AN ABSTRACT OF THE THESIS OF

John Douglas Nelson for the degree of Doctor of Philosophy in Forest Management presented on May 19, 1988

Title: Integrating Short-term, Spatially Feasible Harvesting Plans With Long-term Harvest Schedules Using Monte-Carlo Integer Programming and Linear Programming

Abstract approved: ______________________

Dr. J. Douglas Brodie

Procedures are developed for integrating short-term, area-based plans with long-term, strata-based harvest schedules. These procedures were tested on a 4000 hectare tract of forest land in British Columbia. It is shown that a combination of these two approaches to forest planning provides a spatially feasible short-term solution that is also feasible in terms of strategic harvest goals over the long-term.

Three basic steps are used to combine the area and strata-based plans. First, a 15-decade strata-based plan is solved with linear programming (LP) to establish strategic harvest goals. This LP determines the nondeclining yield of volume and the minimum net revenue that can be produced each decade, and it also determines how much of the forest must be partitioned into harvest units to supply a 3-decade area-based plan.

Second, using the strategic harvest goals as guidelines, 3-decade area-based plans are generated using a random search technique called Monte-Carlo integer programming (MCIP). The area-based plans are selected from 45 harvest units which are accessed by 51 major road projects. Both the harvest units and the road projects are specified as strict binary variables. Adjacency constraints prohibit any two adjoining units from being cut

in the same decade.

Third, the area-based plans become the first 3-decade solution for 15-decade integrated plans that are solved using LP. This is accomplished by using coordinated allocation choices within the FORPLAN model.

It was found that MCIP is an effective technique for generating feasible solutions to large integer problems encountered in area-based planning. No guarantee of optimality can be assured, however, the technique is a major improvement over manual methods, and it is a practical alternative to mixed integer programming where the cost of finding the true optimum is prohibitive.

It was also found that the discount rate is not a factor in determining the optimal basis for an LP that maximizes present net worth and includes a nondeclining net revenue constraint.

INTEGRATING SHORT-TERM SPATIALLY FEASIBLE HARVEST PLANS WITH LONG-TERM HARVEST SCHEDULES USING MONTE-CARLO INTEGER PROGRAMMING AND LINEAR PROGRAMMING

by

JOHN DOUGLAS NELSON

A THESIS
submitted to
Oregon State University

in partial fulfillment of
the requirements for the
degree of

Doctor of Philosophy

Completed May 19, 1988
Commencement June 1989

APPROVED:

____

Professor of Forest Management in charge of major

____

Chairman of the Department of Forest Management

____

Dean of the Graduate School

Date thesis is presented May 19, 1988

Typed by researcher for John D. Nelson

ACKNOWLEDGEMENTS

I would like to thank the following people for their help with this thesis. First, I would like to thank Dean Kennedy of the Faculty of Forestry at UBC for his confidence in me, and for arranging and maintaining the necessary financial support during my study leave. Second, Dr. Doug Brodie and Dr. John Sessions have been of great assistance in providing guidance, and contributing their time towards this study. Third, Dr. Phil Cottell, Brent Sauder, and Rod Tysdal from MacMillan Bloedel are thanked for their assistance with data collection. Funding provided by MacMillan Bloedel for travel expenses was appreciated. Appreciation is also extended to Dr. Logan Norris and Dr. Jeff Arthur for reviewing drafts, and to Dr. Norm Johnson for help with FORPLAN details.

Finally, to my family, I thank-you for your patience and support.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTEGRATING SHORT-TERM SPATIALLY FEASIBLE HARVEST PLANS WITH LONG-TERM HARVEST SCHEDULES USING MONTE-CARLO INTEGER PROGRAMMING AND LINEAR PROGRAMMING

INTRODUCTION

PROBLEM BACKGROUND

The problems of determining what areas should be harvested, how they should be harvested, and when they are to be harvested, are complex decisions facing forest managers. These harvest scheduling problems can be broken into two broad categories. First, there is the long-range plan that looks ahead over several rotations (150 + years), and provides an estimate of what volumes should be cut from various stands within each decade. These plans do not necessarily provide a spatially feasible solution, since the stands are aggregated over vast areas, average costs and yields are used, and individual harvesting units are not specified.

These forest wide, long-range plans are usually solved by either binary search, shadow price search, or linear programming techniques. The advantages and disadvantages of these techniques are summarized by Eldred (1987) and also by Davis and Johnson (1986). LP is the most flexible method because it has the ability to maximize outputs under a variety of constraints. The decision variables in a LP are established to determine how many acres of each stand should be cut during each time period. The model formulation is based on timber strata, and is therefore referred to as strata-based planning. FORPLAN (Johnson, 1987) is a LP model commonly used for forest wide harvest scheduling.

The second category of harvest scheduling problems deals with determining a spatially feasible solution that covers a planning horizon of ten to fifty years. Based on the harvest levels generated in the long-range LP, individual harvest units and road networks are specified for a relatively smaller area in this type of a plan. Now the decision variables are to determine what harvest units should be cut and which roads should be built during each period. Because the problem is formulated from specific harvest units, this type of planning is referred to as area-based planning. Since this approach requires integer solutions, these problems are usually solved with mixed-integer programming (MIP) techniques. Integer variables are needed because road links must be either built or not built - they cannot be partially constructed (as allowed for by continuous variables in an LP) and still provide access to the harvest unit. Harvest units are also specified as integers to prevent them from splitting between time periods. Splitting can complicate adjacency restrictions, and it can also result in a situation where very small percentages of the unit are left for future periods (Moore and Nielson, 1987). From managerial and operational perspectives, this situation is undesirable because of the additional fixed costs associated with returning to the unit. The Integrated Resource Planning Model developed by Kirby and others (1980) is probably the most advanced MIP model available for solving this type of planning problem. It also has a heuristic option that is widely used on large problems. Schuster and Jones (1986), and Jones and others (1985) used this model to examine harvest scheduling in the Rocky Mountain region, but it is noted that only roads (not harvest units) were specified as integers in their formulations.

Integer solutions greatly increase the computational burden of the problem, thus MIP techniques are not well suited to large planning problems. Another reason why MIP is not used for forest wide planning is that the entire forest must be partitioned into specific harvest units, complete with planned roads and logging systems. Not only does this involve an incredible amount of engineering work, but it also assumes that current logging systems and technology will remain unchanged throughout the planning horizon (which often exceeds 100 years). This assumption also applies to the strata-based plans, however, intensive engineering work for activities planned in the distant future is not necessary.

The situation can be summarized as follows. Strata-based planning is an efficient way to determine long-term harvest sustainability. The disadvantage is that strata-based plans may be infeasible because they lack specific area information such as harvest unit boundaries that are needed for developing operational logging plans. Conversely, area-based plans provide the information for implementing operational plans, but do not guarantee that an adequate inventory structure remains so that long-term harvests can be sustained.

This study is directed at integrating short-term, area-based plans with long-range, strata-based plans. A simple and reasonably fast procedure is presented for generating feasible solutions for the area-based plan, and then incorporating these results into the strata-based plan.

LITERATURE REVIEW

Literature relating to combining area and strata plans

The most relevant work done on integrating area-based and strata-based planning was done by Johnson and Crim (1981). They examined the strengths and weaknesses of both approaches. In addition, they proposed procedures and identified many conceptual problems related to the linking of the two methods. They concluded that specific revenues, costs and yields should be used for the projects in the area-based plan, but once selected and harvested, these areas should revert back to their respective timber strata. At this point, these strata would be assigned the original, average yields and net revenues. They proposed a MIP formulation to incorporate both projects and timber strata. Johnson and Crim also cautioned that under this formulation, the problem may have to be rerun and adjustments made to the yields in future decades so that they correspond to the yields used within the projects that were selected in the short-term. The integer variables used in this type of formulation seriously limit its application to practical scheduling problems.

Johnson, Stuart and Crim (1986) suggest that the entire short-term plan can be represented as a single variable within the long-term linear program. In this case, a set of spatially feasible harvest units is proposed for the first decade. Links are then made to pass acres and volumes to future decades. The first-decade plan is a feasible alternative, but it is not necessarily the optimal schedule. To examine the effects of other short-term schedules, new feasible alternatives must be generated, and the problem rerun. Splits in the short-term decision variable may occur unless this variable is specified as an integer.

More recently, Johnson and Stuart (1987) have outlined a procedure which incorporates area-based solutions into the strata-based LP by forcing the necessary acres into the solution. Within the FORPLAN model, coordinated allocation choices (CAC) are binary decision variables, that if selected, force in acres of the timber strata, and trigger specific yields related to the area-based solution. Through the use of accessibility constraints that limit the percentage of acres available for harvesting, area-based solutions covering up to four time periods can be built into the LP formulation. The major advantage of this technique is that future timber inventories are automatically adjusted to reflect cutting patterns in the early time periods. The ability to specify both average and specific yields on a per acre or per area basis is also an important advantage. The work done by Johnson and Stuart overcomes much of the difficulty in handling links between area-based and strata-based decision variables.

This study is directed at developing a method to quickly generate these spatially feasible solutions that make up the CAC's within FORPLAN. Integration of constraints that restrict the harvesting of adjacent units is perhaps the most difficult obstacle to overcome in this study.

Literature relating to area-based plans

Most of the literature relating to area-based planning describes methods other than MIP for solving integer programming problems. While MIP is an exact method, it is unattractive because it is computationally difficult for large problems. Zanakis and Evans (1981) identify this as an important reason for using heuristic "optimization". In a related problem, Steinberg (1970) compared two heuristics with branch and bound integer programming on 90 nonlinear programming problems with fixed charges. These problems had 30 variables and 15 constraints. The heuristic could find solutions within 5% of the optimal value after about 30 iterations. The branch and bound method required an average of 1208 iterations to identify the optimum. Magnanti and Wong (1984) also recommend heuristics for large network problems involving fixed charges. A heuristic can be used for solving the fixed charge problem within IRPM/TRANSHIP problems (USDA Forest Service, 1983).

Moore and Nielson (1987) used the MIP option in IRPM in an attempt to identify the optimal area-based plan for a 3-period, 28-unit problem. With only the road projects specified as integers (54), the solution was found after 17,216 iterations. When the first period harvest units were also specified as integer variables, the total number of integers increased to 73, and an optimal solution was found after 29,720 iterations. The harvest units in the remaining two periods were not specified as integers, and many of these were split between time periods. Moore and Nielson felt that further efforts to solve the entire problem with integer variables would be too expensive.

Difficulty in optimizing integer programs was encountered in all these studies. This has led to the use of heuristics (where possible) and other techniques such as simulation and random search methods to deal with integer problems. On the National Forests in the United States, planning problems can involve upwards of 1000 harvest units and 2500 road projects. If a 3-period area-based plan is desired, this problem can approach 10,000 integers (3 periods X (1000 units + 2500 roads) = 10,500), which is far beyond MIP techniques. Other techniques that have been applied to the area-based problem follow.

Hokans (1983) experimented with artificial intelligence to simulate how managers select harvest units under spatial restrictions. This method selects small polygons until a specified maximum acreage per unit is reached. It provides a guide as to what percentage of the stands are available for cutting in each period, however, it does not consider harvest units that have been specifically designed for the area.

The Project Area Scheduling System (PASS) developed by Tanke (1985) for the USDA Forest Service is a simulation model designed for assessing area-based harvest scheduling problems. An important demand for this tool was the need to dissaggregate FORPLAN solutions into a workable schedule of timber sales and road projects. The PASS software calculates the revenues, costs and yields associated with schedules selected by the user. It provides information that helps the user improve the scheduling choices with each trial. The analyst can make any desired changes, and then run the simulation again. Its major advantage is that it can quickly manipulate large volumes of data necessary to assess alternatives. The major disadvantage is that the analyst must provide the scheduling choices, and given the large number of possibilities, attempting to find optimal or near optimal solutions can be a difficult task. This was demonstrated by Jones et al. (1986) when they showed that PASS solutions were significantly lower than the heuristic solution found by IRPM. Tanke's work is still a valuable contribution when compared to manual methods traditionally used to resolve harvest scheduling problems. When hundreds of variables and possibly thousands of alternatives are involved, arriving at just one or two feasible solutions is a major achievement.

Sessions (1987) has recently introduced a procedure in which random patterns of harvest units are generated, and then tested for adjacency constraints and harvest levels. While this procedure does not guarantee optimality, it is effective in quickly generating feasible alternatives. For large problems, this represents a considerable improvement over manual methods where obtaining just one feasible solution is a time consuming and expensive task. It is also an improvement over PASS in that the algorithm generates the harvesting schedule. Session's method uses a heuristic procedure to identify the "optimal" schedule and road network once feasible patterns of harvest units have been identified.

Conley (1980) has also demonstrated how good solutions for integer and mixed-integer programs can be reached through random sampling of the feasible region. His procedure involves assigning random values to the decision variables, and then testing for feasibility. When this technique is repeated many times, solutions very close to the optimum can be discovered. He calls this method "Monte-Carlo Integer Programming" (MCIP). Conley has examined frequency distributions of the objective function value for 26 integer problems, and demonstrates that the upper end of these distributions have short, dense tails. He has not yet encountered a problem (including a 2000 integer variable problem) where the sample distribution differs from this shape. He concludes that there is a high probability of getting a solution in the upper 1% of the sample distribution. There can be no guarantee of how close this value is to the true optimum, but with a large sample size many good solutions can be obtained.

MCIP has been applied to a stand level optimization problem. Bullard, Sherali, and Klemperer (1985) used this method to estimate optimal thinnings and rotations for mixed-species stands. In this nonlinear-integer programming model, the decision variables were defined as the number of trees harvested from each species/diameter class for a given thinning. By enumerating all possible solutions (2,000,000) the optimal solution was found. Using sample sizes of 1000 and 10000, they demonstrated that the MCIP algorithm was successful in identifying solutions with present net worths within 1 percent of the optimum. To help identify these solutions, a multi-stage MCIP technique described by Conley (1981) was used to narrow the range of the decision varibles.

As part of the preliminary work on this project, Conley's method was tested on a small three-period, twenty-unit planning problem with adjacency and volume constraints. It was very efficient in quickly generating high valued solutions, including the optimum that had previously been found by MIP. Appendix 1 contains a summary of these results. This problem did not involve a sub-optimization of the road network because each harvest unit had only one haul route. It was noted that a number of high valued solutions shared a common pattern of harvesting units in the first planning period. Most differences occurred in the third period, and occasionally minor differences were found in the second period. This indicates that a harvesting strategy for the immediate future can be implemented knowing that flexibility exists in the choice of patterns available for subsequent periods. This is important because with the passage of time and the acquisition of new information, all plans are subject to revision. What is desired is a first-period plan, based on the best information available, that offers spatial feasibility in the near future and compliance with sustained harvests and revenues in the distant future. In other words, we want to arrive at a good solution to our immediate needs without compromising flexibility in the future.

SCOPE OF THIS STUDY

This study will develop a procedure for generating and integrating short-term, area-based plans (decades 1 to 3) within long-term, strata-based plans (decades 1-15). Timber production is the only resource considered in this study. Multiple outputs such as recreation and wildlife are not explicitly dealt with, however, they are implicitly provided for through opening size and adjacency constraints. Monte-Carlo integer programing (MCIP) will be used to generate solutions for the three-decade, area-based plan. These area-based plans will be constrained by adjacency restrictions, volume flows, and net revenue flows. There will be no transportation network optimization once a schedule is established, because each harvest unit has only one logical route to the mill. This "tree" pattern is the result of both terrain conditions and the existing road network. This is typical of many logging sites in British Columbia, but it is not always true. Where multiple routes exist, the road network must be optimized once the schedule is determined (Sessions, 1987).

