or linear programming, the size of the model will be formidable. With 1,000 compartments, 5 site classes, 10 years in the planning period and 5 product categories, this problem will have over 10,000 columns by 1,250 rows. The problem size is very large and may require special decomposition algorithms and computers with large core capacity. However, by careful screening of all compartments and exclusion of those which are not likely to be in the solution, it is possible to reduce the problem size without compromising the final outcome.

In its present formulation, the program will select those compartments for harvesting which will provide maximum product output and/or income during the entire planning period. If we subjectively take up enough compartments from each site class to make up from 120% to 150% of the area indicated by the analysis of the Long Range planning problem, according to those which provide maximum volume and/or value output on a unit area basis, it is possible to reduce the number of columns and rows by over 50%. The extent of reduction will depend on the duration of the planning period-the problem size for a five year planning period will be half of that for a ten year period-and the rotation lengths for reforestation alternatives to be used after harvest.

The solution to the Short Range planning program provides the spatial and temporal distribution of compartments scheduled for harvest during the next five to ten years. It is suggested that the harvest schedule be prepared for a longer period than that for which it is to be used. For example, if it is intended to plan harvesting and reforestation for the next five years, the plan should be prepared for the next seven to ten years. The reasons for preparing a harvesting plan for a longer period than needed are rather subtle. Unless the management plan covers a period long enough so that all existing stands are harvested at least once, the order of harvesting of individual stands is likely to be affected by the duration of the planning period. A long planning period will delay the harvesting of a stand with very high volume and/or value on a unit area basis, so long as it is putting on better growth than the others. Had the planning period been equal to its implementation period these stands, because of their high volume and/or value on a unit basis, would have been harvested ahead of other relatively poorly growing stands. Planning for a longer period and then revising the plan before it expires will interlink successive planning periods and will ensure that well-stocked and better-growing stands are not harvested ahead of others. There appears to be no practical way to ensure this and, at the same time, plan for only short periods at a time. Early revision of the plan, say every five years, should be advisable because the estimates of growth, costs and prices tend to become less reliable as we depart further from the present into the future.

The solution obtained by this program may still suffer from the following drawbacks:

1. The program may indicate its solution strategy in fractions of compartments for reforestation and harvesting in anyone year. This may be undesirable from the administrative point of view and may result in higher per unit area harvesting and reforestation costs.
2. The model regards benefits and costs of the silvicultural and logging operations in a compartment independent of the operations in nearby compartments. In reality, considerable gains can be obtained by doing 'heavy operations' (*i.e.,* thinning or final harvest) on compartments which are in proximity (Fornstad 1971).

Fractionalization of compartments can be prevented by integer programming. However, in its current state of development, integer programming algorithms can be used only for small size problems and, further, are not freely available at all computer installations. Littschwager and Tcheng (1967) used an approximation method for converting a non-integer solution into integer form in a problem dealing with harvest scheduling over 1166 compartments. It is suggested that the non-integer solution be subsequently rounded into an integer solution. This is likely to result in some variation in the area to be harvested and reforested annually. Some loss in the total volume and value may be expected due to this approximation, but the total effect would be only marginal (Littschwager & Tcheng 1967).

The rounding of a non-integer solution could be combined with the relocation of thinnings, final harvesting and reforestation. These operations could be concentrated, if such concentration is likely to result in economies of scale which could not be anticipated earlier, or evenly spread over the entire management unit to take advantage of the location of labor habitats, nursery facilities or existing roads.

Post-optimal analysis may be carried out to test the stability of the solution. **In** the Short Range planning problem, the factors which may vary are the expectations of yield over time and the estimates of stumpage values. As a rule, the harvest scheduling problem may be expected to provide a stable solution except under conditions of drastic variations in the relative prices of various timber products. The product output and revenue goals are not likely to have a significant effect on the outcome, as very little can be done to increase product output and/or revenue within a short period of five to ten years, given the area constraint on the harvest. The same cannot be said of the reforestation planning problem.

Fortunately, the size of the Long Range planning problem is much smaller relative to the Short Range planning problem and, therefore, the time, cost and effort needed for in-depth sensitivity analysis and parametric programming would be negligible. Thus the two-stage formulation of the management planning problem would not only result in two problems of manageable size, but also the post-optimal analysis could be carried out more efficiently and in greater detail.

SUMMARY

Goal programming is an extension of linear programming that is specifically suited to handle management situations where the objectives may be multiple, incompatible and incommensurate.

Two basic issues are involved in forest management planning for timber production, *viz.,* reforestation planning and harvest scheduling. The former may be termed Long Range planning, as the consequences of reforestation planning can be realized only after several decades. Reforestation provides maximum flexibility in planning forest management for timber production. The harvest scheduling may be termed Short Range planning as it deals with specific stand treatment during the next five to ten years.

The concept underlying reforestation planning is investment analysis. The decisions to be taken involve selection of the combination of reforestation alternatives which makes the best use of the available capital, land and other resources, and provides desired product output and income at maturity. **In** harvest scheduling, on the other hand, the idea is to select compartments for harvest scheduling which will provide maximum income and output currently and, at the same time, will ensure a high level of productivity in the remaining stands. This diversity in emphasis necessitates use of different criteria in problem analysis in the two stages.

The goal programming formulation of the reforestation planning problem is small and compact, and provides greater flexibility in handling non-linear weights and in-depth post optimal analysis. The harvesting scheduling problem, on the other hand, is large and, in order to reduce the problem size to manageable proportions, subjective selection of compartments for inclusion in the analysis may be unavoidable.

The sequential analysis of the two-stage formulation is expected to provide answers to the fundamental questions in forest management planning for timber production: when, where, and how much to harvest and how to establish the new stand.

CHAPTER THREE

AN EXAMPLE

A realistic example is presented here to demonstrate how this model would operate in real-life management situations. The example is based on hypothetical data and is purely illustrative of the technique outlined in the previous chapter. Interpretation of the results is thus limited by the data input.

Because of the personal association of the author with the tropical forests of Northern India, this example is set there. The data, though hypothetical, closely represents a typical management situation in that part of the country.

MANAGEMENT SITUATION, OBJECTIVES & CONSTRAINTS

We will use the goal programming formulation of the previous chapter to develop harvesting and reforestation strategies for a forest division in tropical Northern India. The forest division in question has a total forest area of 100,000 hectares which is suitable and available for timber (& fuelwood) production. This area is divided into the following three broad site classes:

Site class I	20,000 hectares
Site class II	50,000 hectares
Site class III	30,000 hectares

This area of 100,000 hectares is divided into about 1,000 compartments ranging in area from 80 to 120 hectares. Each compartment is fairly uniform with respect to site class, species composition and stock density. The entire forest area is expected to remain permanently under timber production.

Based on periodic surveys in the past, it is assumed that estimates are available of the standing timber volume in every compartment and of the expected rate of annual growth during the next ten years. The product output from these forests can be grouped into the following three categories:

a. sawlogs and quality veneer,

b. plywood and matchwood logs,

c. pulpwood and fuelwood.

Depending on the species and the size of trees harvested, the output from each compartment, whether from thinnings or final harvest, is assumed to be distributed among these three product categories. The present per cubic meter (cum) stumpage value is also assumed to be known for each compartment. These values are highest for quality veneer and sawlogs, lowest for pulpwood and fuelwood, and vary with the species, size of the trees and the quantity of harvest.

Table 2 contains a list of reforestation alternatives, with hypothetical biological and economic data, which have been judged suitable for the forest division on silvicultural, economic, ecological and other environmental grounds. The biological data used in this table is based on published yield tables and on observations on fast-growing species made by Qureshi (1968). The economic data has been hypothesized by the author and is based on his personal knowledge and judgement. The emphasis in this example is not on the actual data used but on the kind of information which is needed for meaningful analysis.

Table 1 contains all the information about the reforestation alternatives needed for the first stage formulation of the management planning problem. In all there are 34 reforestation alternatives, as listed in column 1. Only 9 species are being used in this management planning problem (column 2). They all appear in 12 alternatives listed under site classes I and II, and only 7 of these species appear in the 10 reforestation alternatives for site class III. More than one alternative for a species implies that that species may be raised both by direct seeding and by planting. Establishment costs in rupees per hectare and the rotation age are listed in columns 3 and 4 respectively.