Results from the MCIP's will then be used to formulate coordinated allocation choices within a fifteen-decade, strata-based plan, which will be solved as a linear program with the FORPLAN model. A solution from this formulation will provide a spatially feasible plan with specific yields and costs for decades one to three, as well as a long term projection of volumes and revenues for the remaining twelve decades. Assuming that our predictions of net revenues and yields remain unchanged, the alternative with the highest PNW that meets volume and net revenue constraints will be chosen as the best feasible plan.

A portion of MacMillan Bloedel's Tree Farm License (TFL) near Powell River, B.C. is used as a case study. This area is known as the Stillwater logging division, and contains mainly second growth stands of Douglas-fir, western hemlock and western redcedar.

JUSTIFICATION

Harvest scheduling problems, because of their complexity and size, require either simulation or optimization techniques to produce workable and efficient solutions. The resource allocations that result from these plans may be irreversible and have substantial economic impacts on investment requirements, benefit flows, community activity and welfare. Most of the previous work in this field has concentrated on developing long-term, sustainable harvest levels, with recent emphasis on the smaller, spatially feasible area plans. With the introduction of powerful microcomputers and complementary software, it is now possible, and indeed appropriate that complex forest planning issues can be dealt with at the logging division level, where the analyst(s) are more in touch with the structure, constraints and potential of their forest. This trend will lead towards "bottom-up" planning, where the basic building blocks are spatially feasible area plans, which is an improvement over traditional "top-down" planning.

Optimization of area-based plans is difficult because of the integer constraints that are necessary in the formulation. The time, effort and cost of arriving at the true optimum may not be warranted, especially when projected revenues, costs, and yields are all uncertain. Log prices are highly variable, and fire, insects, and disease can dramatically effect yields. This study demonstrates a method whereby managers are supplied with a number of good alternatives, thus providing them with better information and choices than does a single optimal solution. It provides spatially feasible alternatives that also meet long-term harvest objectives. The MCIP technique can also be extended to cover more refined planning problems encountered by engineers and foresters, such as 5-year logging plans.

OBJECTIVES

There is a need to integrate short-term and long-term forest plans to ensure that both spatial feasibility and sustainable harvest goals are met. There is also a need to examine more than just one solution to the planning problem, especially in light of possible deviations from our current expectations of future revenues, costs and yields. The purpose of this study is to develop a method for generating these integrated alternatives.

OBJECTIVE STATEMENT

This study develops a fifteen-decade timber harvest plan for a portion of MacMillan Bloedel's Stillwater division located on the B.C. coast. This harvest plan will maximize present net worth (PNW) subject to constraints that require short-term spatial feasibility, consistency in the production of timber volumes and net revenues, plus ending inventory restrictions. There are three basic steps needed to generate this plan. First, a 15-decade strata-based LP is used to establish the long term sustained yield and the proportion of the forest that must be set aside for harvesting in decades 1 through 3. Second, using the results of step 1 as guidelines, and dividing the portion of the forest into specific harvest units, the first three decades will be formulated as a spatially feasible, area-based plan, and solutions will be obtained by MCIP. Third, these area-based solutions are incorporated into fifteen-decade, strata-based LP's and solved with the FORPLAN model. These final plans are spatially feasible in the short-term and they also meet long-term harvest goals. The methodology used is a composition of existing techniques (LP, MCIP, and coordinated allocation choices within FORPLAN).

Specifically, the objectives of the study are:

1. To formulate and solve a fifteen-decade, strata-based forest plan that will determine the long-term sustainable harvest level for the study site. The objective function to be maximized is PNW, subject to harvests for decades 1 to 3 restricted to a specific zone within the forest, a nondeclining flow of volume, a minimum level of net revenue, and ending inventory restrictions. This fifteen-period plan will be formulated and solved as a Model 1 linear program (Johnson and Scheurman, 1977), using the micro version of FORPLAN (Johnson, 1987). These results are used as guidelines for formulating the area-based plans.

2. To use Monte-Carlo integer programming to select the best three solutions for a three-decade, spatially feasible plan that includes adjacency, harvest level, and net revenue constraints. Volumes must lie within specified tolerances of those found in objective 1. These tolerances are defined later in the procedures. Net revenue must be at least as large as the minimum level found in objective 1. Random search MCIP will sample harvests in all three decades to identify 200 feasible solutions (called temporary solutions). The three highest valued temporary solutions will then be subjected to further analysis. To allow for future flexibility, these solutions must have high valued alternative harvest patterns for periods two and three. Selective searches with MCIP will generate five additional solutions for each temporary solution by fixing the first decade harvest pattern, and allowing decades 2 and 3 to vary. The three best area-based plans (called permanent solutions) are identified as the highest valued solutions resulting from each selective search.

3. To determine the integrated plan with the largest PNW that meets both spatial and sustainable harvest goals as defined above. The area-based plans (found

in objective 2) will form the first 3-decade solution in 15-decade strata-based LP's. The three integrated plans (one for each alternative) will be formulated and solved with the FORPLAN model using coordinated allocation choices.

DATA COLLECTION AND CALCULATION OF VARIABLES

Before proceeding further, it must be stressed that the objectives of this study are centered around developing procedures, rather than obtaining precise results. For this reason, imprecise estimates of some data were tolerated, provided the method of estimation was consistently applied. For the purpose of developing the procedures in this study, all independent variables are treated as deterministic. The description and method of estimation of these variables follows. The inventory data used are found in Appendix 2, and the economic data are found in Appendix 3.

STAND AND HARVEST UNIT VOLUMES

The most recent inventory of the entire study site was done in 1962, which is antiquated given the variation and rapid development of the young second-growth stands. Generally, the only information available from this inventory is the date of origin, site index, percent of normal yield stocking, and the species present in the stand. To arrive at net merchantable volumes per hectare, assumptions regarding species composition, cull factors, and growth rates were needed (see Appendix 2). As an alternative, it was decided to project yields with the Stand Projection System (SPS) growth model (Arney ,1985).

The DFSIM growth model (Curtis et al., 1981) was rejected because it does not handle multiple species. SPS volumes projected to 1987 were checked against recent operational cruises in adjacent stands, and also reviewed by MacMillan Bloedel staff. Where major discrepancies occurred, adjustments were made to the SPS volumes.

There are 109 individual stands grouped into 62 analysis areas (AA's). An analysis area is a timber stratum, and it is defined by 5 identifiers (1:zone, 2:logging system, 3:site, 4:species, and 5:age). Specific information on AA's, volume projections and the structure of the existing forest is found in Appendix 2.

Harvest unit volumes are obtained by summing the analysis area volumes that make up the harvest unit. There are 45 harvest units that are eligible to be included in the area-based plans. Figure 1 illustrates the location and relationship of analysis areas and harvest units.

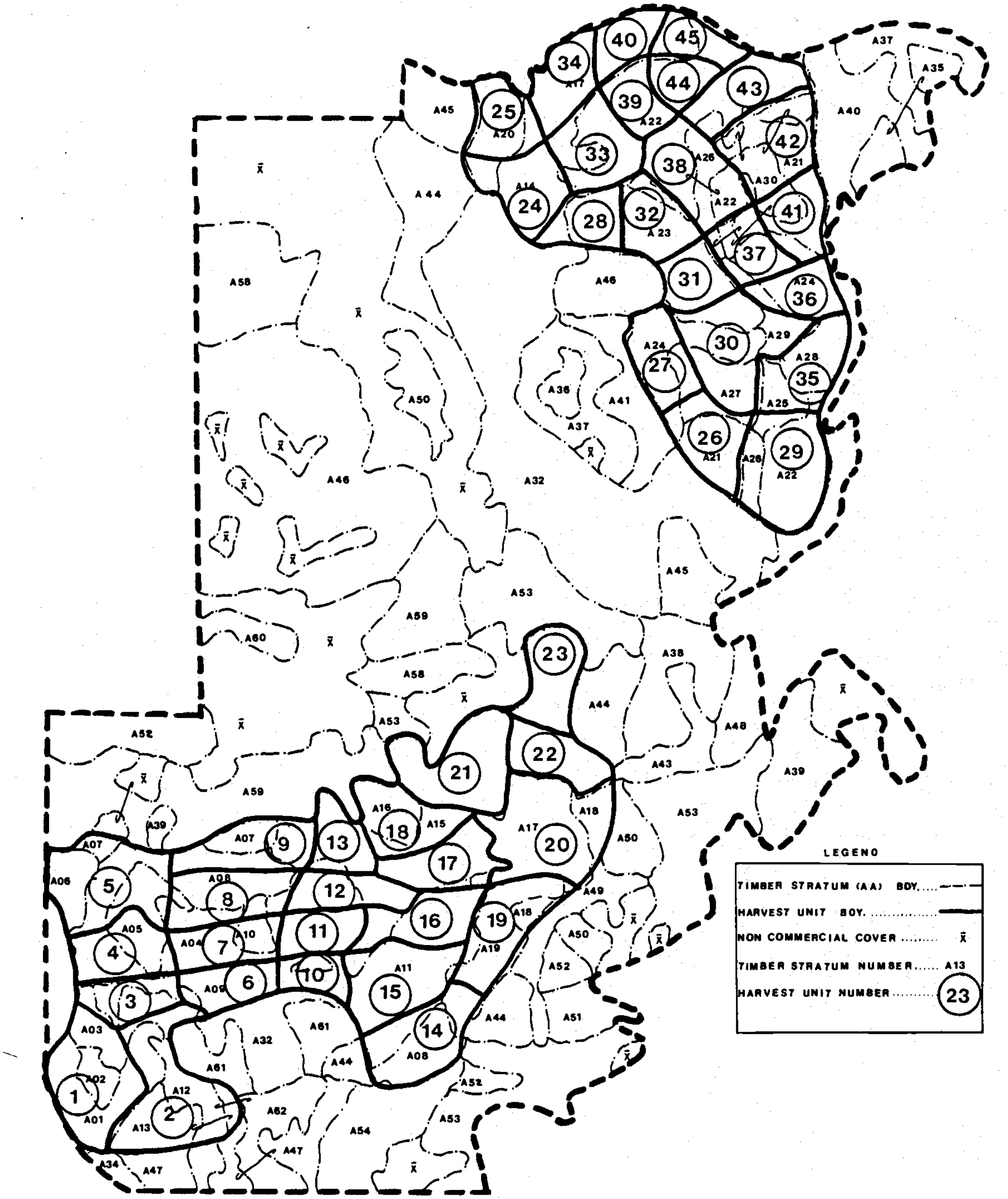


Figure 1. Location of analysis areas and harvest units.

VALUE OF TIMBER

In this study, market prices are estimated for each of the three species according to the average diameter at breast height (DBH). These prices are based on regression equations developed by Williams and Gasson (1986) and MacDonald (1987). Price data are found in table 11, located in Appendix 3. Prices per m^3 for the harvest units are a weighted average of the value of the analysis areas contained within the units. In the interest of simplicity, there are no real price increases built into future log prices, although provisions for price increase assumptions would cause little difficulty.

ROAD CONSTRUCTION COSTS

Road construction costs needed to develop the harvest units are based on projected roads and road construction costs as estimated by the divisional engineer. Road maintenance costs are included in these values. There are 51 major road links (roads connecting harvest units) and each harvest unit has secondary roads (roads and landings fully contained within a harvest unit). Costs for main road projects and secondary roads are given in tables 13 and 14 respectively, which are in Appendix 3. An average road construction cost per cubic metre harvested is used in the strata-based portions of the analysis. This figure was arrived at by examining the total road cost/m^3 for various area-based plans. Figure 2 shows the location of road projects within the study site.

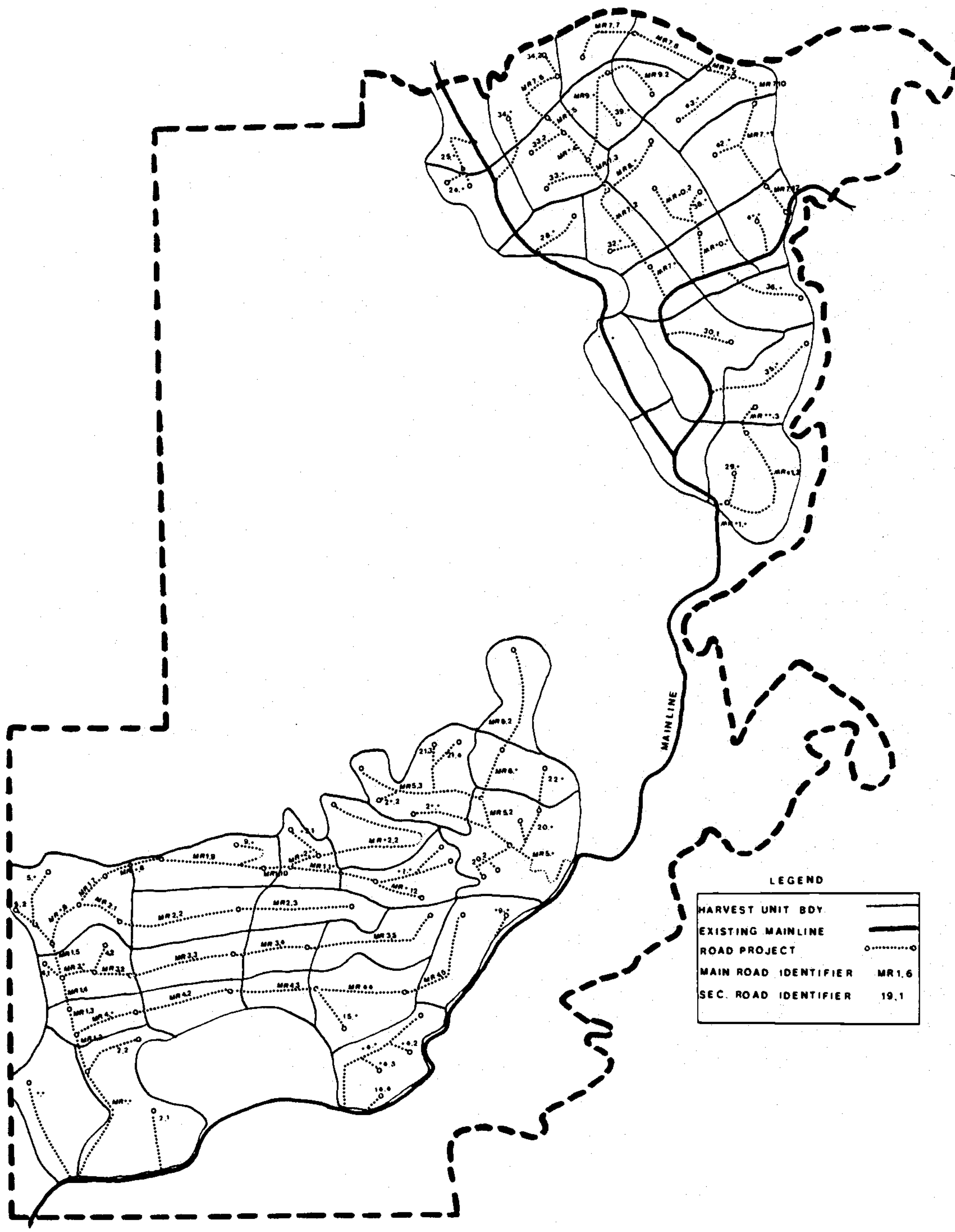


Figure 2. Location of road projects within the study site.

HARVESTING COSTS

Two logging systems are used, depending on the timber and terrain. These are ground skidding and grapple yarding. Costs are based on the average DBH of the stand, according to regression equations developed by Morrison et al. (1985) and MacDonald (1987). These figures include all phase costs from felling through hauling to the sort yard, and are found in table 11 located in Appendix 3.

ADMINISTRATIVE OVERHEAD AND OTHER PHASE COSTS

A fixed rate/m^3 is used for operational and administrative overhead plus sorting and transport to the mill. This figure was also obtained from the study done by Morrison et al. (1985), and is found in table 11.

DISCOUNT RATE:

The real discount rate was set at 4 percent. This value was chosen because it represents the opportunity cost of capital in the private economy (Row, Kaiser and Sessions, 1981). This rate may be somewhat dated, however, it is sufficient for the purpose of developing the procedures for this study. All costs and revenues are discounted from the midpoint of the decade in which they occur.

METHODS AND PROCEDURES

SITE SELECTION

The Stillwater division was selected as a study site for several reasons. First, is the cooperation of MacMillan Bloedel in supplying data and assisting in funding the project. Secondly, the 4000 hectare site provides an interesting mix of second growth timber that will serve as a long term log supply for winter harvesting operations. The timber types and terrain conditions offered the opportunity to incorporate different logging systems into the analysis. Finally, the study site is typical of logging conditions that MacMillan Bloedel will face in the near future at their other coastal logging divisions.

PROCEDURES

The procedures outlined below are organized according to the three objectives of the study.

PROCEDURES FOR OBJECTIVE 1: Determine long-term sustained harvest with a 15-decade strata-based LP.

Before describing the mathematical formulation, an outline of the procedure used and its justification is presented. First, a Model 1 linear program (maximize PNW) with nondeclining yield (NDY) less than or equal to long term sustained yield plus an ending inventory constraint was formulated and solved for the entire forest. This formulation was labelled LP1. This provides a uniform flow of timber while maintaining an ending inventory that is at least as large as the average inventory of the solution taken over the planning horizon. Additional formulations were needed as other constraints such as minimum net revenue and harvests restricted to specific zones within the forest were added.

Restricting the initial three-period harvest to a specific zone was needed because it would be unreasonable to plan initial harvesting in inaccessible portions of the forest. Using an undeveloped drainage as an example, early harvesting would be confined to a zone at the entrance to the drainage. As road construction progresses, more of the drainage becomes accessible, thus allowing more flexibility in the location of harvest units. In the Stillwater example, harvesting (decades 1 to 3) is restricted to two accessible areas that contain mostly mature timber. These two areas are collectively labelled zone A, and the remainder of the forest is labelled zone B (see figure 1). It is from within zone A that the area-based plans are generated. During periods 4 through 15, the entire forest is eligible for cutting. Limiting harvests in zone B is done by restricting the earliest available timing choices for those stands.

To determine what stands should be included in zone A is an interesting problem in itself. In the Stillwater example, the choice of the size of the zone was unknown, but because of the age structure of the existing forest (high percentage of second-growth timber not old enough for cutting) it was fairly obvious that the zone had to contain most of the stands of mature timber. In the case of an old-growth forest, with several tracts of accessible timber, the answer is not so obvious. Here, the analyst must consider area-based plans from each of these zones in order to establish the harvest schedule.

Returning to the question of what stands should be included in zone A, the following procedure was used. Successive LP's were run with increasingly more hectares added to the zone until the harvest levels (decades 1 to 3) were not restricted by the availability of timber. Using a NDY constraint in these LP's showed an upward step in volume after period 3 if the zone was limiting the initial cut. The point at which there is no discontinuity in the volume harvested indicates that the zone is of sufficient size, and will not be constraining the overall timber flow. This formulation was labelled LP2.

The minimum net revenue constraint was added because under NDY only, the LP will harvest the highest valued stands in the early periods and lower valued stands at the end of the planning horizon. This results in very high initial net revenues that sharply declined in the latter periods, a situation that is unacceptable for long term consistency in profitability. Our expectations from the forest include consistency not only in harvest levels (for manpower and equipment requirements) but also consistency in future cash flows (needed for the survival of a perpetual business entity). Implicit in this proposal for uniform cash flows is the assumption that the discount rate is zero. Future cash flows are weighted equally with current cash flows.

A strict nondeclining net revenue constraint was not used in these LP's, because it complicates the procedure, and while it is recognized that including it would provide a more rigorous analysis of the problem, the additional effort is not warranted because we still do not have a spatial solution to work with. The complications arise because adding additional hectares of stands will increase the available timber, but the net revenue of these additional stands may or may not help satisfy the nondeclining net revenue (NDNR) constraint. For example, low valued stands help to satisfy the constraint, but high valued stands create difficulty in subsequent periods. Also, specifying NDNR reduces the PNW, and in view of this, it was decided to just satisfy or at least bound net revenues rather than use NDNR. The problems encountered under both NDY and nondeclining net revenue constraints will be discussed later.

It is at this point that the LP is run with a minimum net revenue constraint. This lower bound raises cash flows in the future at the expense of the earlier periods. While a lower bound does not necessarily eliminate the peaks in the early cash flows, it does reduce them, and guarantees a minimum net revenue per period. This final formulation is called LP3. The volume and net revenue levels found in LP3 are used as targets (with tolerances) for area-based planning.

The mathematical formulation of LP3 is based on the more general description given by Johnson and Stuart (1987). It is simplified here because there is only one output (timber) and one treatment type (clearcut). Note that LP1 lacks the zone and revenue restrictions, while LP2 only lacks the revenue constraint. The zone restriction is simply a reduction in the timing choices available to the analysis areas within zone B (no harvests allowed until decade 4).

$$\text{Maximize } Z = \sum_{s=1}^{S} \sum_{k=1}^{K_s} C_{sk} X_{sk}$$

subject to:

$$(1) \quad \sum_{k=1}^{K_s} X_{sk} \leq AREA_s \qquad (s=1,\ldots,S)$$

$$(2) \quad \sum_{s=1}^{S} \sum_{k=1}^{K_s} H_{skj} X_{sk} - H_j = 0 \qquad (j=1,\ldots,n)$$

(3) $- H_j + H_{j+1} \geq 0$ $(j=1,...,n-1)$

(4) $\sum_{s=1}^{S} \sum_{k=1}^{K_s} CLTSY_{sk} X_{sk} - LTSY = 0$

(5) $H_n - LTSY \leq 0$

(6) $\sum_{s=1}^{S} \sum_{k=1}^{K_s} CI_{skn} X_{sk} - ACTINV = 0$

(7) $\sum_{s=1}^{S} \sum_{k=1}^{K_s} CI_{sk} X_{sk} - AVEINV = 0$

(8) $ACTINV - AVEINV \geq 0$

(9) $\sum_{s=1}^{S} \sum_{k=1}^{K_s} CNR_{skj} X_{sk} - NETREV_j = 0$ $(j=1,...,n)$

(10) $NETREV_J - MINREV \geq 0$ $(j=1,...,n)$

(11) $X_{sk}, H_j, \geq 0$ $\forall s, \forall k, \forall j$

where:

$S=$ the number of timber stands (analysis areas)

$K_s=$ the number of timing choices for stand s

$n=$ the number of planning periods

$C_{sk}=$ the present net worth from harvesting one hectare of stand s under timing choice k

$X_{sk}=$ the hectares of stand s harvested under timing choice k

$AREA_s$= the total hectares of stand s

H_{skj}= the volume of timber per hectare yielded from stand s under timing choice k in period j

H_j= the total volume harvested in period j

$CLTSY_{sk}$= the contribution (volume growth) of one hectare of stand s under timing choice k towards LTSY

LTSY= accounting variable that measures long term sustained yield capacity of the solution

CI_{skn}=contribution of one hectare of stand s under timing choice k to the last period's inventory (before harvest)

CI_{sk}= contribution of one hectare of stand s under timing choice k towards the average inventory (before harvest)

ACTINV=accounting variable that measures the actual inventory (before harvest) in the last period

AVEINV=accounting variable that measures the average inventory (before harvest)

CNR_{skj}=contribution of one hectare of stand s under timing choice k to net revenue in period j

$NETREV_j$=accounting variable that measures the net revenue in period j

MINREV= a lower bound on periodic net revenue

The constraint equations are described below.

(1) Land accounting constraints.

(2) Harvest accounting rows.

(3) Nondeclining yield constraints.

(4) LTSY accounting row.

(5) Harvest in last period not to exceed LTSY. This row, in combination with the nondeclining yield constraint, ensure that the harvest must be less than or equal to LTSY in all periods.

(6) Accounting row to measure ending inventory.

(7) Accounting row to measure the average inventory (over all periods)

(8) Ending inventory must be greater than or equal to the average inventory.

(9) Accounting rows to measure net revenue in each period.

(10) Net revenue in period j must be at least as large as the minimum value specified.

(11) Nonnegativity constraints.

The FORPLAN model was used to generate the linear program in Mathematical Programming System (MPS) format, and the LP software Hyper LINDO/PC (Linear INteractive and Discrete Optimizer) was used to solve the problem. There were about 1930 variables and 130 rows in a typical LP formulation during this stage of the analysis.

PROCEDURES FOR OBJECTIVE 2: Generating feasible solutions for the area-based plan

The results from procedure 1 defined the zone in which harvesting units were to be located. The area-based plan was formulated and solved as a Monte-Carlo integer program. The plan covers the first three decades, and includes 45 harvest units, 51 main road links, and 45 secondary roads. Since the costs of secondary roads can be included in the cost for each harvest unit, this problem has 288 integer variables (3 time periods X (45 units + 51 road projects)=288).

The objective was to find harvest patterns that give high PNW's subject to the volume constraints found in the 15-decade LP, constraints that specify a minimum net revenue in each period and constraints that prevent two adjacent units from being cut in the same period. Harvest units were designed so that the maximum clear cut size of 80 hectares would not be violated. Volumes produced each decade must lie within specified tolerances of the long term sustained yield (LTSY) found in LP3. These tolerances bound the volumes produced to within -5% and +10% of the LTSY. These tolerances were chosen because they represent a range in which a reasonable degree of flexibility is available without radically departing from the LTSY. The lower bound is more stringent than the upper bound because a 10% drop in volume would cause long-term operational problems, such as crew and equipment layoffs. Conversely, an increase in volume harvested could be accommodated with increased contract logging during the short-term.

One further constraint specifies that the PNW of the area-based plan must be at least as large as a specified threshold value. This ensures that only high valued solutions are recorded. Through testing of the algorithm on the area-based problem, it was found that a minimum PNW of $4.5 million gave satisfactory results in terms of the number and the value of the solutions. At this lower bound, an average time per solution was 8 minutes, which was deemed to be the maximum time in which it would be reasonable to generate 200 alternatives (approximately 26 hours).

For the purpose of simplicity, constraints that specify the maximum/minimum volumes of individual species were not incorporated into the problem. Some consistency in the species harvested may be partially accomplished through the cash flow restrictions used. Because there is only one dump site for the timber (at the ocean), one main haul road to the dump, and one logical route from the harvest units to the main road, this problem does not involve optimization of a road network. Traffic flow over the roads will be far below capacity, so it is unnecessary to include such constraints.

There were two major methods followed to arrive at the three best solutions. In the first method, the MCIP was used to generate 200 feasible solutions (labelled temporary solutions) for the planning problem. This method, called the random search, was free to choose harvest patterns in all three periods.

In the second method, called selective searches, the three temporary solutions with the highest PNW's (TS1, TS2, and TS3) were selected for further analysis. The first period harvest pattern from these temporary solutions was fixed, and only periods two and three were allowed to vary. The two objectives of the selective searches were first, to try to find better solutions, and secondly, to demonstrate that other alternatives exist even though the first period is fixed. This is useful information that demonstrates that flexibility is available in future periods, regardless of the action taken in period one. Finally, the highest valued solution found in each of the three selective searches was chosen as a "permanent solution" (PS1, PS2 and PS3), and subsequently used as a coordinated allocation choice within the integrated plans.

The random search method is described first. The MCIP algorithm is outlined in figure 3, and described below. It is basically a three stage procedure (with each period representing a stage) in which harvest units are randomly selected for cutting at each stage. Random numbers are generated with the random number generator described by Law and Kelton (1982), which originates from Schrage (1979). Random numbers are converted into binary variables (0 or 1) for each harvest unit. If a unit is assigned a value of 1, then it is to be cut in that period, otherwise it is assigned a value of 0, and will not be cut during that period.

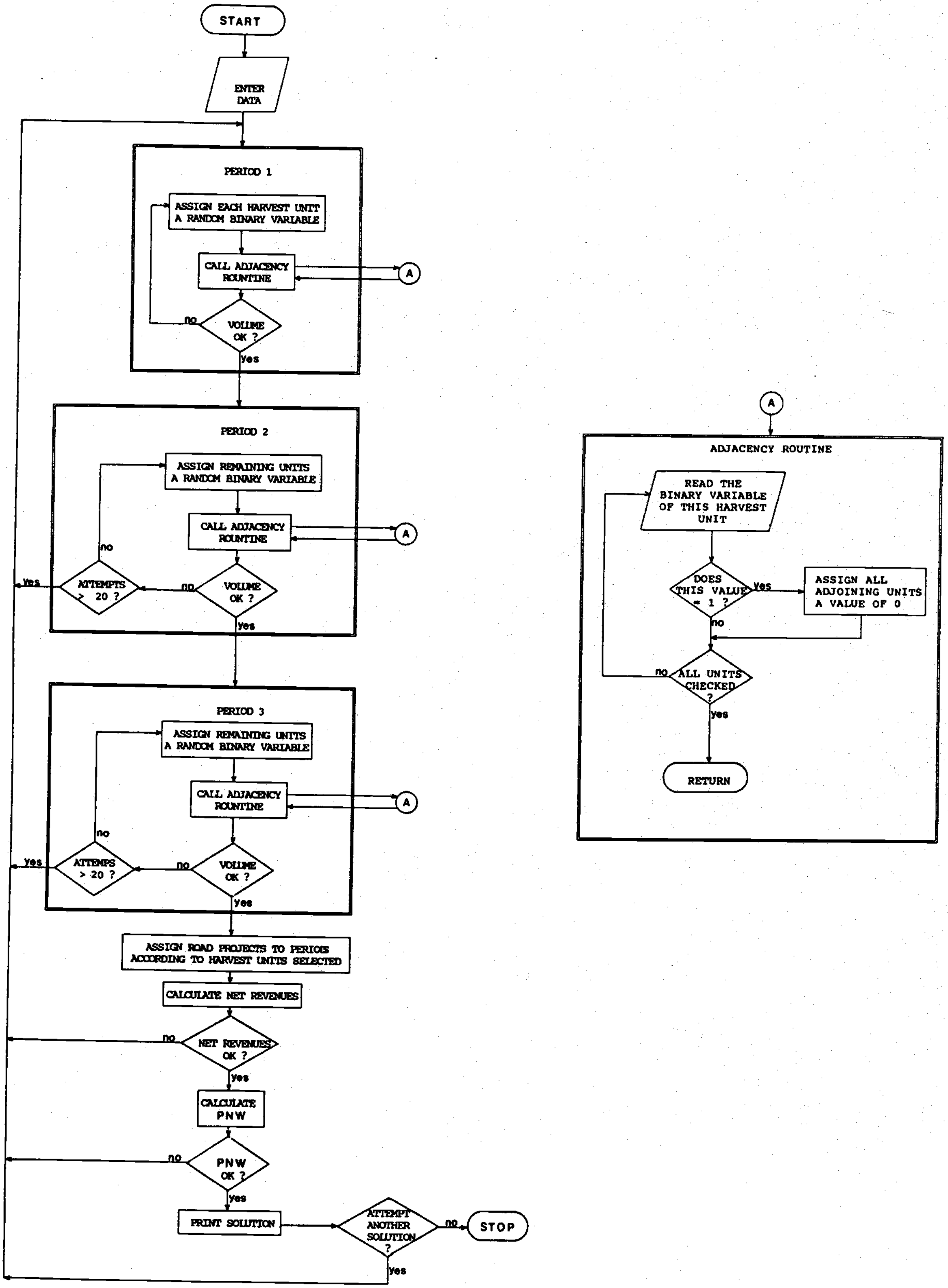


Figure 3. Flow chart of the random search Monte-Carlo Integer Program.