The annualized land rent values have been listed under columns 5 and 6. These have been computed according to a 5% discount rate and in the manner described in chapter III. Two sets of stumpage values have been used in the computation of the annualized land rent. The first assumes that the stumpage prices, in real money values, will remain unchanged over time; the second, that they are expected to increase by an amount ofRs 10.00 per *cum* for pulpwood and fuelwood and by about Rs 20.00 per *cum* for all other wood products. The reason for using two sets of stumpage prices is to test the stability of the solution under changing prices. The annualized

TABLE 1
Biological and economic data on reforestation alternatives

Alter-native	Spp	Establish. cost in Rs per hectare	Rota-tion years	Annualized land rent in Rs per hectare for stumpage value: Unchanged	Increased	Mean annual increment in cum per hectare: Sawlogs	Plywood	Pulpwood
1	2	3	4	5	6	7	8	9
				SITE CLASS I				
01	A	1,000.00	20	77.40	161.00	–	–	12.0
02	A	800.00	25	54.70	116.50	–	–	10.0
03	B	1,500.00	40	48.70	140.00	–	–	10.0
04	C	1,200.00	15	101.00	193.70	–	–	13.3
05	D	1,200.00	40	117.20	182.10	–	6.0	3.0
06	E	1,300.00	40	118.70	176.00	–	5.5	3.0
07	E	1,000.00	50	80.90	122.20	–	5.5	2.5
08	F	1,500.00	40	107.10	170.80	–	7.0	2.5
09	G	1,200.00	60	148.80	179.40	6.0	–	2.0
10	H	1,500.00	60	103.40	136.60	6.5	–	2.5
11	H	1,000.00	70	66.30	97.80	5.5	–	3.0
12	I	1,200.00	60	92.10	129.40	6.0	–	2.0
				SITE CLASS II				
13	A	1,000.00	20	36.60	102.00	–	–	9.0
14	A	800.00	25	13.40	53.00	–	–	8.0
15	B	1,500.00	40	25.20	91.90	–	–	8.0
16	C	1,200.00	15	48.20	117.60	–	–	10.0
17	D	1,200.00	40	52.10	91.50	–	4.5	2.0
18	E	1,300.00	40	62.30	98.90	–	4.0	2.5
19	E	1,000.00	50	42.60	70.40	–	4.0	2.5
20	F	1,500.00	40	47.60	92.60	–	5.0	2.0
21	G	1,200.00	60	55.30	74.70	4.0	–	2.0
22	H	1,500.00	60	33.40	67.10	5.0	–	2.0
23	H	1,000.00	70	30.40	46.20	4.0	–	2.0
24	I	1,200.00	60	51.20	78.20	4.5	–	2.0
				SITE CLASS III				
25	A	1,000.00	20	14.40	59.60	–	–	7.0
26	A	800.00	25	13.20	47.30	–	–	6.0
27	B	1,400.00	40	11.60	58.50	–	–	6.5
28	C	1,200.00	15	9.10	61.00	–	–	7.5
29	D	1,100.00	50	7.90	32.70	–	3.6	2.0
30	E	1,300.00	50	8.30	37.50	–	3.5	2.5
31	E	950.00	60	2.50	29.60	–	3.0	2.5
32	F	1,400.00	50	-0.60	25.70	–	3.5	2.0
33	H	1,000.00	70	10.90	27.00	3.0	–	2.0
34	H	800.00	80	0.20	15.80	3.0	–	2.0

land rent in column 5 is based on the assumption of no change in the stumpage prices; in column 6, on the basis that these prices will go up by the amounts listed above. Other criteria such as percent annual increase in the stumpage prices could have been used instead of the lump sum increase in the stumpage values.

Column 7, 8 and 9 list the mean annual increment (MAl) in *cum* per hectare for all alternatives. These have been computed on the basis of total volume output in thinnings and final harvest. The raw data from which Table 1 was prepared is listed in appendix A.

As expected, the mean annual increments and annualized land rents are higher in the better site classes. However, there is variation in the output and in the land rent among alternatives for the same product category. For example, in site class I among pulpwood alternatives, the mean annual increment ranges from 10 to 13 *cum* per hectare, and the annualized land rent from Rs 116.50 to Rs 193.70 (column 6). These variations are to be expected and are primarily due to the difference in the rate of growth and stumpage values associated with different species.

Suppose that the state government-the owner of the forest in this case-has laid down the following Long Range planning goals:

1. Sustained annual output of 350,000 *cum* of sawlogs and quality veneer logs, 150,000 *cum* of plywood and matchwood logs, and *200,000 cum* of pulpwood and fuelwood. Government planners have further stated that they attach twice as much importance to achieving production goals of sawlogs, quality veneer logs, plywood and matchwood logs than those for pulpwood and fuelwood.
2. Annual reforestation budget of Rs 2.5 million. This amount has been arrived at after deducting other expenses associated with management of a forest property. The budget goal is ten times as important as the production goals for sawlogs, quality veneer, plywood and matchwood.
3. In addition to the recovery of the capital invested in reforestation and the annual administration and protection costs with compound interest at 5%, an average annual return from the land of Rs 60.00 per hectare. However, only one hundredth of the weight of the budget goal is attached to this goal.

We now have all the information we would need for the first stage formulation of the forest management planning problem, which would provide answers to the following questions:

1. Can these goals be met? If not, what would be the extent of the deviations.
2. What reforestation alternatives are to be used? What should be the area under each?
3. What total area must be harvested annually in each site class on sustained yield basis to make these reforestations possible?

The answer to the last question will provide the area constraint for the second stage formulation of the harvest scheduling problem.

LONG RANGE PLANNING-REFORESTATION PLAN

Let 'Xzzz' be the decision variable representing the area in a site class which is to be reforested annually by one of the available reforestation alternatives. The 'zzz' stands for numbers. The first z can either be 1,2 or 3 depending on the site class. The last two zs are for reforestation alternatives and can take values from 01 to 34. For site class I, the decision variables will take values from XI0l to X1l2; from X213 to X224 for site class II; and from X325 to X334 in site class **III.** For example X217 indicates the area of site class II which is to be reforested by alternative 17.

The goal programming formulation consists of one goal for each of the three product categories, and one each for the reforestation budget and the return from the land. There is one area constraint for each of the three site classes. The objective function consists of the weighted sum of the deviational variables associated with the five goals. We will first formulate the goals, then the area constraints, and finally the objective function.

Goals

(i) *Sawlogs & Quality Veneer.* There are only four reforestation alternatives in each of the two site classes I and II, and only two in site class **III** which provide this product output (Table 1). Therefore, this goal equation consists of ten decision and two deviational variables. The value of each coefficient for the decision variable is the product of the rotation length (column 4) and the mean annual increment (column 7). For example, the value of the coeffient for X109 is 60 X 6 = 360. We can now represent this goal as:

$$360\ X109 + \ldots + 240\ X334 - d1^{+} + d1^{-} = 350{,}000 \quad (1)$$

(ii) *Plywood & Matchwood.* There are four reforestation alternatives for each of the three site classes. Thus there are 12 decision and 2 deviational variables for this goal. The values of the coefficients were computed in the same manner as was done for the first goal. The equation for this goal is:

$$240\ X105 + \ldots + 175\ X332 - d2^{+} + d2^{-} = 150{,}000 \quad (2)$$

(iii) *Pulpwood & Fuelwood.* Each reforestation alternative provides at least some of this output. Therefore, this goal equation includes 34 decision and 2 deviational variables. The value of each of the 34 coefficients was computed in the same manner as was done for the first goal. The equation for this goal is:

$$240\ X101 + \ldots + 160\ X334 - d3^{+} + d3^{-} = 200{,}000 \quad (3)$$

(iv) *Reforestation Budget.* Each of the 34 decision variables plus 2 deviational variables are included in this goal. The establishment cost (column 3) for each reforestation alternative would be the coefficient of the corresponding decision variable. The equation for this goal is:

$$1{,}000\ X101 + \ldots + 800\ X334 - d4^{+} + d4^{-} = 2{,}500{,}000 \quad (4)$$

(v) *Return from Land.* Here, also, all of the 34 reforestation alternatives are represented. There are 34 decision and 2 deviational variables in the equation for this goal. As there are two sets of annualized land rent values (Table 1: columns 5 & 6), two formulations of this goal are possible though only one of them will be used at a time. The coefficients of the decision variables for this goal are the product of the corresponding rotation and the annualized land rent. Thus, with unchanging stumpage prices, the coefficient of the first reforestation alternative is $77.40 \times 20.0 = 1{,}548.00$. The equation for this goal, with lower stumpage values is:

$$1{,}548\ X101 + \ldots + 16\ X334 - d5^{+} + d5^{-} = 6{,}000{,}000 \quad (5a)$$

Similarly, on the basis of higher stumpage values (column 6), the equation for this goal is:

$$3{,}220\ X101 + \ldots + 1{,}264\ X334 - d5^{+} + d5^{-} = 6{,}000{,}000 \quad (5b)$$

Constraints

The purpose of area constraints is to ensure that the reforestation plan developed as a result of the goal programming application can be sustained in perpetuity, *i.e.*, an equal area can be harvested and reforested annually without running out of land due to over-cutting. There is one area constraint for each site class.

Site Class I. As there are only 12 reforestation alternatives for this site class, the constraint has only 12 decision variables. In order to ensure sustained output in the future, each hectare of reforestation by one alternative will require that as many hectares as years in the rotation be set aside for that alternative. Therefore, the coefficients of the decision variables are their corresponding rotation age. The constraint for site class I is:

$$20\ X101 + \ldots + 60\ X112 \leq 20{,}000 \quad (6)$$

Site Class II. This constraint has the next 12 decision variables and is formulated as:

$$20\ X213 + \ldots + 60\ X224 \leq 50{,}000 \quad (7)$$

Site Class III. As there are only 10 reforestation alternatives for this site class, this constraint has only 10 decision variables and is formulated as:

$$20\ X325 + \ldots + 80\ X334 \leq 30{,}000 \quad (8)$$

Objective Function

The objective function consists of the deviational variables of the five goals. As the penalty for deviations from the stated goals is only in one direction—for shortages in product output and income from the forest land, and for exceeding the reforestation budget—only one of the two deviational variables for each goal has a non-zero weight. The coefficients of the deviational variables in the objective function are the relative weights specified by the decision maker. The objective function is:

$$\text{MINIMIZE} \quad \left. \begin{aligned} & 10\, d1^- + 10 d2^- + 5\, d3^- + 100\, d4^+ + d5^- \\ & + 0\, d1^+ + 0\, d2^+ + 0\, d3^+ + 0\, d4^- + d5^+ \end{aligned} \right\} \qquad (9)$$

It may be mentioned here that it is only the relative weights which affect the solution strategy in goal programming. If all weights are multiplied by 100 or divided by 1,000, the final solution strategy will still be the same.

Analysis of Results

The problem has 44 columns (including 10 for deviation variables) and 8 rows. It was solved on the IBM System/370 at the Yale Computer Center using the MPS/360 LP package. Under the assumption of constant stumpage values over time, and with the relative weights specified by the decision maker, the following results were obtained. (All amounts are in units of 1,000. The stated goals have been given in parentheses for comparison.)

sawlogs	plywood	pulpwood	total	budget	land rent	
288.8	150.0	209.1	647.9	2,221.3	6,000.0	(10)
(350)	(150)	(200)	(700)	(2,500)	(6,000)	

Under the given conditions, plywood production and land rent goals will be achieved in full. Pulpwood will be over-produced, sawlogs under-produced and there will be substantial savings in the reforestation budget.

To prevent over-production of pulpwood, a high weight was assigned to its surplus deviational variable ($d3^+$) and the problem was solved again with the following results:

307.2	150.0	200.0	657.2	2,207.0	5,742.8	(11)

There is still a substantial shortage in the sawlog production, though there are further savings in the reforestation budget. The land rent is lower than the stated goal. A comparison of (10) and (11) shows that increasing production of sawlogs by 18,400 *cum* will cost 9,000 *cum* of pulpwood and Rs 257,240 in land rent annually. Which of the two planning strategies is to be preferred will depend on the decision maker's choice between 18,400 *cum* of sawlogs and Rs 14,-300 savings in the reforestation budget on the one hand and 9,000 *cum* of pulpwood and Rs 257,240 in additional land rent on the other.

In order to examine whether the physical production targets can be met in full and to determine the corresponding annual reforestation cost and the return from the land, this problem was solved with weights on the product goals only, with the following results:

341.0	150.0	210.0	701.0	2,485.0	3.997.2	(12)
(350)	(150)	(200)	(700)	(2,500)	(6,000)	

Though the physical production targets can be met, this has been possible only at the expense of land rent, which is down by over two million rupees. The reforestation cost is also higher by Rs 260,000 when compared with (10).

So far we have considered only one set of production goals. In order to examine the effect of different product goals on the reforestation budget and land rent, three more sets of product output goals were formulated and the modified problem (10) was re-solved. The results of multiple product goal analyses are summarized below:

202.0	243.7	211.6	657.3	2,500.0	5,712.0	(13)
(250)	(250)	(200)	(700)	(2,500)	(6,000)	
10.0	400.0	258.3	668.3	2,500.0	5,712.0	(14)
-	(400)	(400)	(800)	(2,500)	(6,000)	
435.0	-	200.0	635.0	1,828.6	5,863.0	(15)
(500)	-	(300)	(800)	(2,500)	(6,000)	

The effect of transferring 100,000 *cum* from the sawlog production goal to the plywood production goal ((10) & (13)), is that the land rent goal cannot be achieved in full even with the complete utilization of the reforestation budget, though the same can be fully realized and with a smaller budget as indicated in (10). The total product output in (13) has gone up but the output of sawlogs has been reduced to 213,000 *cum* from 288,800 *cum* in (10).

A comparison of (14) and (15) shows that sawlog production is more profitable than the production of plywood. However, a higher total product output is possible with plywood and pulpwood than with sawlogs and pulpwood.

The Effect on Planning of Changing the Reforestation Budget

In order to examine the effect of different reforestation budgets on the achievement of physical production goals and on the return from the land, a set of problems with six differet budget levels (from 1.5 million rupees to 3.0 million rupees) was formulated and solved. Another set of similar problems was solved for maximization of land rent without any weights on production goals to maximize land rent. The results of these studies are presented in Table 2a & 2b, and in Figures 2 & 3.

The following observations may be made on the basis of Table 2a and Figure 2:

a. Till an upper limit of 678,000 *cum* is reached, the total product output increases with the reforestation budget. Beyond Rs 2.415 million, the reforestation budget shows no improvement either on the product output or on the income from the land unless the weights on all goals are altered. The rate of increase in the product output, however, decreases with the increase in the budget level from Rs 1.5 million to Rs 2.415 million. This is consistent with the economic principle of diminishing marginal returns.

b. In our example, pulpwood (& fuelwood) is produced only as a by-product at all budget levels. This is because the output goal for pulpwood corresponds to a mean annual increment of 2.0 *cum* per hectare, and at least this much pulpwood is produced by every reforestation alternative. The reason for less than *200,000 cum* of pulpwood production with the budget level of Rs 1.5 million is that this amount is inadequate for bringing the entire forest area under sustained-yield management.

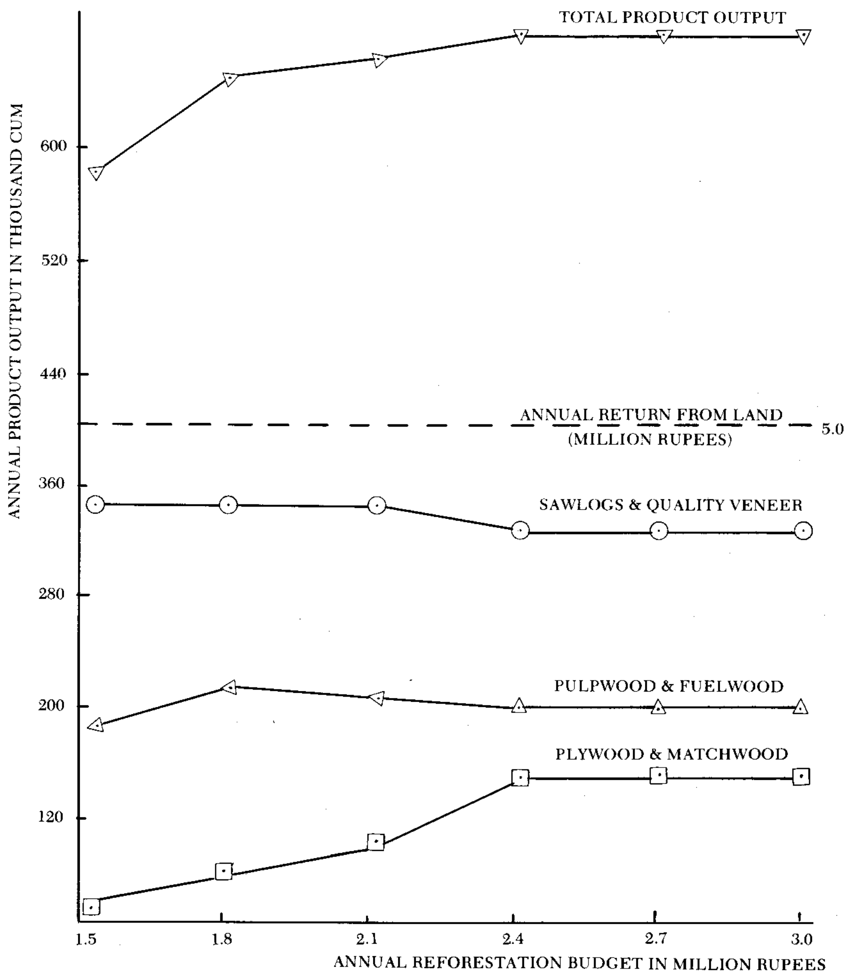

FIGURE 2. Multiple product goal achievement under different fixed budget levels.

c. At lower budget levels, production of sawlogs is favored over plywood. This is because longer rotations are associated with sawlog production, so that the area to be reforested and the annual reforestation cost, on a sustained yield management basis, is lower. With Rs 1.5 million reforestation budget, the area to be reforested annually is only 1,430 hectares, and this

TABLE 2a

Multiple goal achievement under different fixed budged levels[1]

Budget in thousand Rs		Product output in thousand cum				Land rent in thousand rupees
allocated	utilized	sawlogs	plywood	pulpwood	total	
		(350)	(150)	(200)	(700)	(5,000)
1,500	1,500	350.0	45.0	189.8	584.8	5,000.0
1,800	1,800	350.0	85.8	207.7	643.5	5,000.0
2,100	2,100	350.0	110.2	204.3	664.5	5,000.0
2,400	2,400	332.4	145.5	200.0	677.9	5,000.0
2,700	2,415	328.0	150.0	200.0	678.0	5,000.0
3,000	2,415	328.0	150.0	200.0	678.0	5,000.0

TABLE 2b

Maximum land rent and level of product output under different budget levels[1]

Budget in thousand Rs		Product output in thousand cum				Land rent in thousand rupees
allocated	utilized	sawlogs	plywood	pulpwood	total	
		(350)	(150)	(200)	(700)	(5,000)
1,500	1,500	341.0	–	154.0	495.0	5,817.3
1,800	1,800	404.0	–	196.0	600.0	6,046.0
2,100	2,100	323.1	86.9	210.9	620.9	6,220.0
2,400	2,400	227.1	182.9	222.9	632.9	6,388.0
2,700	2,700	168.3	200.0	280.6	648.9	6,450.0
3,000	3,000	120.0	200.0	345.8	665.8	6,488.0
3,600	3,525	120.0	200.0	395.0	715.0	6,523.0

[1]The stated goals have been given in parentheses for comparison.

increases steadily and reaches 1,837 hectares when the reforestation budget increases to Rs 2.415 million.

d. With the product output and land rent goals as specified, and with the given relative weights on different goals, the output level for sawlog production falls with the increase in budget level. This is because the marginal return on the total product output is greater with plywood production alternatives than with the sawlogs. It is also clear that, no matter how much increase is made in the reforestation budget, with the given specifications of goals and relative weights, it is not possible to meet all output goals.

e. The land rent goal of Rs 5.0 million can be achieved with the annual reforestation budget of Rs 1.5 million, but with substantial deviations in plywood and total product output, even though the land rent goal has the lowest priority. This is possible because with some of the sawlog and plywood alternatives, the associated land rent is over ten times its sawlog and plywood output and over five times its pulpwood output. In fact, with the budget level of Rs 1.5 million, the total land rent from site class I (20% of the total land area) comes to Rs 2.976 million (59.5% of the land rent goal).