Starting with the first period, all 45 units are eligible for cutting, so each is be assigned a binary variable. The next step is to ensure that no two adjacent units are selected in the same time period. This is accomplished with an adjacency routine that sequentially reads in the binary variables for each unit. If a particular unit has a binary variable equal to one, then all adjacent units are set equal to zero. When the adjacency routine is completed, a spatially feasible pattern of harvest units has been established. At this point, the volume produced from the selected units is summed, and the total is tested to see if it falls within the allowable tolerances. If not, we return to the start and generate a new set of binary variables, otherwise we have an acceptable solution in terms of adjacency and volume requirements, and we can proceed to the second period (stage).

The net revenue for the first period solution is not checked at this point because, through testing, it was found that fully checking each period offered no speed advantage over checking an entire three-period solution. It takes very little time (about 1.5 seconds) for the algorithm to arrive at a three-period solution that meets adjacency and volume constraints. The minimum net revenue constraint drastically reduces the feasible region of the problem, and it takes approximately 8 minutes to generate a fully acceptable solution.

In period two, harvest units that were selected in period one are no longer eligible for cutting, so binary variables are generated for the remaining units only. From this point on, the same procedures described for the first period case are repeated. If an acceptable solution cannot be found in twenty attempts, we return to the start and try a new period one solution. In most cases, a second period solution is found after about 4 attempts. Raising the twenty trial limit slowed solution time and did not produce additional alternatives.

In the third period, the MCIP can only select units that were not cut in either of the preceding periods. Since the number of units available decreases with each period, solution time also decreases. Once again, there is a limit of twenty attempts before quitting period three and returning to the start of period one. Returning to the start of period two, in an attempt to utilize the first period solution, failed to offer any advantage over completely starting over at the beginning of period one.

When a feasible alternative to period three is found, then a routine to trigger road projects according to the harvest unit selection is initiated. All road projects needed to access a selected unit are assigned a value of 1 in that decade. Since this can result in a major road project being assigned to more than one time period, a short routine to eliminate redundancies is used. If a road project was scheduled in two or more periods, then only the earliest period is allowed to retain a value of 1, while the latter periods are set to zero. Following this routine, the net revenue for each period is calculated and checked against a threshold value. If unacceptable, the solution is rejected, otherwise it is checked against a minimum PNW value. A solution that passes this final test is recorded as a feasible area-based plan (previously defined as a temporary solution).

Having completed the 200 random searches, and identifying the three highest valued solutions (TS1, TS2, and TS3), three selective searches are initiated. Other than fixing the first period harvest pattern, and increasing the threshold PNW to $5 million (to select only the very high valued solutions), the MCIP algorithm operates the same way as described in the random search method. Each selective search was used to identify five new (and unique) solutions. The highest PNW solution from each selective search was then chosen as a permanent solution (PS1, PS2, and PS3). Figure 4 illustrates how random and selective searches are used to determine the area-based plans that are subsequently used in the integrated plans.

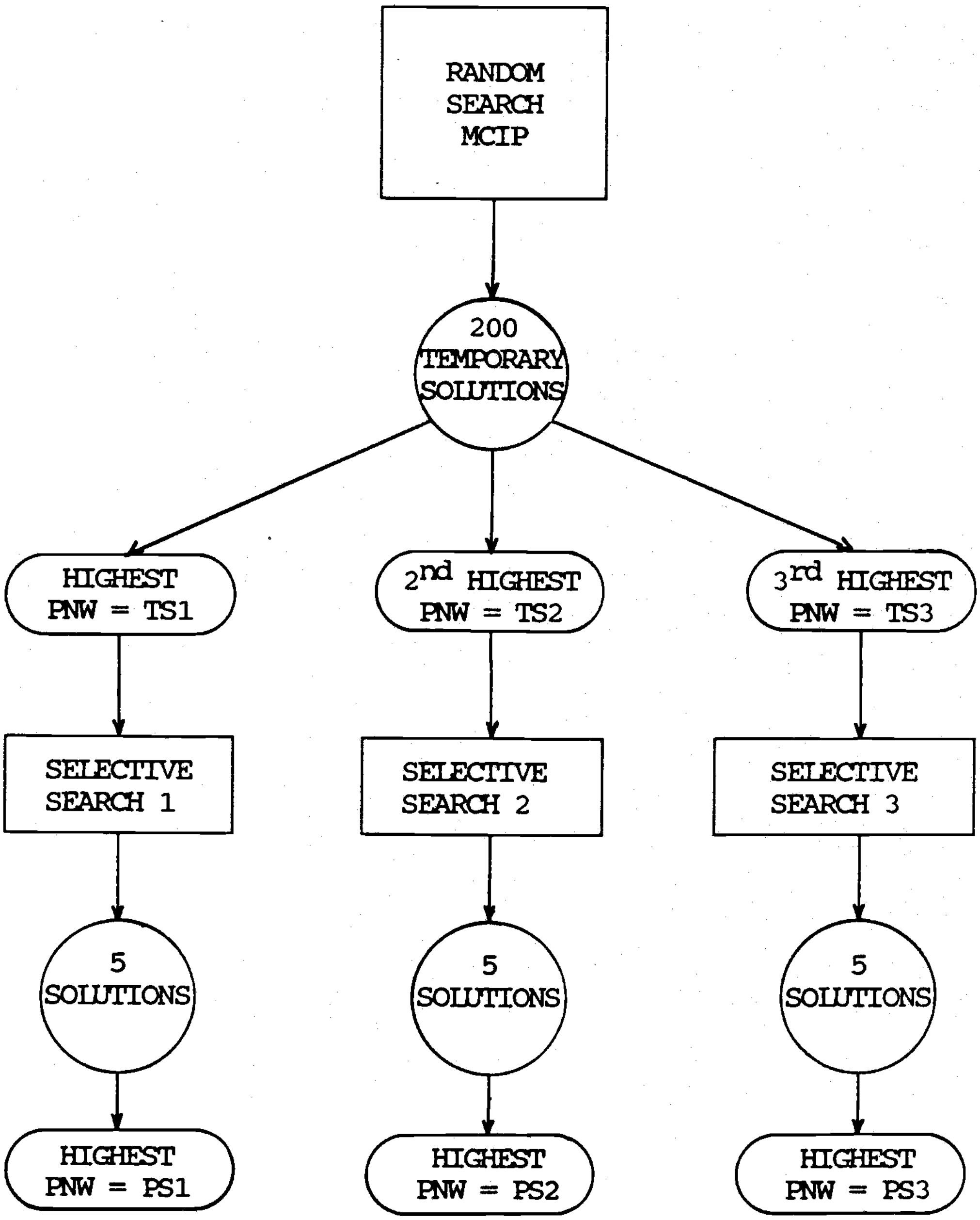


Figure 4. Relationship between random and selective searches in establishing area-based plans.

The MCIP was written and compiled in Turbo Basic, and run on a Compaq Deskpro 386 computer.

PROCEDURES FOR OBJECTIVE 3: Integrating area-based and strata-based plans

The three area-based plans identified above were then incorporated into fifteen-decade linear programs. These integrated plans are labelled ILP1, ILP2, and ILP3. Before presenting the mathematical formulation, a description and justification of the procedure is given.

Using the FORPLAN model, each area-based plan was treated as a coordinated allocation choice (CAC) that was selected from the zone containing the harvest units. The CAC contains all the hectares of the analysis areas that are within the harvest units selected for cutting. Constraints that set a lower bound on the total number of hectares harvested in each period force the necessary analysis areas (AA's) into the solution. Accessibility constraints are used to ensure that the correct number of hectares of each AA are harvested in each of the three periods. The accessibility constraints create an upper bound on the total number of hectares by limiting the percentage of each AA that is available in a given period. The combination of these two constraints forces the area-based plan into the solution.

The next issue to be dealt with is the specific road costs associated with this plan. This is accomplished by specifying in a yield file the sequence of total road costs found by the MCIP. When the CAC is implemented, it includes these costs in the solution. The average road cost/m^3 used in the initial plan is used only during decades 4 through 15 when spatial feasibility is not considered. Volumes and other harvesting costs do not need to be adjusted because total harvest unit volumes and costs are calculated as a weighted average of the analysis area yields.

When implemented, the CAC forces a cutting schedule for the existing stands on each respective analysis area. It is important to note that the timing choices of the regenerated stands that result are not restricted by this method. The spatially feasible pattern occurs as scheduled, but it does not necessarily repeat itself in subsequent rotations. Other than forcing a particular set of AA's and road costs into the first three periods, these integrated linear programs (ILP's) are typical strata-based models.

In the previous LP's, volume was constrained by nondeclining yield, and an absolute lower bound was set on net revenue. For the purposes of comparing the three integrated plans, it was desirable to have a uniform flow of both volume and net revenue during periods 4 through 15. With the nondeclining yield constraint on volume and a nondeclining constraint on net revenue, the solution was unacceptable because the initial volumes were too low. In the first decade, volumes dropped to 120,000 m^3. Adding a lower bound on the volume harvested per period in an attempt to overcome this difficulty resulted in infeasibility. This problem is due to the cutting of high valued stands in the early periods and low valued stands in the ending periods - which is a fundamental planning problem associated with discounting cash flows over long periods of time. In order to maintain a constant level of net revenue, a much higher volume of timber must be cut from low valued stands than from high valued stands. Under nondeclining yield, it is therefore impossible to cut low valued stands in the early periods because this will result in declining volumes when higher valued stands are cut in future periods. Further analysis of this problem is presented in the discussion of results.

To overcome this problem, volumes were allowed to fluctuate slightly (1 to 2%) from period to period, while net revenue was not allowed to decline. This provided enough flexibility to spread harvesting of the low valued stands throughout the planning horizon. The problem then becomes one of finding a uniform cash flow over the last twelve periods, subject to minor volume changes. It is interesting to note that under this formulation of the planning problem, discount rate variation does not affect the optimal basis. Periods 1 to 3 are fixed, and periods 4 through 15 require the maximum, uniform cash flow that can be obtained from the timber flows. Whether the discount rate is zero or very high, the maximum cash flow must be met, according to the definition of the problem. Therefore, the discount rate does not determine the harvest schedule, but it does influence the present net worth of the cash flows generated by the solution.

An advantage of using a zero discount rate in the ILP is that scaling problems that result from discounting objective function coefficients can be minimized. At 150 years, using a 4% discount rate, the discount factor is 0.002786. This small factor can cause scaling problems when the resource matrix coefficients and right hand side parameters are orders of magnitude larger than the objective function coefficients. For this reason, a zero discount rate was used in these ILP's. The resulting net revenues were discounted at 4% to determine the PNW of each solution.

The integrated plan with the largest PNW was selected as the best plan to implement, assuming that future prices, costs, and yields do not deviate from the expectations upon which the model was built. The mathematical formulation of the integrated linear program is presented below. It is based on the more general formulation by Johnson and Stuart (1987), with simplifications resulting from one CAC, one prescription, and one timing choice for implementing the CAC.

Mathematical formulation of the CAC linear program:

$$\text{Maximize } Z = R_a Y_a + \sum_{z=1}^{Z} \sum_{s=1}^{S} \sum_{k=1}^{K_s} C_{zsk} X_{zsk}$$

subject to:

(1) $$\sum_{k=1}^{K_s} X_{zsk} \le AREA_{zs} \qquad (s=1,\ldots,S), \quad (z=1,2)$$

(2) $$\sum_{s=1}^{S} \sum_{k=1}^{K_s} X_{zsk} - Y_a\, ZONE_z = 0 \qquad (z=1)$$

(3) $$-\sum_{s=1}^{S} \sum_{k=1}^{K_s} P_{zskj}\, ZONE_z + \sum_{s=1}^{S} \sum_{k=1}^{K_s} X_{zsk} + \sum_{s=1}^{S} \sum_{k=1}^{K_s} W_{zskjq} = 0 \qquad (j=1,\ldots,3)$$

where $j < q$ and $z=1$

(4) $$\sum_{s=1}^{S} \sum_{k=1}^{K_s} X_{zskj} + \sum_{s=1}^{S} \sum_{k=1}^{K_s} W_{zskcj} - \sum_{s=1}^{S} \sum_{k=1}^{K_s} W_{zskjq} - HECT_j = 0 \qquad (j=1,\ldots,3)$$

where $c < j < q$ and $z=1$

(5) $$\sum_{z=1}^{Z} \sum_{s=1}^{S} \sum_{k=1}^{K_s} H_{zskj} X_{zsk} - H_j = 0 \qquad (j=1,\ldots,n)$$

(6) $$-0.98\, H_j + H_{j+1} \ge 0 \qquad (j=4,\ldots,n-1)$$

(7) $$-1.02\, H_j + H_{j+1} \le 0 \qquad (j=4,\ldots,n-1)$$

(8) $$\sum_{z=1}^{Z} \sum_{s=1}^{S} \sum_{k=1}^{K_s} CLTSY_{zsk} X_{zsk} - LTSY = 0$$

(9) $\sum_{z=1}^{Z} \sum_{s=1}^{S} \sum_{k=1}^{K_s} CI_{zskn} X_{zsk} - ACTINV = 0$

(10) $\sum_{z=1}^{Z} \sum_{s=1}^{S} \sum_{k=1}^{K_s} CI_{zsk} X_{zsk} - AVEINV = 0$

(11) $ACTINV - AVEINV > 0$

(12) $\sum_{z=1}^{Z} \sum_{s=1}^{S} \sum_{k=1}^{K_s} CNR_{zskj} X_{zsk} - NETREV_j > 0$ $(j=4,...,n)$

(13) $-NETREV_J + NETREV_{J+1} > 0$ $(J=4,...n-1)$

(14) $X_{zsk}, H_j, > 0$ $\forall s, \forall k, \forall j$

(15) $Y_a \in \{0,1\}$

where:

R_a= the discounted road costs for zone A

Y_a= a variable to indicated if the CAC is in the solution. Y_a is set =1 in order to force a desired CAC.

Z= the number of zones

S= the number of timber stands (analysis areas)

K_s= the number of timing choices for stand s

n= the number of planning periods

C_{zsk}= the present net worth from harvesting one hectare of stand s in zone z under timing choice k

X_{zsk}= the hectares of stand s located in zone z harvested under timing choice k

$AREA_{zs}$= the total hectares of stand s located in zone z

P_{zskj}= the proportion of stand s located in zone z under timing choice k that is made available in period j

$ZONE_z$= the total number of hectares in zone z

W_{zskij}= the hectares of stand s located in zone z, under timing choice k that were made available in period i, but were transferred to period j

H_{zskj}= the volume of timber per hectare yielded from stand s located in zone z under timing choice k in period j

$HECT_j$= number of hectares to be harvested in period j

H_j= the total volume harvested in period j

$CLTSY_{zsk}$= the contribution (volume growth) of one hectare of stand s located in zone z under timing choice k towards LTSY

LTSY= accounting variable that measures long term sustained yield capacity of the solution

CI_{zskn}= the contribution of one hectare of stand s located in zone z under timing choice k to the last period's inventory (before harvest)

CI_{zsk}= contribution of one hectare of stand s located in zone z under timing choice k towards the average inventory (before harvest)

ACTINV= accounting variable that measures the actual inventory (before harvest) in the last period

AVEINV= accounting variable that measures the average inventory (before harvest)

CNR_{zskj}= contribution of one hectare of stand s located in zone z under timing choice k to net revenue in period j

$NETREV_j$= accounting variable that measures the net revenue in period j

The constraint equations are described below.

(1) Land accounting rows for each stand within each zone.

(2) Sum of the areas of the stands within zone A must equal the total area of that zone.

(3) The total hectares made available from the stands in period j must equal the proportion of the zone made available in period j.

(4) Sets a lower bound on the total number of hectares to be harvested in each of the first three periods.

(5) Accounting rows for harvest volume.

(6) and (7) Sequential harvest constraints that allow no more than plus or minus 2 percent variation per period (decades 4-15).

(8) Accounting row to measure LTSY.

(9) Accounting row to measure ending inventory.

(10) Accounting row to measure the average inventory (over all periods)

(11) Ending inventory must be greater than or equal to the average inventory.

(12) Accounting rows to measure net revenue in each period.

(13) Net revenue per decade not allowed to decline (decades 4-15).

(14) Nonnegativity constraints.

(15) The CAC defined by Y_a takes on the value of 0 or 1.

RESULTS

This section is organized in a similar fashion to the methods and procedures section. Results are presented in three main sections corresponding to the objectives of this study. The results of the study have been summarized in tables and figures throughout this section and the appendices. The MCIP program code listing, FORPLAN data, yield, and output files are available upon request from the Department of Forest Management, College of Forestry, Oregon State University, Corvallis, Oregon 97331.

RESULTS FOR OBJECTIVE 1: Determine the long term sustained yield with a fifteen-decade, strata-based LP

The first LP (labelled LP1) was constrained by NDY, volume less than or equal to LTSY, and an ending inventory constraint. The volumes and net revenues produced under this formulation are shown in figure 5.

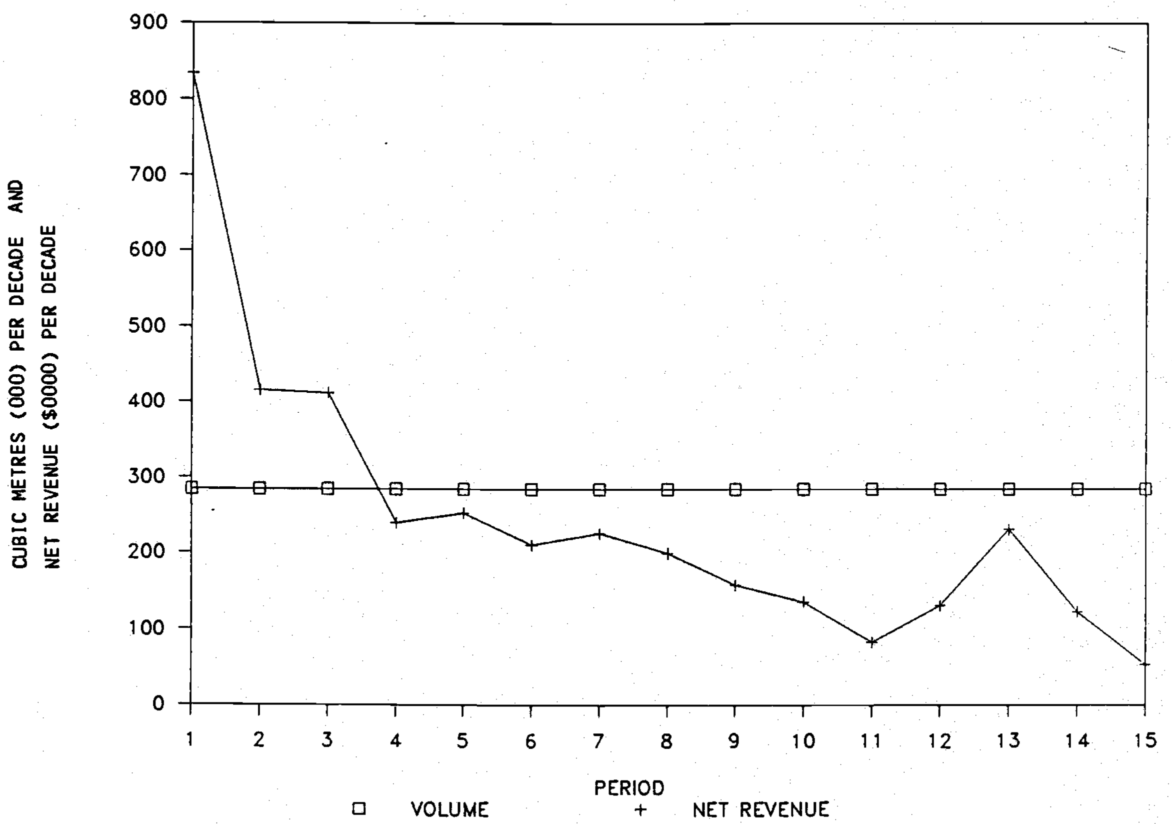


Figure 5. LP1: Volume and net revenue produced from the entire forest under nondeclining yield.

In figure 5, note the sharp decline in net revenue as the valuable stands are exhausted. Revenues continue to decline until high site, regenerated stands become available for harvest in period 12. Revenues again decline after these stands are cut. The volume produced each decade was 285,500 m^3, which is also the long term sustained yield. The PNW of this schedule was $12,416,100. More detailed data from the solution of LP1 are found in Appendix 4.

The second LP formulation (LP2) had the same constraints as LP1, but in addition, timing choices were used to forced all harvesting to be within zone A during the first three periods. There were a number of these LP's run with increasingly more stands added to zone A, until the volume did not change during the transition to zone B. LP2 was the final formulation in this series that established the size of zone A. Figure 6 shows the resulting volume and net revenue flows over time. Appendix 5 contains additional information relating to the LP2 solution.

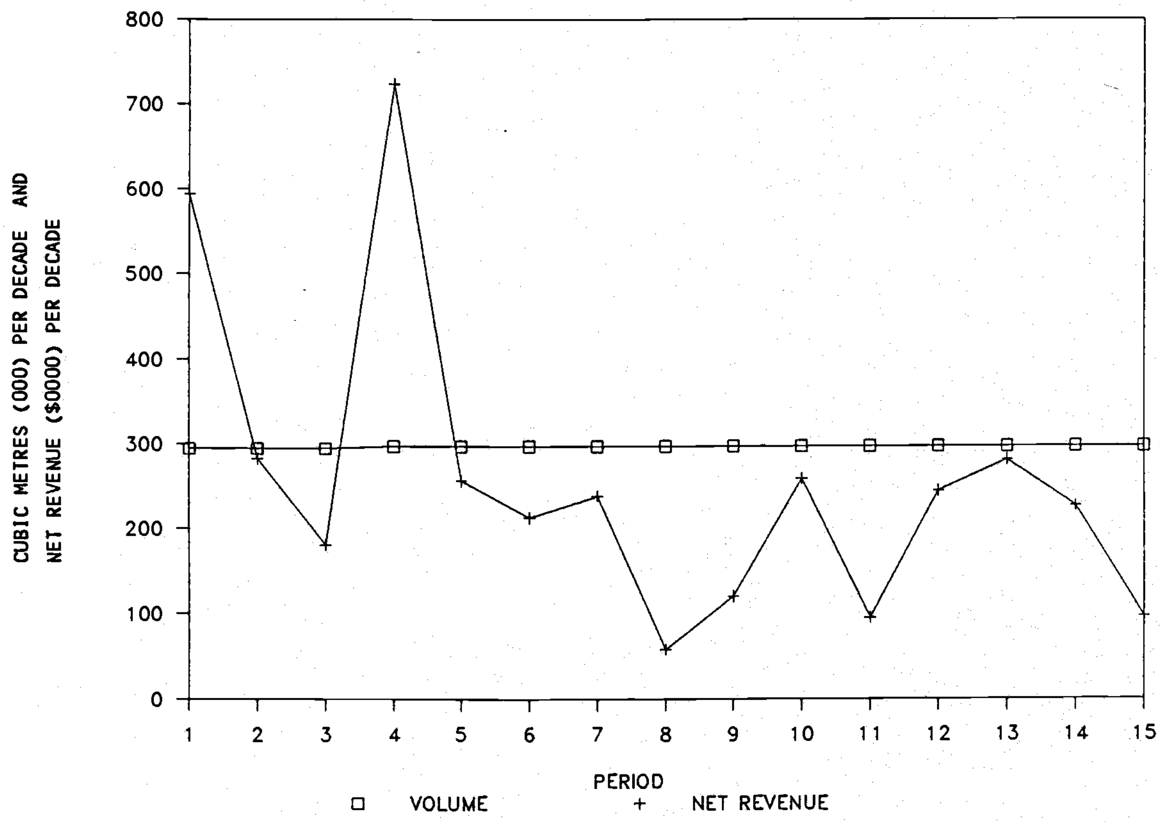


Figure 6. Solution to LP2: Volume and net revenue produced under NDY plus harvests in periods 1 through 3 restricted to zone A.

In figure 6, there is a very slight step upwards in the NDY at period 4, however, this result was felt to be sufficiently accurate for our needs. Net revenue drops sharply in the first three periods, and then rises dramatically as high valued stands in zone B become accessible. These stands are rapidly depleted, and net revenue declines until the availability of regenerated stands cause it to fluctuate in the latter periods. The volume cut was 294,240 m^3/decade and 296,970 m^3/decade for periods 1 to 3 and periods 4 to 15 respectively. The PNW of LP2 was $10,049,400.

As mentioned above, LP2 also established the size and composition of zone A. In terms of the initial inventory, this represents 42.6% and 61.9% of the total area and total volume respectively. Figures 7 and 8 illustrate these statistics.

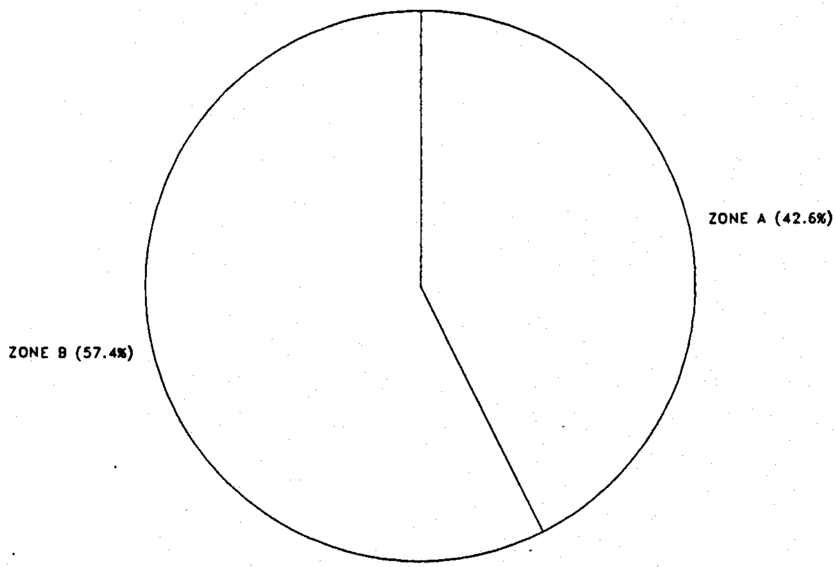


Figure 7. Distribution of total area by zone.

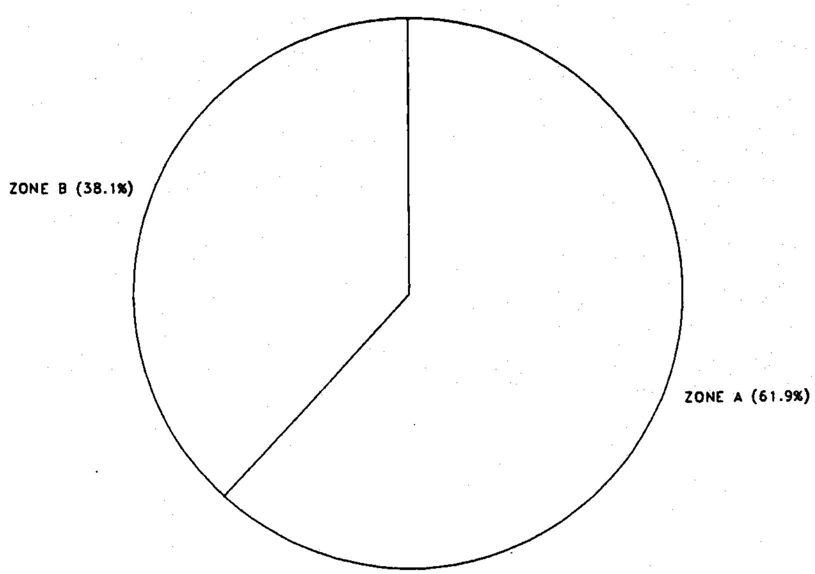


Figure 8. Distribution of total initial volume by zone.

The large fluctuations in net revenues that resulted from LP2 were judged to be unacceptable in terms of consistency in cash flows. Therefore, constraints were added to this formulation to smooth out the cash flows over time. LP3 was formulated similar to LP2, except that a minimum level of net revenue was required in each period. The link with LTSY was needed to prevent excessively high harvests at the end of the planning horizon. A lower bound of $250,000/period was set for the minimum net revenue after several trials. This lower bound still leaves two peaks in the cash flows (periods 1 and 4), however, raising this bound further causes sharp reductions in the volume produced during the early periods. The problem of balancing volume and cash flows will be dealt with in the section titled "Discussion of Results". The volume and net revenues produced under the LP3 formulation are illustrated in figure 9, and supplemental information is provided in Appendix 6.