If the ownership is willing to accept some changes in the output levels of different products, it is possible to increase the return from the land for a given budget level. To find out the maximum possible land rent that could be realized from a given budget, the problem of multiple goal achievement of Table 2a was reformulated as a land rent maximization problem and solved for different budget levels. A large positive weight was assigned to the slack deviational variable and a corresponding negative weight to the surplus deviational variable associated with the land rent goal and zero weights to the deviational variables associated with the product output goals. The results are summarized in Table 2b and Figure 3. The following conclusions may be drawn from this analysis:

a. A diminishing marginal return from the land is associated with an increase in the budget level. A maximum land rent of Rs 6.52 million can be realized with a reforestation investment of Rs 3.53 million.

b. The total product output also increases with the increase in the budget level. Because of the absence of weights on product

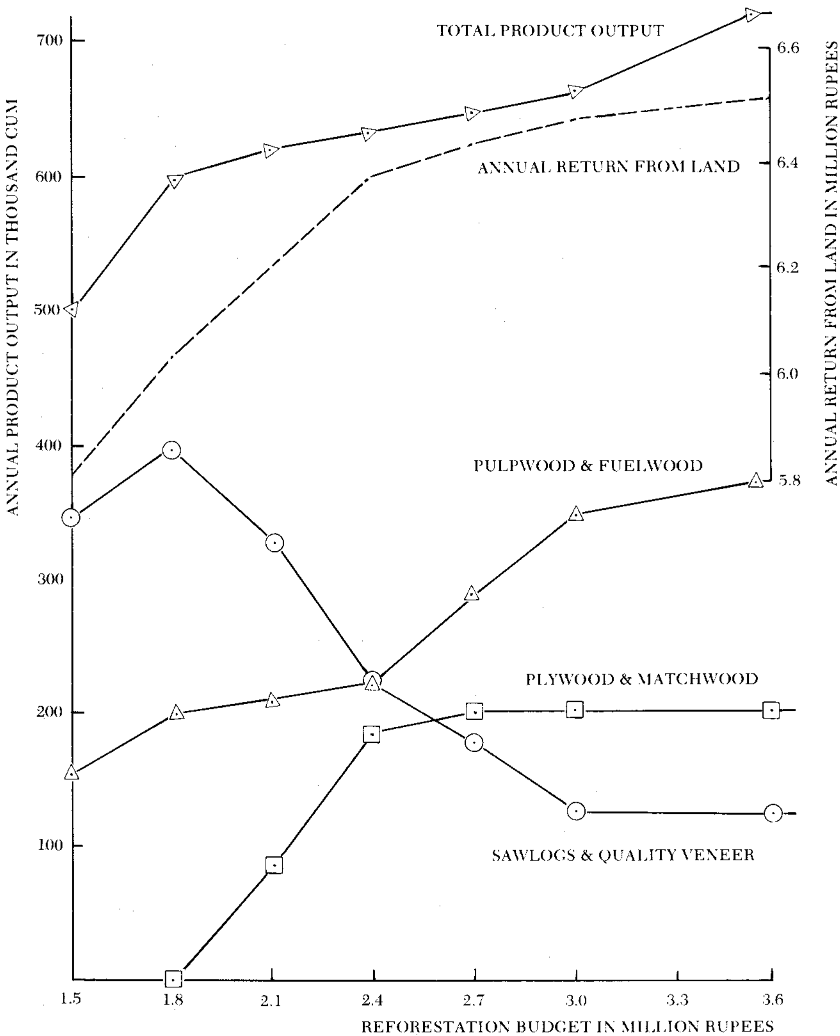

FIGURE 3. Land rent maximization under different budget levels with corresponding output levels of different products.

output goals, the rise in the product output is not as smooth as for the land rent.

c. With the objective of maximization of land rent, and with only Rs 1.5 million in reforestation investment, it does not pay to include more than 7,000 hectares of site class III forest land under sustained-yield management. Adding another Rs 300,000 to the reforestation budget increases the area of site class **III** land under sustained-yield management to 28,000 hectares. This increase in the effectively managed area explains the increase in sawlog output when the budget is increased from Rs 1.5 million to Rs 1.8 million.

d. With no restriction on the reforestation budget, the production of sawlogs is limited to site class I (alternative 09) as this alternative provides the maximum annualized land rent. Similarly, in site class II production of plywood is most profitable (alternative 18), and it is most profitable to grow pulpwood in site class III (alternative 25). As a result, with the reforestation budget of Rs 3.53 million and with the objective of maximization of land rent, the total output of sawlogs, plywood and pulpwood is 120,000, 200,000 and 395,000 *cum* respectively. This is significantly different from the product output of Table 2a. Therefore the land rent from a reforestation investment can be maximized only at the cost of substantial departures from the product output goals, unless these happen to coincide with what can actually be obtained under profit maximization.

Problems in Management Planning Due to a Changing Budget

The sensitivity analysis of the management planning problem provides an insight into the interaction between different goals when the goal levels or their relative weights are altered. This should be helpful in deciding on the level of different product output and income from the land that should be aimed at in the long run. Production expectations based on need must be adjusted on the basis of what can be most efficiently made available. However, it is very likely that the size of the refcrestation budget, which will be needed to realize Long Range production possibilities may not be forthcoming at once and the forest management planning may have to be adjusted to an increasing budget. This may create some complications, because the alternatives and the area to be reforested annually under each may vary materially with every change in the reforestation budget.

This may affect management planning in two ways. It may call for reforestation of the same species by different methods with different corresponding rotations, or the species composition may change with every change in the reforestation budget level. This may be quite confusing to the managerial staff and may complicate the planning of nurseries as they have to be planned a couple of years ahead of reforestation.

The other effect of the changes in the reforestation alternatives, particularly the rotation, may be of a far more serious nature. The Long Range planning model is based on the assumption that each new stand will be harvested at the predetermined maturity age. This may not hold true if the alternatives-particularly the rotations-keep changing with every change in the reforestation budget. It has already been pointed out that the area to be reforested annually increases with the budget. With increasing budget levels, it may become necessary to prematurely harvest some stands which are being raised now with the expectation that they will be harvested only at maturity. Harvesting of these stands at any other age may adversely affect the product output or land rent or both.

These objections can be circumvented by modifying the current reforestation decisions on the basis of Long Range production planning. When the budget level is less than the maximum expected to be available only those reforestation alternatives with rotations found optimal at the maximum budget level should be considered. With the choice of alternatives thus restricted, the current budget should be used for maximizing return or product output or both, according to given goals and priorities. Better sites should be covered first so that excluded areas, if any, are restricted to the poorer sites. The goal programming model should take care of that. This will become clear from the example that follows.

Suppose that the decision maker is inclined towards achieving the Long Range production possibilities presented in Table 3a. Even though the reforestation budget will remain around Rs 1.5 million annually during the next few years, it is expected that an amount of Rs 2.42 million will be available annually within the next 15 to 20 years. The reforestation strategy for an annual budget level of Rs 1.5 million includes: 1) reforestation of 333.3 hectares of site class I by alternative 09; 2) 225.1, 301.6 and 293.9 hectares of site class II by alternatives 19,23 and 24 respectively; and 3) reforestation of 275.8 hectares of site class **III** by alternative 34. The optimal reforestation program for an annual budget of Rs 2.42 million includes: 1) reforestation of 0.9 and 332.7 hectares by alternatives 08 and 09 in site class I; 2) 208.7 and 694.2 hectares by alternatives 20 and 22 in site class II; and 3) 600.0 hectares by alternative 29 in site class III. Even though the best sustained reforestation strategy, given a fixed annual budget of Rs 1.5 million is as stated, it is no longer so if the budget is expected to change, resulting in a major shift in the reforestation alternatives. For example, the rotation for alternative 34 in site class III is 80 years, which is expected to be replaced by alternative 29 with a 50 year rotation when the budget goes up from Rs 1.5 million to Rs 2.42 million. This means that the reforestation planning problem at a lower budget level will have to be reformulated with the additional constraint on alternatives which could be considered in each site class. **In** our example, only alternatives 29, 30 and 32, which all have a rotation of 50 years in site class III, should be considered for reforestation planning at all budget levels lower than Rs 2.42 million. A 50 year rotation may also be explored for other reforestation alternatives in site class **III.** Similar restrictions will be required in other site classes.