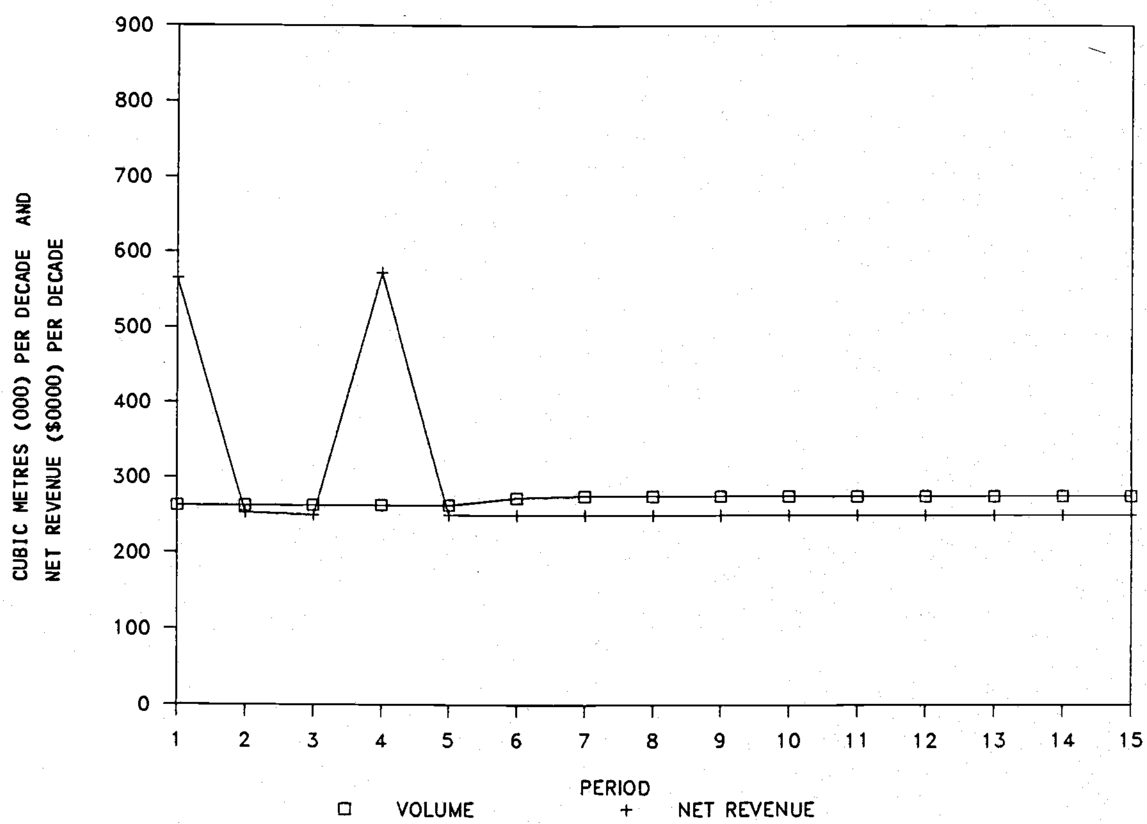
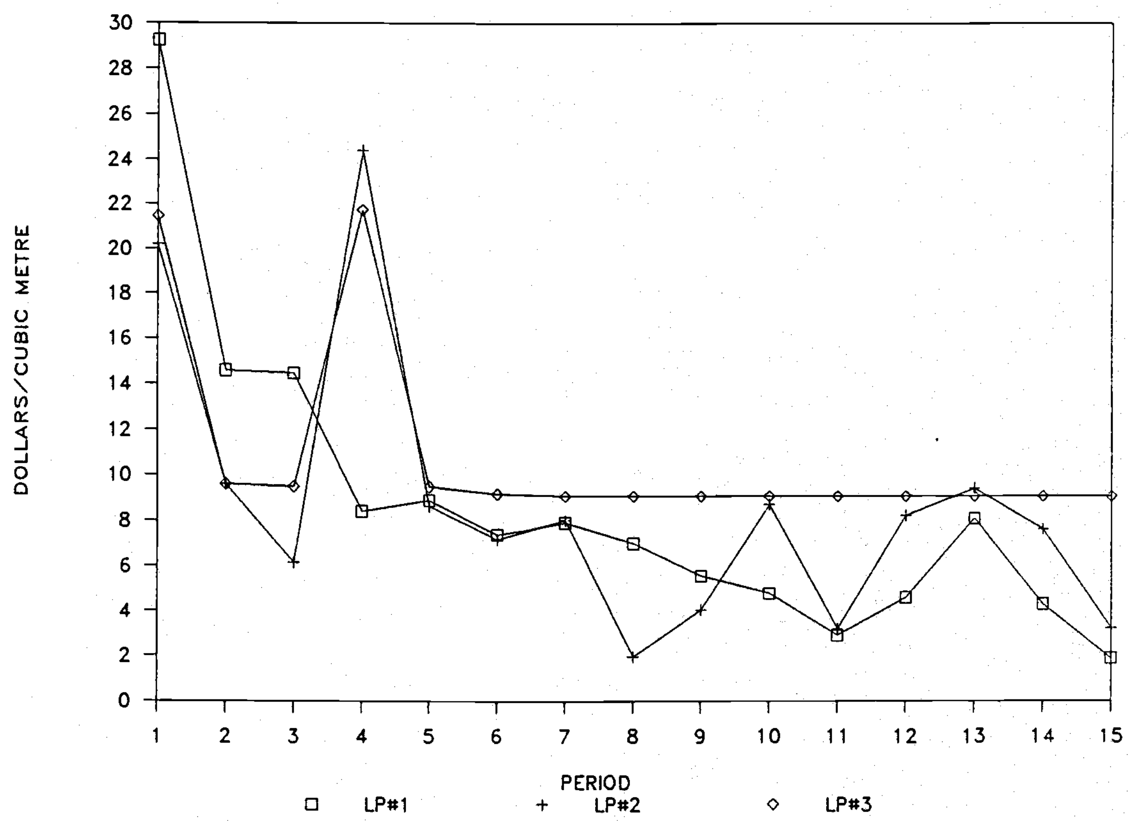


Figure 9. LP3: Volumes and net revenues produced under NDY, period 1 to 3 harvests from zone A, and a minimum cash flow/period.

Figure 10 graphically displays how the average net revenue per m^3 is affected by the various constraints that were included in each formulation (LP1,LP2, and LP3).



<u>Figure 10. Graph of the average net revenue per m^3 for LP1, LP2 and LP3.</u>

At this point, we have come as close as we can to solving the harvest scheduling problem with strata-based planning. It is therefore appropriate to map the first three periods of the LP3 solution as a test for spatial feasibility. This is done in figure 11, which demonstrates that the solution is not spatially feasible. Figure 11 is based on the information contained in table 18 which is located in Appendix 6. This solution violates the maximum clear cut size, and it does not correspond to the harvest unit boundaries that were established by area-based planning. It is possible to identify the harvested areas on figure 11 because virtually all of the hectares within each AA were cut. If only portions of the AA's had been cut, it would be impossible to show a unique harvesting pattern of the LP3 solution.

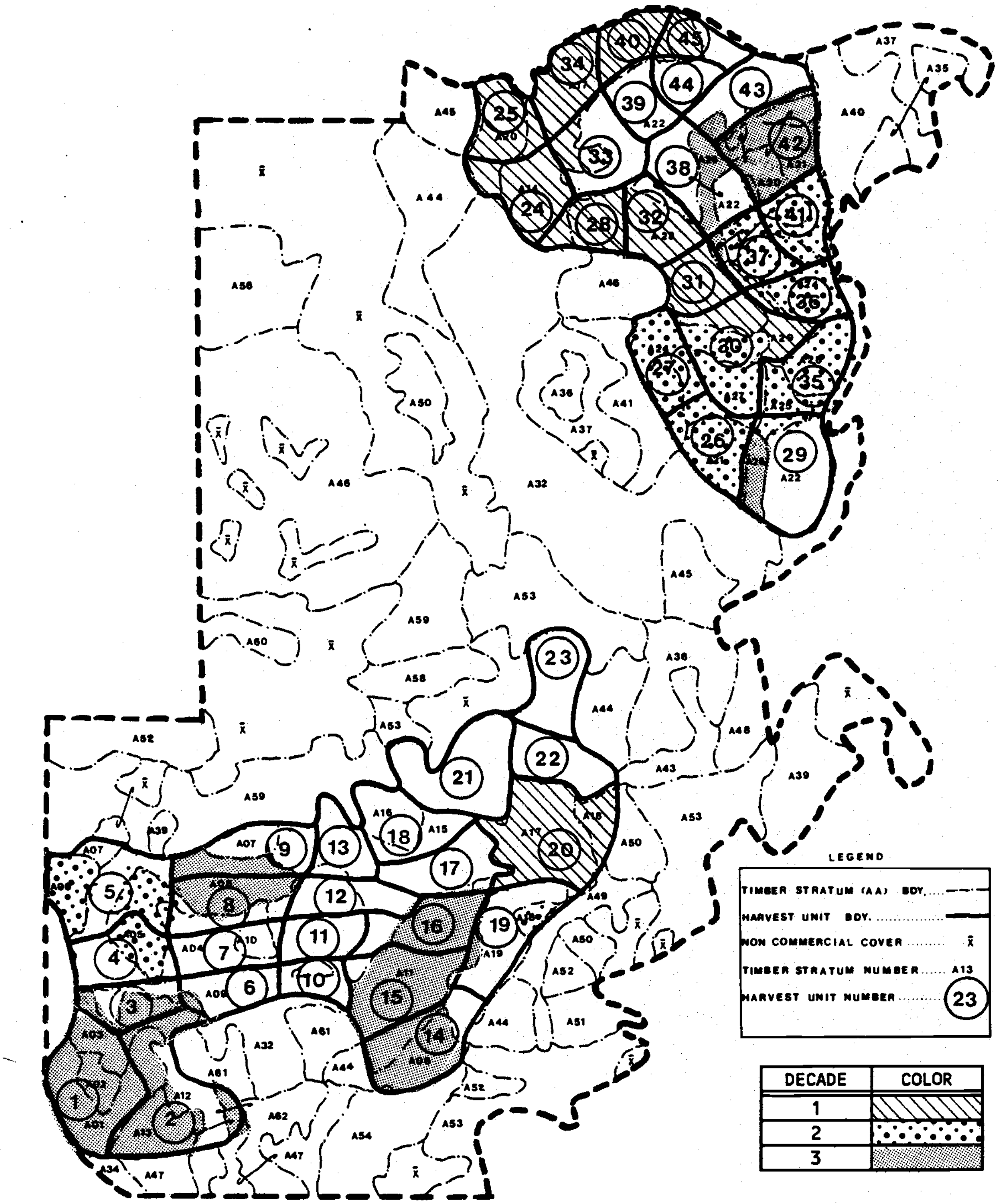


Figure 11. Map of the first three-decade harvest of LP3, showing the lack of spatial feasibility.

The results of LP3 justify the need to introduce spatially feasible area-based plans into the harvest schedule. The LP3 solution does provide some useful information in the form of volume and net revenue targets for the area-based planning phase. Since we will no longer be dealing with continuous variables, tolerances must be provided for the discrete solutions that will be provided by the MCIP. The LTSY from LP3 was 276,000 m^3/period, and the minimum net revenue was $250,000/period. As outlined in the procedures section, the volume must lie within -5% and +10% of the LTSY, which corresponds to approximately 263,000 m^3 and 304,000 m^3 respectively. Net revenues must be greater than or equal to $250,000/period, as in LP3.

Finally, it is interesting to note that the area cut/period in LP3 is generally under 425 hectares, with only three exceptions (table 17, Appendix 6). In testing the MCIP, it was found that on average, 425 hectares was the maximum area that could be cut without violating adjacency constraints. Since the areas cut in LP3 are mostly well below this limit, it was not necessary to set an upper bound on total hectares harvested per period.

RESULTS FOR OBJECTIVE 2: Determine three best area-based plans with MCIP

Two hundred unique solutions were found by the random search method. These are temporary solutions, as defined in the procedures. A list of the objective function values of these solutions are found in table 19, Appendix 7. Figure 12 is a frequency distribution of the values of the objective function (PNW) for the 200 MCIP temporary solutions.

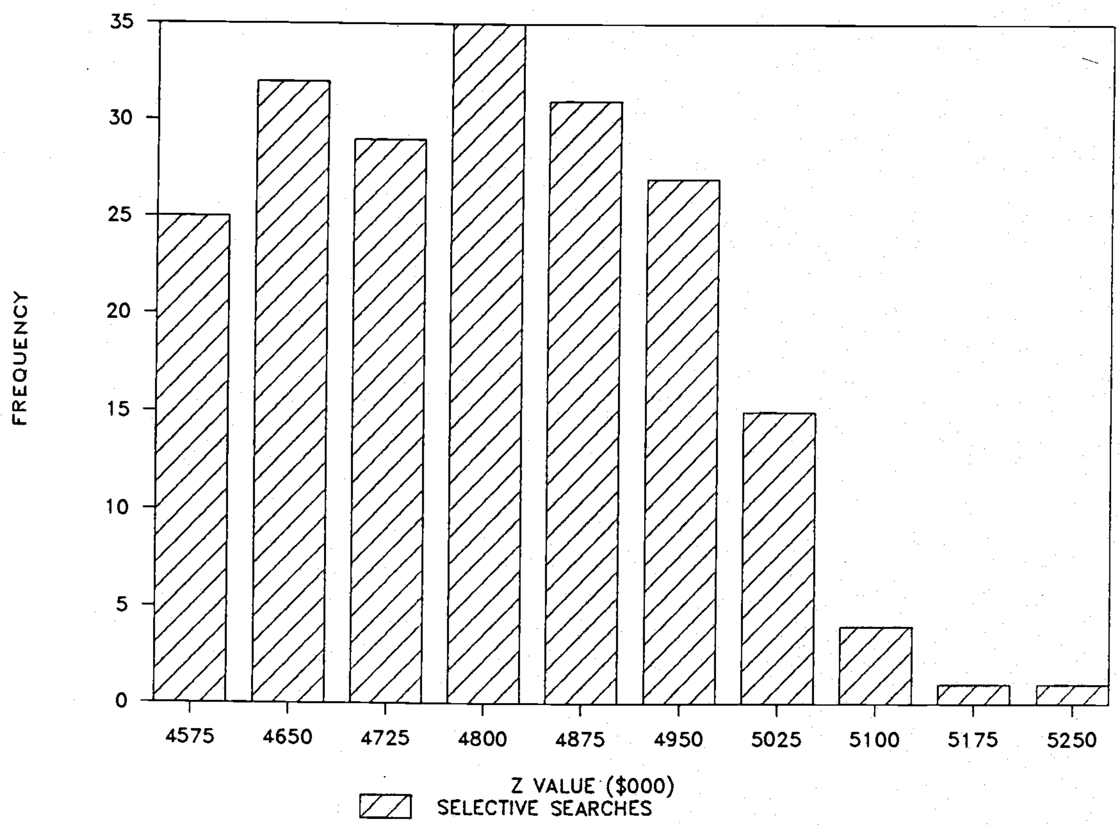


Figure 12. Frequency distribution of the PNW's of 200 MCIP temporary solutions found with the random search method.

The three solutions with the highest PNW found in the random search method are summarized in table 1. They are labelled TS1, TS2,and TS3 (TS for Temporary Solution). Detailed summaries of these solutions, including the road projects undertaken, are found in tables 20 through 22,located in Appendix 7.

Table 1. Summary of random search MCIP temporary solutions TS1, TS2, and TS3

	TS1			TS2			TS3		
	HARVEST UNITS PERIOD 1	HARVEST UNITS PERIOD 2	HARVEST UNITS PERIOD 3	HARVEST UNITS PERIOD 1	HARVEST UNITS PERIOD 2	HARVEST UNITS PERIOD 3	HARVEST UNITS PERIOD 1	HARVEST UNITS PERIOD 2	HARVEST UNITS PERIOD 3
	4	1	2	2	4	1	3	1	2
	9	5	7	7	11	6	5	4	8
	20	6	15	13	17	9	12	9	14
	30	12	27	14	24	15	18	15	22
	32	14	28	20	27	18	20	21	27
	34	18	29	23	29	30	24	25	28
	42	22	36	25	32	34	30	26	35
	45	24	38	26	36	38	32	31	37
		26	40	28	40	45	41	40	43
		31		31	42		45	42	
		39		41					
		41		43					
HECTARES	348	444	363	463	355	382	405	400	354
VOLUME (000)	266	301	264	296	280	270	280	276	274
NET REV.($000)	319	267	284	303	299	277	310	259	281
PNW ($000)	5168			5189			5043		

TS1, TS2, and TS3 provided the first period harvest patterns that were used as a starting point for the selective search method. Selective searches were conducted on each of these temporary solutions until five additional ones were found. The solutions with the highest PNW originating from TS1, TS2, and TS3 were labelled PS1, PS2, and PS3 respectively (PS for permanent solution). Table 2 summarizes these results, which are fully documented in tables 23 through 28, found at the end of Appendix 8.

Table 2. Summary of selective search MCIP permanent solutions PS1, PS2, and PS3.

	PS1			PS2			PS3		
	HARVEST UNITS PERIOD 1	HARVEST UNITS PERIOD 2	HARVEST UNITS PERIOD 3	HARVEST UNITS PERIOD 1	HARVEST UNITS PERIOD 2	HARVEST UNITS PERIOD 3	HARVEST UNITS PERIOD 1	HARVEST UNITS PERIOD 2	HARVEST UNITS PERIOD 3
	4	1	2	2	4	1	3	4	1
	9	5	7	7	11	6	5	9	6
	20	6	13	13	17	9	12	10	8
	30	12	25	14	24	15	18	14	15
	32	15	27	20	27	18	20	22	27
	34	24	28	23	29	30	24	25	29
	42	26	29	25	32	34	30	26	34
	45	31	36	26	36	38	32	28	36
		39	38	28	40	45	41	31	38
		41	40	31	42		45	39	
				41				42	
				43					
HECTARES	348	378	369	463	355	382	405	397	383
VOLUME	266	268	273	296	280	270	280	291	292
GROSS MARGIN	3638	3194	3243	3608	3307	3171	3692	3262	3129
MAIN RD. COST	245	170	145	289	138	201	375	101	126
SEC. RD. COST	206	164	182	290	178	200	213	240	183
NET REVENUE	319	286	292	303	299	277	310	292	282
PNW	5302			5189			5230		

The results of the area-based planning problem, including the random and temporary searches, are summarized in figure 13.

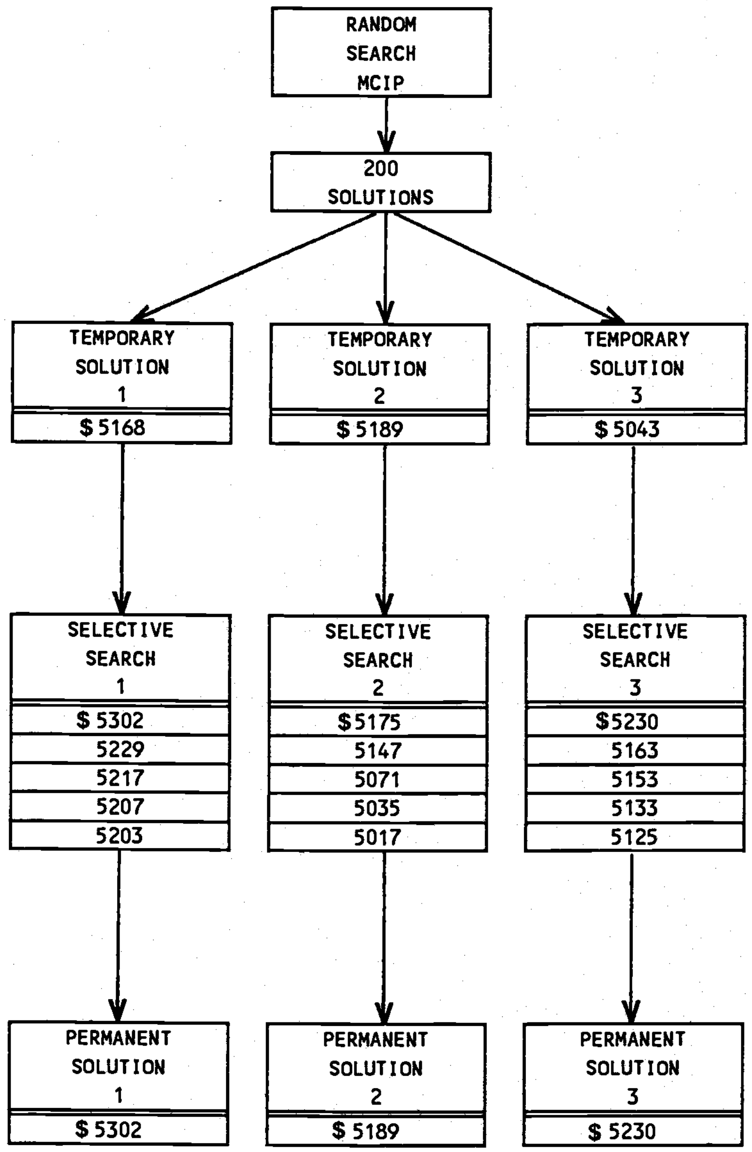


Figure 13. Summary of results obtained from the random and selective search MCIP's.

Figures 14, 15, and 16 are maps showing the harvesting patterns for PS1, PS2, and PS3 respectively.

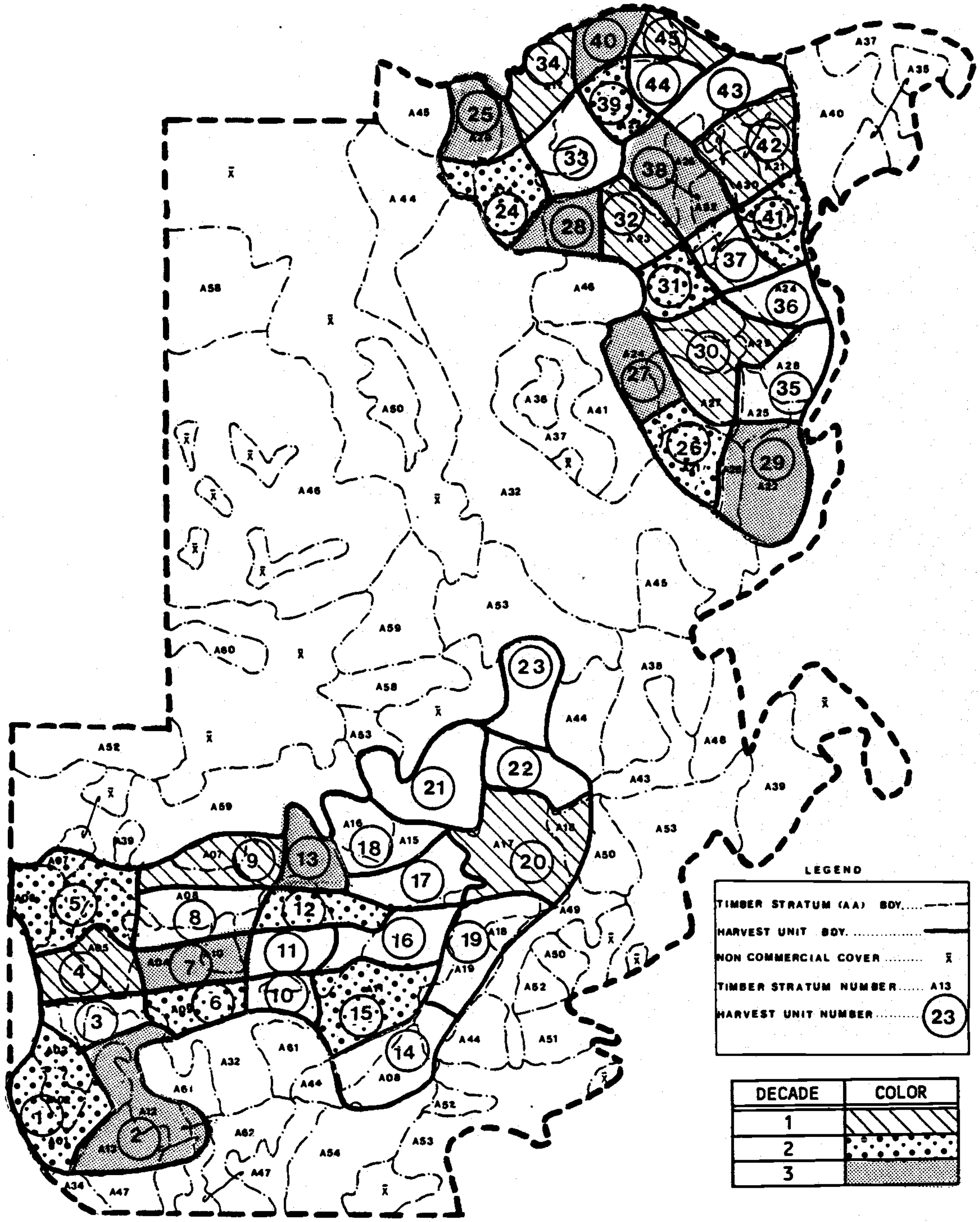


Figure 14. Map showing the harvesting pattern of PS1.

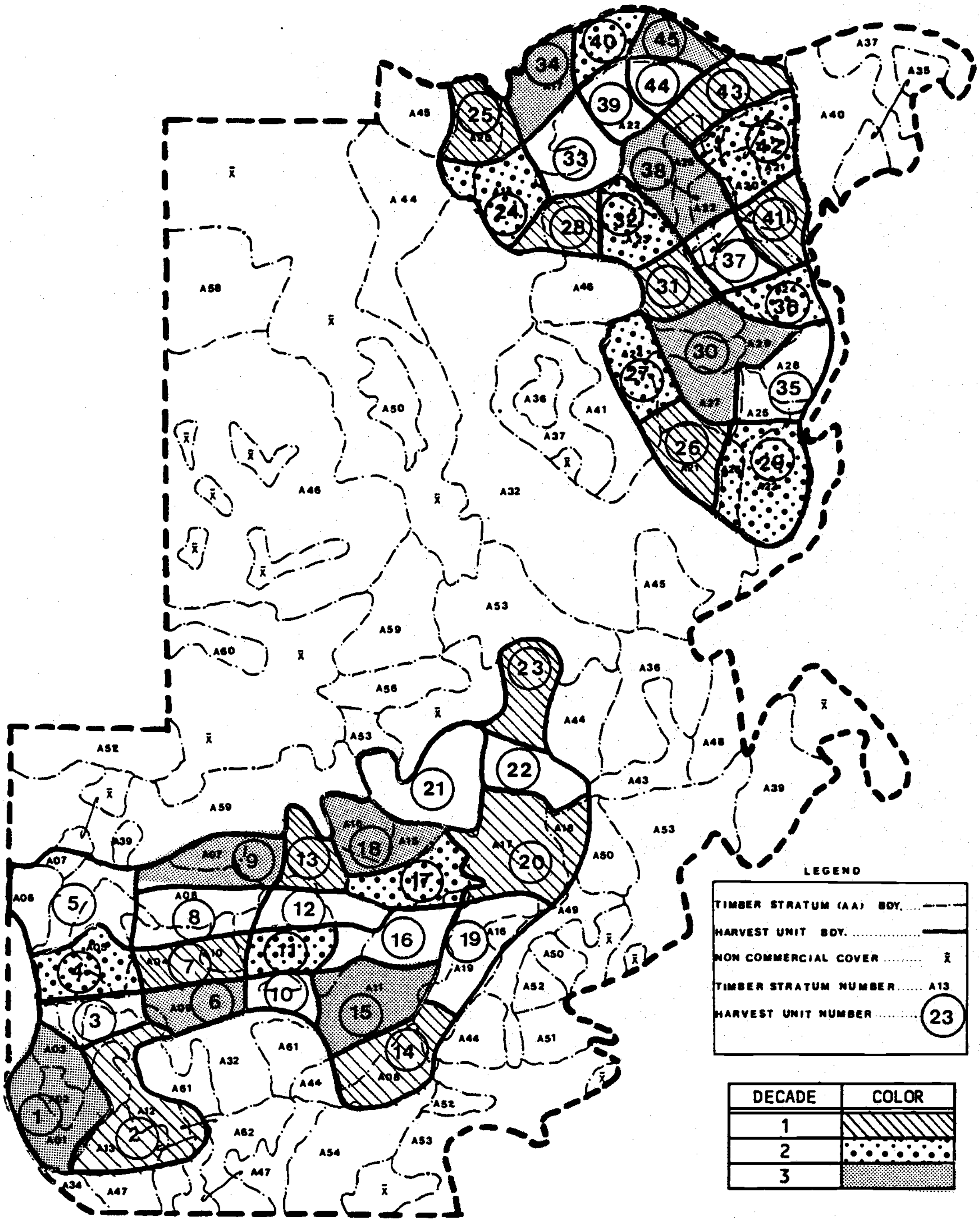


Figure 15. Map showing the harvesting pattern of PS2.

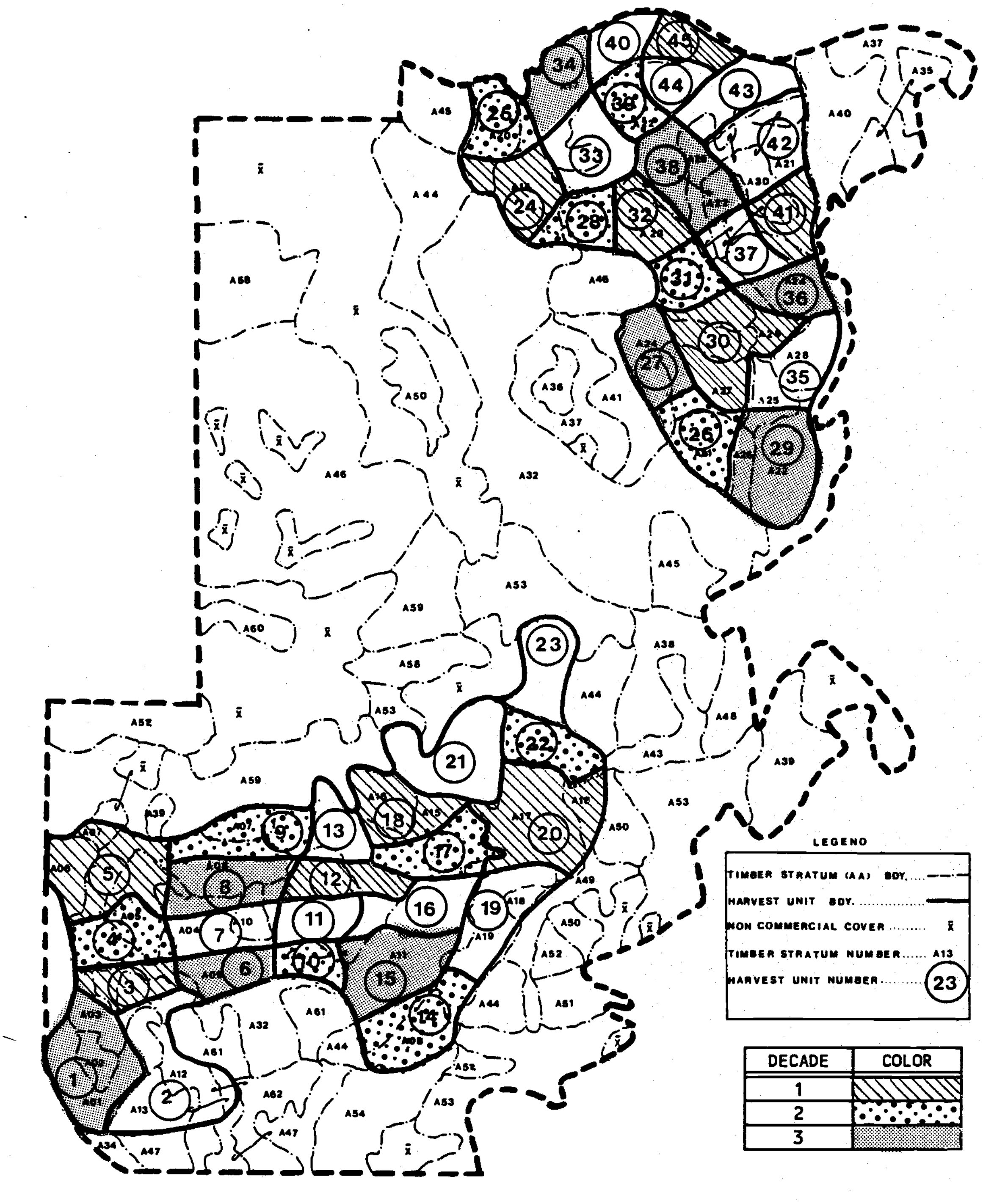


Figure 16. Map showing the harvesting pattern of PS3.

The results of the selective searches provided PS1, PS2 and PS3, which are the highest valued area-based plans that were found with the MCIP technique. These spatially feasible alternatives make up the CAC's within the final FORPLAN models used to integrate area and strata-based plans.