At the maximum budget level, the solution includes reforestation by alternative 08 of 0.9 hectares in site class I. This is due to the fact that both linear programming and goal programming permit fractionalization. It is obvious that this alternative will have to be eliminated from the solution. This kind of final adjustment is unavoidable, particularly when reforestation preceded by harvesting is to be by entire compartments.

The solution of the reformulated planning program will provide the reforestation strategy to be followed in situations where the reforestation budget is likely to change over time. The analysis of such a reformulated problem is presented in Table 3 and Figure 4. As the analysis in Table 3 and Figure 4 is of a much more restricted formulation than of the formulation analysed in Table 2a and Figure 2, the product output and land rent at lower budget levels should be much lower in the latter than the former case.

Comparison of Table 3 with 2a and of Fig. 4 with 2 shows that the net result of restricting the alternatives at a lower budget level only to those with rotations equivalent to the alternatives in the solution at the maximum budget level is that the output of sawlogs and pulpwood is lower at lower budget levels. The land rent, on the other hand is higher at these budget levels. The lower product output resulted from the fact that at low budget levels a relatively smaller

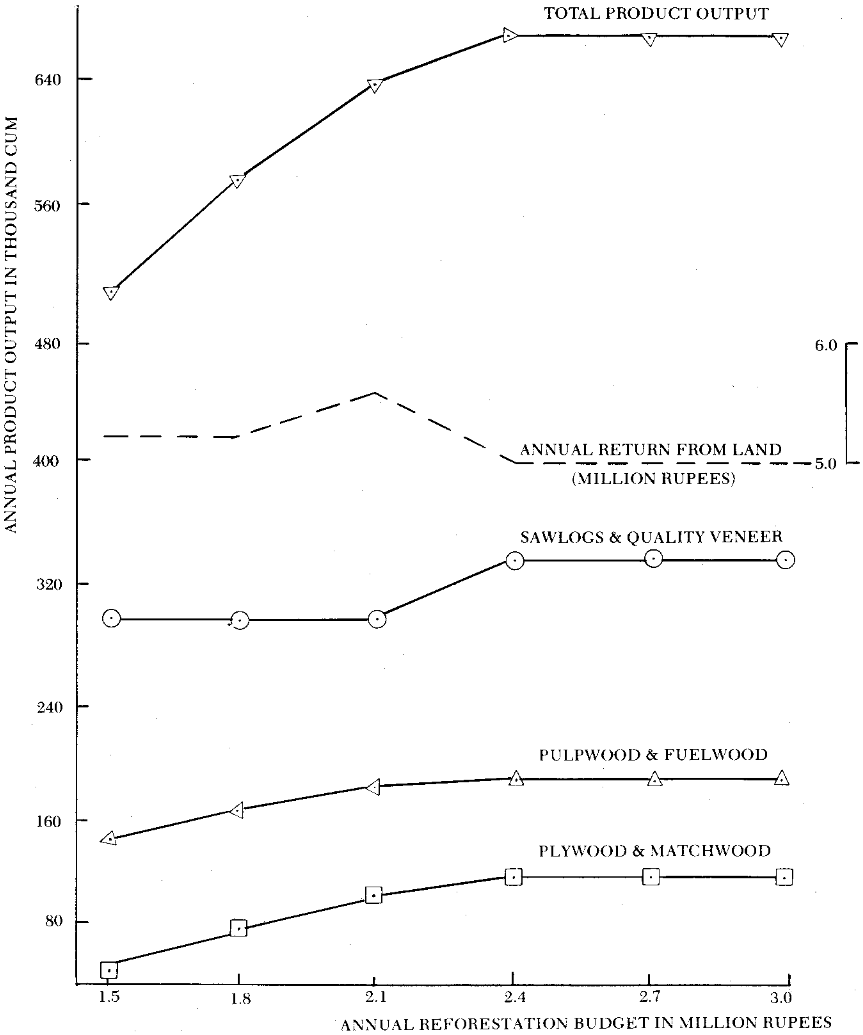

FIGURE 4. Multiple product and land rent goals achievement under changing budget levels.

area is being reforested—1,270 hectares as against 1,430 hectares at the Rs 1.5 million reforestation budget—and the increase in the land rent is due to the fact that plywood production alternatives are being forced into the solution in part of site class II and entirely in site class

III in place of the sawlog production alternatives. In both of these site classes, a higher land rent is associated with plywood production alternatives (Table 1). However, as the budget level reaches Rs 2.4 million, the reforestation strategies converge and are the same for budget levels exceeding Rs 2.4 million. There is minor difference in the optimal strategies for budget levels over Rs 2.4 million which is primarily due to the fact that 0.9 hectares of annual reforestation by alternative 08 in site class I, was eliminated from the solution strategies of Table 3.

TABLE 3

The effect of changes in the budget level on multiple goals achievement under limited choice of reforestation alternatives[1]

Budget in thousand Rs		Product output in thousand cum				Land rent in thousand rupees
allocated	utilized	sawlogs	plywood	pulpwood	total	
		(350)	(150)	(200)	(700)	(5,000)
1,500	1,500	307.4	43.7	147.6	498.7	5,204.4
1,800	1,800	307.4	92.8	174.8	575.0	5,312.2
2,100	2,100	307.4	139.0	197.1	643.5	5,705.0
2,400	2,400	328.3	148.8	200.0	677.1	5,010.2
2,700	2,414	328.3	149.7	200.0	678.0	5,001.5
3,000	2,414	328.3	149.7	200.0	678.0	5,001.5

[1]The stated goals have been given in parentheses for comparison.

It is clear that an optimal strategy with a constant reforestation budget over time may not remain optimal if the budget is expected to vary. In public forest management, variation in the annual budget is a rule rather than an exception. This point has to be kept in mind while planning reforestation in public forests. The above strategy should work well in management situations where the reforestation budget is expected to vary over time. There would be little possibility of premature or post-mature harvesting of reforested stands. However, in a situation where Long Range reforestation planning changes due to any reason, premature or post-mature harvesting of some stands may be unavoidable. These changes may be due to changes in the product output goals, development of more promising reforestation alternatives or due to developments in timber technology and utilization practices.

Another welcome feature of this strategy is that changes in the budget may occur in an unpredictable manner. For example, the budget may increase annually or it may increase (or decrease) periodically. So long as the ultimate budget is expected to be the same (Rs 2.42 million in the above example), the planning strategy will remain optimal. In fact, unexpected reductions in the budget-which occur from time to time in public forests-may be handled by this strategy.

Effect of Variations in Stumpage Values on Reforestation Strategy

The sensitivity analyses discussed so far were related to changes in management goals and priorities. There are two other factors which may affect management planning. These include changes in the estimated product output and changes in the stumpage prices over time. As annualized land rent of a reforestation alternative depends on a combination of factors such as reforestation cost, timing and value of stumpage, it is not easy to foresee the effect of changes in the stumpage values on the annualized land rent. Even though the land rent values in column 6 (Table 1) are based on anticipated increases by Rs 10 per *cum* for pulpwood and by Rs 20 per *cum* for plywood and sawlogs, the relative ranking of alternatives for the same product output has been significantly altered. If maximization of product ouput, under given output goals, were the only management objectives, the planning strategy would remain unchanged by variations in the stumpage values. However, it is unlikely that in any management situation monetary returns from the land will be entirely subjugated to the product output goals.

In order to examine the effect of changes in stumpage values on the multiple product output and income goals and the effect of changes in the reforestation budget on the multiple product output goals, the management situation discussed in (10), (13), (14), (15) and Table 2a was reformulated. In the multiple goal situation, where the effect of changes in the product output goals on the reforestation strategy were examined, the land rent goal was kept at the earlier low value of Rs 6 million. In the situation where the effect of changes in the budget was studied, the land rent goal was raised to Rs 6.5 million from the earlier value of Rs 5.0 million. The planning strategy resulting from changes in the product output goals is summarized below:

sawlogs	plywood	pulpwood	total	budget	land rent	
250.0	242.2	225.0	717.2	2,500.0	7,890.1	(16)
(250)	(250)	(200)	(700)	(2,500)	(6,500)	
-	400.0	329.0	729.0	2,500.0	8,471.7	(17)
-	(400)	(400)	(800)	(2,500)	(6,500)	
470.0	-	210.0	680.0	2,050.0	6,561.0	(18)
(500)	-	(300)	(800)	(2,500)	(6,500)	
341.0	150.0	210.0	701.0	2,485.0	7,273.2	(19)
(350)	(150)	(200)	(700)	(2,500)	(6,500)	

Comparison of (16) with (13) shows that, as a result of higher stumpage values, the land rent goal is easily met. Thus the program tends to select those alternatives in each site class which maximize the product output. As a result, the product output goes up by 60,000 *cum*, the most significant increase being in the sawlog output.

Comparison of (17) with (14) shows that it has now become very profitable to grow plywood and pulpwood. Land rent increases by over 60%, pulpwood output goes up by over 70,000 *cum*, and sawlog production does not enter the solution. Here again, the reforestation alternatives are entirely different from what they were when the lower stumpage values were used.

The least change in the reforestation strategy occurs when the output goals include production of sawlogs and pulpwood only. As pulpwood is also obtained as a by-product in sawlog production, no alternative specifically for pulpwood production enters the solution. The only difference in reforestation alternatives is in site class III, where alternative 33 is replaced by 34. With a given increase in stumpage prices, the production of sawlogs has become least attractive financially, whereas earlier (14), the production goal of an equal amount of plywood and pulpwood was least economical.

Between (10) and (19) too, there are significant changes. As the land rent goal is the same in both cases, the effect of higher stumpage values has been to select alternatives which maximize product output. In fact the solution strategy in (19) is the same as was found for maximization of product output without any weight on land rent with unchanged stumpage values (12).

The major effect of the increase in stumpage values on profitability has been that plywood and pulpwood production has become more attractive financially than before. As the output resulting from current reforestation will be available only after several decades, it will be desirable to take into account the expected stumpage values in Long Range planning. However, the present state of knowledge in this field is extremely limited, and considerable research will be needed to develop methods for predicting changes in the stumpage values.

TABLE 4

Multiple goal achievement under expectations of higher stumpage values and different fixed budget levels!

Budget in thousand Rs		Product output in thollsand cum				Land rent in thousand rupees
allocated	utilized	sawIngs	plywood	pulpwood	total	
		(350)	(150)	(200)	(700)	(6,500)
1,500	1,500	350.0	65.3	201.2	622.0	6,500.0
1,800	1,800	350.0	96.7	210.0	656.7	6,566.3
2,100	2,100	350.0	122.8	212.8	685.6	7,208.6
2,400	2,400	338.4	149.8	225.0	713.2	7,430.9
2,700	2,485	341.0	150.0	210.0	701.0	7,273.2
3,000	2,485	341.0	150.0	210.0	701.0	7,273.2

'The stated goals have been given in parentheses for comparison.

Another set of management planning problems with the same product output goals and reforestation budget as in Table 2a, but with an increased land rent goal of Rs 6.5 million and using higher stumpage values was formulated and solved using goal programming. The analysis is presented in Table 4. The following observations may be made:

a. The output of all products individually and collectively is significantly higher in Table 4 than in Table 3a.
b. Except for the budget level of Rs 1.5 million, it is possible to exceed the land rent goal even when the product output goals are not met.
c. The total product output and land rent is not maximum at the maximum utilized budget of Rs 2.485 million. In fact, as a result of the additional reforestation expenditure of Rs 85,000 the output of sawlogs and plywood rises by 2,600 and 200 *cum* respectively. But the pulpwood output and land rent decreases by 15,000 *cum* and Rs 157,000 respectively.

The explanations for these observations are not hard to find. The fact that the land rent goal is easily exceeded points out that it has been set too low and, except for the budget level of Rs 1.5 million, is not at all instrumental in forcing reforestation alternatives into the solution. As a result, the program is forcing those alternatives into the solution which maximize the total product output according to the set goals. In fact the solution strategy with a budget level of over Rs 2.4 million is the same in (12) and (19).

Even though the total product output and land rent goes down when the reforestation budget increases over Rs 2.4 million there is improvement in the solution. In the absence of any penalty cost (positive or negative) for exceeding the product output and land goals, the reduction in pulpwood production and land rent does not affect the value of the objective function. A nominal increase in the sawlog and plywood production, on the other hand, decreases the value of the objective function which is being minimized.

As a result of the above analyses and the examination of the range of input parameters and decision variables within which the program basis will remain stable, decisions can be taken on the Long Range planning of forest management and the development of the current reforestation strategy leading towards the Long Range production and income goals. Through sensitivity analysis, the marginal effect of an increase in the reforestation investment on product output and land rent in different management units could be evaluated. This could lead to a better allocation of production goals and reforestation budget in different management units and to a better estimate of the total production possibilities and forestry investment needs at the national level.

SHORT RANGE PLANNING-HARVEST SCHEDULE

Suppose that, as a result of Long Range planning, 330 hectares in site class I, 700 hectares in site class II and 250 hectares in site class III are to be reforested annually during the next eight years. We must now determine the sequence of harvests in individual compartments.

Management Goals, Constraints and the Objective Function

The decision variable now is the area of a compartment to be harvested in anyone year. In this example, the 113 compartments with the largest volume and value per unit of area were chosen subjectively from the 1,000 available. Of these, 28 were from site class I, 61 from site class II, and 24 from site class III. The total area of these compartments was more than the total area to be actually harvested during the next eight years. This was done to ensure that the subjective selection process did not exclude any borderline compartment from consideration.

Production from these compartments was arbitrarily assumed to take only two forms: logs (which included sawlogs, veneer logs and plywood) and pulpwood (& fuelwood). Thus the formulation had only three goal equations for each year, *viz.,* two for the product output and one for the revenue from harvest. The coefficients of the decision variables in product output goals consisted of the per hectare yield of the logs or pulpwood from a particular compartment in a particular year. The coefficients of the decision variables in the revenue goal were the corresponding per hectare total expected stumpage value in the final harvest. This allowed for complete flexibility for assigning stumpage values in each compartment on the basis of the quality and quantity of harvest as well as the terrain and the logging distances.

As each compartment could be taken up for harvest in anyone or more of the eight years in the planning period, there were eight decision variables for each compartment in the problem. For 113 compartments, the number of decision variables came to 904. In addition, there were 48 slack and surplus variables corresponding to 24 goal equations, thus raising the total number of columns in the second stage formulation to 952.

Besides 24 goal equations, there were two sets of constraints. The first ensured that the total area to be harvested annually in each site class equalled the area to be annually reforested. There was one such constraint for each site class and for each year of the planning period. The second set of constraints ensured that the total area to be harvested during the eight-year period in a compartment did not exceed the area of that compartment. There was one such constraint for each compartment. The total number of rows (goals and constraints) in the formulation came to 16l.

The order in which different compartments are taken up for harvest would depend on the management objective(s). If the objective is to maximize total undiscounted revenue from the final harvest during the next eight years, the stands which are putting on maximum value growth on an area basis are not taken up for harvest till the very end of the planning period. Similarly, if the objective is to maximize the total log output during the planning period, the stands which are putting on the maximum volume growth on an area basis will not be taken up for harvest till the end of the planning period. Unless the stumpage values are the same for all species growing in the management unit, the two formulations may provide different harvest schedules. The management objectives could also be to maximize the discounted present worth of income from harvests during the planning period. In that case the harvest of those compartments which are putting on maximum percentwise value growth is expected to be delayed till the end of the planning period. Anyone of these or a combination thereof may be used in the objective function.

In order to examine the effect of different management objectives on the harvest schedule, three objectives were formulated as follows:

MAXREVI-maximization of the undiscounted total revenue from the final harvest during the eight-year planning period.

MAXREV2-maximization of the discounted present worth of the total revenue from the final harvest during the eight-year planning period.

MAXPROD-maximization of the total log output from the final harvest during the eight-year planning period.

As all of these objectives are single valued, the Short Range planning problem can be handled by linear programming (Curtis 1962, Loucks 1964, Kidd *et al.* 1966, Littschwager & Tcheng 1967). However, a goal programming formulation was used to permit the solution of three different objective function formulations in one run without changing rows. Row changing would have been unavoidable with MPS/360 if a standard linear programming formulation had been used for optimizing three different objective functions.

The problem required nearly ten minutes of central processor time and 1891 iterations for the determination of all optimal solutions. As the formulation consisted of either maximization of total revenue from final harvest (discounted or undiscounted) without any volume constraint or the maximization of the total log volume output without any constraint on the annual revenue, this problem could be partitioned into three independent subproblems-one for each site class. These smaller problems, in total, required less than 50% of the computer time needed by the original version to reach the same solution.

Analysis of Results

The result of the computer runs may be summarized as follows:

Objective	Total revenue in million rupees (undiscounted)	(discounted)	Total log output in thousand cum
MAXREV1	184.6	155.4	1,617
MAXREV2	183.7	156.3	1,610
MAXPROD	184.0	154.8	1,620

Among these three objective function formulations, the difference between the maximum and minimum values of the undiscounted total revenue is less than a million rupees. The difference for the discounted total revenue, though larger, is only Rs 1.5 million, and the log output difference among the three is only 10,000 *cum*. This indicates that the adoption of anyone of the three objective functions would lead to the same overall performance. This is not surprising, because of the annual area constraint by site classes. In the example, the differences in the rate of growth of different species and in their stumpage values was only nominal and this may have been responsible for the less than 1% variation in the final outcome under different management strategies. In actual management situations, the differences may be larger, but even then the variations in the overall outcome in a planning period of five to ten years may not exceed 5%. The effect of the different objective functions is primarilyon the order in which different compartments may be taken up for harvest, with only marginal possibility of some compartments being included under one objective and excluded under another. If any other objective function is used, it may be assumed that the outcome of harvest scheduling will not be significantly different.

However, the aggregate figures presented earlier do not tell the whole story. Even though the total output or income may not differ materially under different objectives, the annual revenue and output may differ significantly from year to year and under different objectives in the same year. Figure 5 shows the yearly variations in the revenue and log output under different objectives. The upper set of curves represent the distribution of log output and the lower set the distribution of annual revenue. MAXREVI and MAXPROD follow closely. This is to be expected, due to the strong correlation between the log volume and revenue. The minor differences in the two are primarily due to differences in the stumpage values of different species.

If the first year-in which there is very little difference in the volume and value output under different objectives-is ignored, MAXREVI and MAXPROD increase with time and reach their maximum in the eighth year. MAXREV2, on the other hand, decreases with time and has the maximum value in the second year. This is to be expected. In the former case, those stands which are making the least contribution to the volume and value growth are being taken up for harvest first. In the latter case, those stands are being taken up for harvest first which are contributing least to the present value growth.

The explanation for the abnormal behavior in the first year is quite simple. The data for the compartments included in the study was generated hypothetically and, according to the basal area test, most of these compartments become due for thinning in the very first year. Unless harvested, these compartments are to be thinned in the first year, with the result that the yield in subsequent years falls sharply. This causes the program to select for final harvest in the first

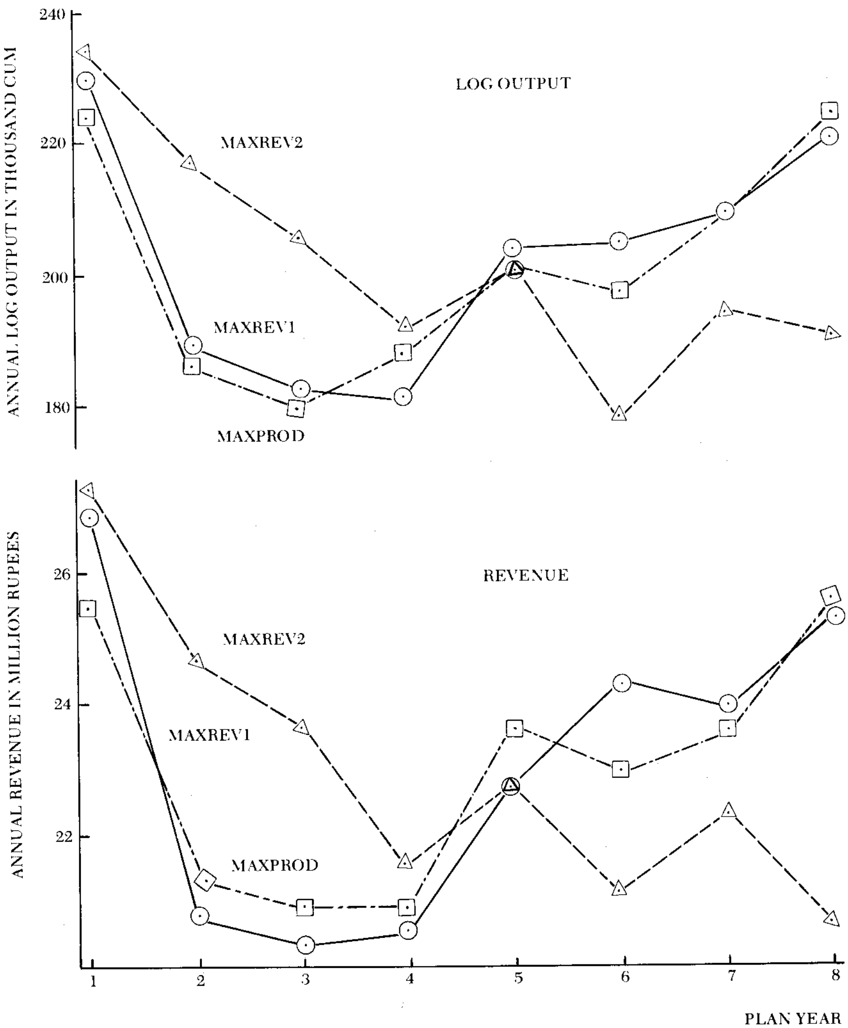

FIGURE 5. Annual sawlog output and revenue from final harvest under different management objectives.

year only those compartments which would otherwise be thinned. These compartments, obviously, had the maximum per hectare volume and stumpage value. In the present formulation, the volume and value yield from thinnings has been entirely omitted and should be added to the volume and value of the yield from final harvest.

In order to examine the effect of a shorter planning period on the sequence of harvests, the planning problem for site class I was solved for a five year period. The results, as expected, were that the sequence of harvest in the first five years of the eight-year plan and the sequence of harvest according to the five-year plan were different. This difference was more marked for MAXREVI and MAXPROD, and only nominal in the case of MAXREV2. The total log output and revenue according to the five-year plan were significantly larger than the total log output and revenue during the first five years of the eight-year plan. The effect of planning for a longer perod and implementing the plan for a shorter period is the same as if planning for an indefinitely long period, in which the harvest of stands which are putting better volume and value growth on area or percent basis, is delayed. As the program selects only those compartments which maximize the total volume or value output during the planning period, all such stands which have maximum stumpage volume or value will be included in the harvest schedule, regardless of whether the rate of growth is high or low. If the rate of growth is higher, their harvest will be delayed to the end of the planning period, but they would be taken up for harvest unless the plan is revised earlier.

Goal programming, as linear programming, provides solutions in fractions of compartments. Theoretically, one compartment may be expected to be fractionalized in every site class and in every year of the plan, as there is only one area constraint for each site class and year which may force fractionalization. However, in actual practice the number of fractionalized compartments may be much smaller. For example, in site class I, only five compartments were fractionalized during the eight-year planning period. The number of fractionalized compartments does not depend on the total number of compartments, but on the ratio of the area of one compartment to the total area to be harvested annually and on the uniformity in the areas of different compartments. If all compartments are of equal area and the total area to be harvested is a multiple of the area of a compartment, the solution will be in terms of whole compartments even without integer programming. In real life situations, the areas of compartments vary and therefore fractionalization of compartments is unavoidable. However, the fractionalized solution may be converted into a solution in terms of whole compartments with little effect on the total plan performance. One of the effects of rounding off of the results in terms of whole compartments would be that somewhat unequal areas may be taken up for harvesting and reforestation annually. It may be dificult to find a harvest schedule in terms of whole compartments which also satisfies the equal area constraint. Ten percent or even higher variations in the annual areas for harvest, annual volume output, and the revenue therefrom are not uncommon.

The mathematical programming model ignores the effect of the concentration of harvesting and thinning operations on stumpage returns. For example, the stumpage prices used in the computation of the revenue were based on the assumption that no other compartment in the vicinity would be taken up for harvest simultaneously in that year. By modifying the harvest and thinning schedule in such a manner that the operations are carried out over whole compartments in a year and that the operations are concentrated wherever possible, financial returns may be increased over and above those indicated by the optimal solution. This underscores the importance of managerial tempering of the mathematical programming results on the basis of personal judgement and other practical considerations.

There might still be considerable annual variation in the volume and revenue output in different years of the plan as shown in Figure 5. One may obtain an equal volume and/or revenue yield by rescheduling the thinning program. For example, if the objective is to maximize the total undiscounted revenue, more thinnings may be carried out in the second, third and fourth year of the plan and very little in the first and the eighth year.

SUMMARY

The manner in which the goal programming model would operate in an actual situation has been presented through a hypothetical example. The advantage of using the two-stage formulation has also been demonstrated.

The need for sensitivity analysis is far greater in the Long Range planning, because the current decisions have far-reaching consequences in the future. In fact, the main focus of this study has been on the selection of that combination of reforestation alternatives which best satisfies the Long Range management objectives within the limitations of the available resources. The Long Range planning decisions, by their very nature, can best be described as policy decisions, as the outcome of these decisions will determine the extent of future supplies.

The Short Range planning, on the other hand, tries to provide the management strategy for the treatment of existing stands till the reforestations being planned now mature. The fundamental question at this level is when and where to cut. These decisions would be based on the condition of existing stands. Area limitations set as a result of the Long Range planning would ensure sustained supply.

Fornstad (1971) and others have pointed out the limitations of mathematical programming analysis. The goal programming analysis of this study suffers from two limitations. The first is that the solution for harvesting and reforestation may be in fractions of compartments. The second is that the analysis does not take into account the economies resulting from the concentration of harvesting and thinning operations. Though the former can be handled by integer programming, there appears to be no practical method for incorporating the latter into the analysis. However, both can be taken care of at the managerial level by suitable modification of the goal programming results.

CHAPTER FOUR

CONCLUSIONS

A goal programming model has been presented for preparing and revising management plans for forests which are likely to remain permanently under timber production. The model provides a reforestation plan based on the future expectations of different product output and return from the land, available land, capital and other resources, and the possible reforestation alternatives which may be available. **It** is followed by a harvest schedule for the next five to ten years which maximizes the undiscounted or discounted total revenue from harvests or which maximizes the total product output or a combination of these. Because of their effect on management planning, the optimal rotation, criteria for evaluating financial profitability, and the rate of interest for discounting have been considered in some detail.

The task of forest management for timber production has been considered as a two-stage problem with two different types of decisions involved. Long Range analysis deals with the planning of reforestations. Due to increased. demands and growing scarcity of wood products in India and many other countries of the world, slow and uncertain natural regeneration methods are being replaced by artificial regeneration and tree improvement techniques. Active management is supplanting passive utilization of natural stands. The fundamental question to which the Long Range planning model addresses itself is the optimal allocation of land and money among the numerous reforestation alternatives which may be available and suitable for a particular management unit.

The Short Range planning model focuses attention on the order in which specific stands are to be taken up for harvesting during the next five to ten years. Though the amount of product output and revenue from annual harvest may vary within a certain range, there is little that can be done to improve the overall quantity of harvest or revenue during a planning period of five to ten years. This is because the area to be harvested annually is fixed as a result of the Long Range planning and the only flexibility available is in the early or delayed harvest scheduling of individual compartments.

The Long Range plan would determine the area to be harvested in each site class on the basis of an available expenditure budget for reforestation. An estimate of the annual revenue from harvests would be available as a result of the Short Range planning. A small reforestation budget-with the binding constraint that all harvested areas must be immediately reforested-will result in a lower annual revenue from harvests. In management of public forests, a strong case can be made for additional funds for reforestation at lower budget levels, as the increased reforestation budget will provide a larger revenue from the harvest and may even result in a bigger budget surplus than would have been possible at lower reforestation budget levels.

Though not considered explicitly, other constraints such as manpower and equipment availability could be incorporated into the model and their effect on planning strategy evaluated. Both stages of the model are flexible enough for incorporation of new constraints and goals and the modification of the existing ones. The most welcome feature of the model is that it uses a standard LP formulation and the size of the two-stage formulations are small enough not to cause problems on most computer installations. The cost of computer analysis would also be relatively small and is not likely to constrain the application of the model.

Two factors affect the usefulness of operations-research based forest management planning models: 1) the degree to which the model approaches reality; 2) the extent of time, effort and money needed to collect, process and periodically update the data needed in its application. The main objective of this study-the development of a mathematical model as a forest management planning tool-has been accomplished.

As forest management plans are expected to be revised every few years, the data for the application of this model will also have to be revised periodically. Continuous forest inventory, periodic sampling by compartments, or any other sampling method can provide most of the biological data needed by the model. But there is also need to develop an efficient method for collection of data on costs of various forestry operations and values of different timber products. Both costs and prices affect the financial rotation and the annualized land rent which, in turn, affect the resulting planning strategy. This is a possible area of follow-up research.

Most of the previous applications of operations research in forest management have assumed either private ownership (Thompson *et* al. 1968) or that the intensity of forest management is not constrained by capital and other limited resources (Clutter 1968). But such constraints commonly exist. If several management units are involved in one ownership-a common feature of public forests-piecemeal optimization of forest management on individual units may not lead to overall optimization for the entire ownership. Chapter II indicates how sensitivity analysis features could lead to a more efficient allocation of production goals and expenditure budget among different management units. This appears to be a useful area for further research.

In the example of Chapter III, mono-culture was assumed to be the standard reforestation practice. This was done not because the model cannot handle mixed stands, but because the silvicultural and mensurational data on artificially raised mixed stands is very scanty. Similarly, pre-harvest stands were assumed to consist of single species. This too was done because of the lack of mensurational data on mixed stands. There is an obvious need for research in the silvicultural and mensurational aspects of mixed stands.

Finally, though the model has been designed for application in forest management for timber production, there is nothing inherent in the formulation to restrict its application only to timber management. Other situations of conflicting and incommensurate goals, amenable to linear formulation can be handled by goal programming. This is obvious from its application in the diverse fields of production, financial and other planning (Lee 1972).

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APPENDIX

Data on reforestation alternatives from which Table 1 (chapter III) has been derived.

Ref. alter.	Spp	Establish-ment cost in Rs per hectare	Age	Type of harvest	Total volume output in cum per hectare			Stumpage value in rupees per cum		
					saw	ply	pulp	saw	ply	pulp
1	2	3	4	5	6	7	8	9	10	11
				SITE CLASS I						
01	A	1,000	12	Th	–	–	40	–	–	25
			20	F	–	–	200	–	–	35
02	A	800	15	Th	–	–	40	–	–	25
			25	F	–	–	210	–	–	35
03	B	1,500	10	Co	–	–	125	–	–	30
		300	20	Co	–	–	115	–	–	30
		300	30	Co	–	–	90	–	–	30
		300	40	F	–	–	70	–	–	30
04	C	1,200	15	F	–	–	200	–	–	35
05	D	1,200	15	Th	–	–	30	–	–	15
			25	Th	–	40	40	–	70	20
			40	F	–	200	50	–	110	25
06	E	1,300	15	Th	–	–	30	–	–	15
			25	Th	–	30	40	–	80	20
			40	F	–	190	50	–	120	25
07	E	1,000	20	Th	–		30	–	–	15
			35	Th	–	50	40	–	80	20
			50	F	–	225	50	–	120	25
08	F	1,500	15	Th	–	–	20	–	–	10
			25	Th	–	50	40	–	70	15
			40	F		230	40	–	110	20

Explanation of abbreviations is given at the end of this Appendix.

APPENDIX A (continued)

1	2	3	4	5	6	7	8	9	10	11
			SITE CLASS I (continued)							
09	G	1,200	15	Th	–	–	20	–	–	25
			25	Th	30	–	30	100	–	30
			40	Th	60	–	30	120	–	35
			60	F	270	–	40	170	–	35
10	H	1,500	15	Th	–	–	20	–	–	30
			25	Th	40	–	40	70	–	35
			40	Th	80	–	40	100	–	35
			60	F	270	–	50	120	–	40
11	H	1,000	20	Th	–	–	30	–	–	30
			35	Th	40	–	50	70	–	35
			50	Th	80	–	60	100	–	35
			70	F	265	–	70	120	–	40
12	I	1,200	20	Th	10	–	30	80	–	30
			40	Th	50	–	40	110	–	30
			60	F	300	–	50	140	–	35
			SITE CLASS II							
13	A	1,000	12	Th	–	–	30	–	–	25
			20	F	–	–	150	–	–	35
14	A	800	15	Th	–	–	20	–	–	25
			25	F	–	–	140	–	–	35
15	B	1,500	10	Co	–	–	100	–	–	30
		300	20	Co	–	–	90	–	–	30
		300	30	Co	–	–	75	–	–	30
		300	40	F	–	–	55	–	–	30
16	C	1,200	15	F	–	–	150	–	–	35
17	D	1,200	15	Th	–	–	20	–	–	10
			25	Th	–	20	30	–	60	15
			40	F	–	160	30	–	100	20
18	E	1,300	15	Th	–	–	20	–	–	10
			25	Th	–	15	40	–	70	15
			40	F	–	145	40	–	120	20
19	E	1,000	20	Th	–	–	25	–	–	10
			35	Th	–	30	40	–	70	15
			50	F	–	170	60	–	120	20

Explanation of abbreviations is given at the end of this Appendix.

APPENDIX A (continued)

1	2	3	4	5	6	7	8	9	10	11
			SITE CLASS II (continued)							
20	F	1,500	15	Th	–	–	20	–	–	10
			25	Th	–	30	30	–	60	15
			40	F	–	170	30	–	100	20
21	G	1,200	25	Th	–	–	25	–	–	25
			40	Th	40	–	45	100	–	30
			60	F	200	–	50	165	–	35
22	H	1,500	20	Th	–	–	40	–	–	30
			40	Th	60	–	40	80	–	35
			60	F	240	–	40	120	–	40
23	H	1,500	20	Th	–	–	30	–	–	30
			35	Th	10	–	40	50	–	35
			50	Th	50	–	30	90	–	35
			70	F	220	–	40	120	–	40
24	I	1,200	20	Th	–	–	30	–	–	30
			40	Th	30	–	40	110	–	30
			60	F	240	–	50	140	–	35
				SITE CLASS III						
25	A	1,000	12	Th	–	–	20	–	–	20
			20	F	–	–	120	–	–	35
26	A	800	15	Th	–	–	20	–	–	20
			25	F	–	–	130	–	–	35
27	B	1,400	10	Co	–	–	80	–	–	30
		200	20	Co	–	–	70	–	–	30
		200	30	Co	–	–	60	–	–	30
		200	40	F	–	–	50	–	–	30
28	C	1,200	15	F	–	–	112	–	–	35
29	D	1,100	20	Th	–	–	20	–	–	10
			35	Th	–	25	40	–	55	15
			50	F	–	155	40	–	95	20
30	E	1,300	20	Th	–	–	20	–	–	10
			35	Th	–	35	30	–	70	15
			50	F	–	140	75	–	110	20

Explanation of abbreviations is given at the end of this Appendix.

APPENDIX A (continued)

1	2	3	4	5	6	7	8	9	10	11
			SITE CLASS III (continued)							
31	E	950	20	Th	–	–	20	–	–	10
			40	Th	–	40	40	–	70	15
			60	F	–	140	90	–	110	20
32	F	1,400	25	Th	–	20	30	–	60	15
			50	F	–	155	70	–	100	20
33	H	1,000	25	Th	–	–	30	–	–	30
			45	Th	30	–	55	80	–	35
			70	F	180	–	55	115	–	40
34	H	800	25	Th	–	–	30	–	–	15
			50	Th	40	–	50	70	–	25
			80	F	200	–	80	100	–	25

Abbreviations:

- ☐ Ref. alter. – reforestation alternative
- ☐ Spp – species; as the species were hypothetical no specific names have been used
- ☐ saw – sawlogs & quality veneer
- ☐ ply – plywood and matchwood
- ☐ pulp – pulpwood & fuelwood
- ☐ Th – thinning
- ☐ F – final harvest
- ☐ Co – reproduction by sprouts after harvest; additional expense required for cleanings etc.

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