RESULTS FOR OBJECTIVE 3: Integrating area-based and strata-based plans

The solutions for the three integrated plans are labelled ILP1, ILP2, and ILP3 (ILP for integrated linear program). Figures 17, 18, and 19 show the volume and net revenue per period for ILP1, ILP2, and ILP3 respectively. Appendices 9 through 11 contain the detailed information corresponding to these solutions. Hectares harvested by AA, site class, logging system, age class, zone, and species are contained in each of these appendices.

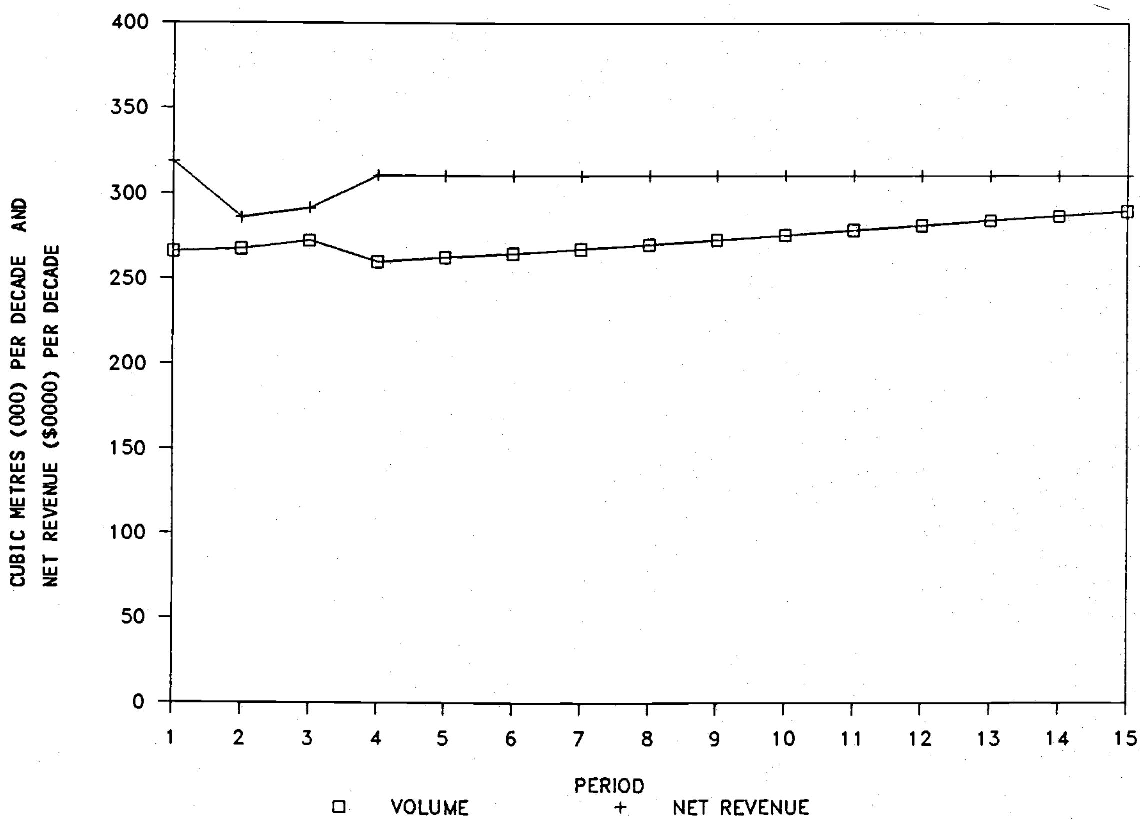


Figure 17. Volume and net revenue produced from ILP1.

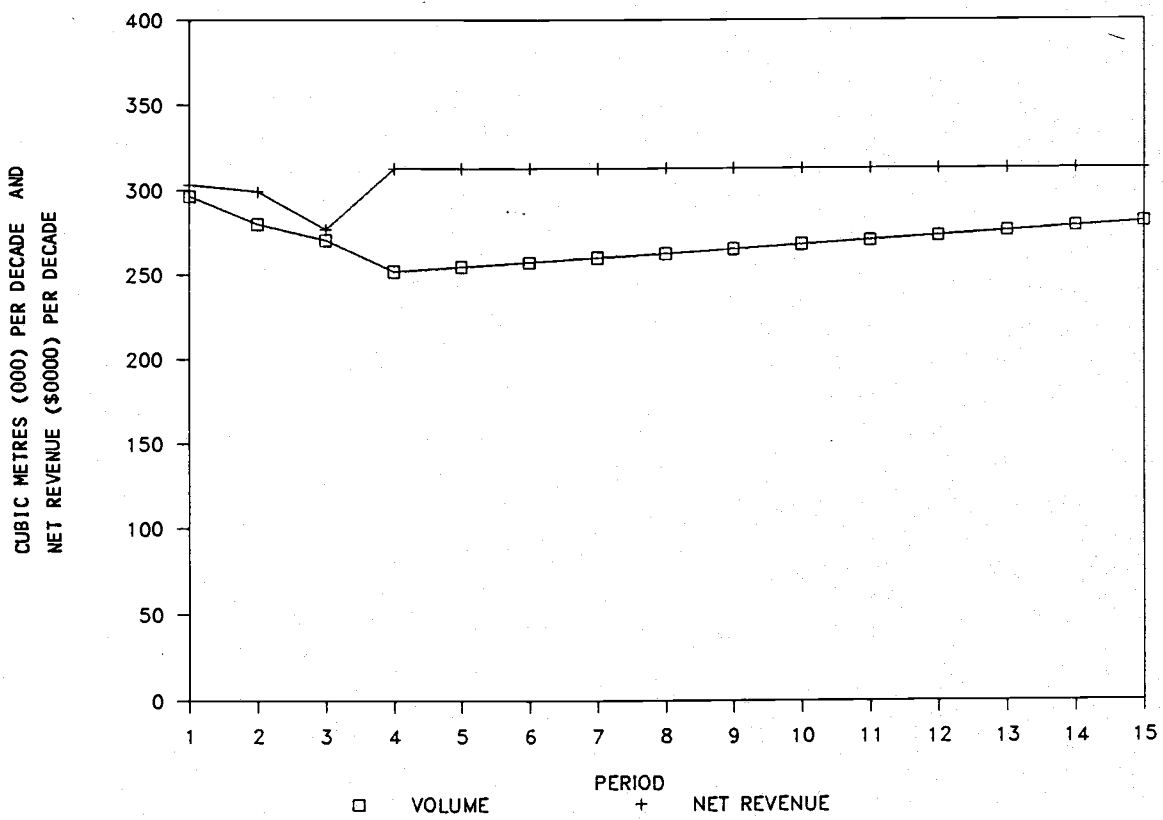
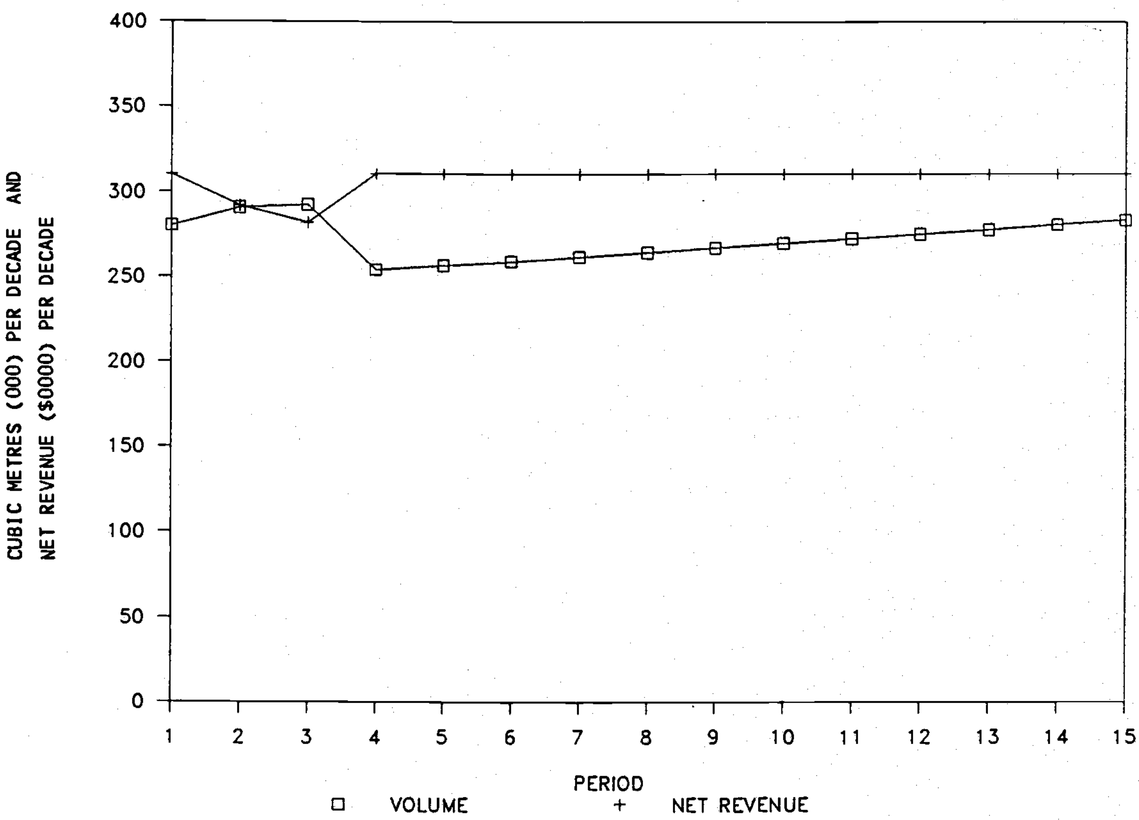


Figure 18. Volume and net revenue produced from ILP2.



<u>Figure 19. Volume and net revenue produced from ILP3.</u>

Table 3 summarizes the volume produced from the three integrated plans.

Table 3. Summary of volumes produced from ILP1, ILP2, and ILP3 (figures in thousands of cubic metres).

DECADE	ILP1	ILP2	ILP3
1	266.23	296.46	280.31
2	267.93	280.1	290.75
3	272.63	270.49	292.46
4	260.05	252.24	254.05
5	262.65	254.76	256.59
6	265.28	257.31	259.15
7	267.93	259.89	261.74
8	270.61	262.48	264.36
9	273.32	265.11	267
10	276.05	267.76	269.67
11	278.81	270.44	272.37
12	281.6	273.14	275.1
13	284.42	275.87	277.85
14	287.26	278.64	280.62
15	290.13	281.42	283.43
DECADES 1-3	806.79	847.05	863.52
DECADES 4-15	3298.11	3199.06	3221.93
DECADES 1-15	4104.9	4046.11	4085.45

Table 4 provides a financial summary of the three integrated plans.

Table 4. Net revenue of IPL1, IPL2, and IPL3 ($0000).

DECADE	ILP1	ILP2	ILP3
1	318.7	302.9	310.4
2	286	299.1	292
3	291.6	276.9	282
4	310.84	312.66	310.51
5	310.84	312.66	310.51
6	310.84	312.66	310.51
7	310.84	312.66	310.51
8	310.84	312.66	310.51
9	310.84	312.66	310.51
10	310.84	312.66	310.51
11	310.84	312.66	310.51
12	310.84	312.66	310.51
13	310.84	312.66	310.51
14	310.84	312.66	310.51
15	310.84	312.66	310.51
DECADES 1-3	896.30	878.90	884.40
DECADES 4-15	3730.8	3751.92	3726.12
DECADES 1-15	4626.38	4630.82	4610.52
PNW	770.74	760.92	763.39

DISCUSSION OF RESULTS

The following section discusses the results of the three main objectives of the study, which are, first, strata-based planning to get strategic harvest levels, second, area-based planning to get short-term spatially feasible plans, and third, integrated strata/area-based planning which combines the two approaches.

Discussion of strata-based LP's

The results of the integrated plans show that LTSY and PNW are overestimated using the strata-based approach. It is important to note that the LTSY figures used here are those reported by the FORPLAM model. The traditonal definition of LTSY is the constant growth potential of the forest under specific rotations and management intensities. FORPLAN reports LTSY as the growth potential for a specific LP solution, and since rotations are allowed to vary according to the optimization procedure, the LTSY will also change with different LP solutions. As constraints are added and the model is refined to include the area-based plans (ILP's), LTSY and PNW drop. Table 5 provides LTSY and PNW figures for comparing the LP and ILP solutions.

Table 5. Comparison of LTSY and PNW figures.

	LP1	LP2	LP3	ILP1	ILP2	ILP3
LTSY (m^3/year)	28500	28000	27600	27330	27190	27230
PNW ($ million)	12.42	10.05	9.73	7.74	7.61	7.63

The constraints in LP3 that restrict access to zone A and place a lower bound on net revenue/decade give a more realistic estimate of LTSY and PNW. The LP3 solution proved to be sufficient for estimating strategic harvest levels, however, the optimal basis (i.e. which stands to harvest over time) is not an operationally feasible alternative. As demonstrated in figure 11, the LP3 solution violates clearcut size and adjacency constraints.

The net revenue constraint added in LP3 works towards generating a solution that is more stable over time. If a series of LP's (with NDY as the only constraint) are solved sequentially at future planning periods, so that the first decade solutions provide beginning inventories to subsequent LP's, both volumes and revenues are likely to decline over time. This situation has been called the declining even flow effect (DEFE) by MacQuillan (1986). It occurs when negative valued stands exist in the forest, and a discount rate is applied to future cash flows. Because discounting favors immediate cash flows over future returns, the best stands are cut immediately, and the low valued timber is scheduled for harvest in the distant future. The discount factor applied to these stands is very small, and they have little impact on the PNW of the schedule. With the passage of time, the best stands are depleted, and the poor stands make up a greater proportion of the inventory. These poor stands can no longer be pushed off into latter decades, and now the discount factor is much higher, causing them to have a significant impact on PNW. The net effect is that the poor stands will not be cut because they would lower the PNW of the harvest schedule, thus causing a drop in the volume harvested (hence the DEFE). No negative valued AA's were encountered in this study, but the result applies in a parallel fashion for the very low net revenue stands that were included.

In the integrated plans that were developed for this study, it was possible to eliminate discounting because of the way in which the problem was formulated. With the first 3 decades fixed as a result of the area-based plan, the problem then became one of finding the largest, uniform cash flow that could be maintained from decades 4 through 15. As mentioned earlier, the discount rate is irrelevant in determining the optimal schedule under this formulation. The resulting cash flows are then discounted to give the PNW of the entire schedule, which is the appropriate measure on which to judge the economic viability of the alternatives. These efforts directed at maintaining not just volume, but also net revenues are important steps at overcoming the DEFE.

Figures 42, 49, and 59 show the distribution of site classes harvested over the planning horizon for each ILP, and illustrate that low valued stands get cut in the early decades as well as the latter decades. This trend is also apparent in figures 41, 51, and 61 which illustrate that the cheaper skidder logging areas are spread out over the 15 decades, rather than bunched into the first few decades. The net revenue constraint is providing this mix of stands so that "high grading" does not occur as it does prevalently in LP's lacking this restriction.

In hindsight, it would have been more consistent with the long-term plan if the objective function of the area-based plan had been to maximize the total undiscounted cash flow, rather than PNW. Discounting favored those solutions with a high net revenue in decade 1, and lower returns in decades 2 and 3 (see figures 17, 18, and 19). To be consistent, maximum undiscounted solutions should have been put into the ILP's, and the resulting cash flows discounted to PNW for comparison purposes.

One final observation concerning the LP formulations involves the problems that can arise if NDY is combined with nondeclining net revenues. In the LP portion of the study, NDY was used because it provided a good indicator as to how large zone A (the zone containing the harvest units) needed to be in order to provide sufficient volumes for the first 3 decades. In trial runs where the minimum net revenue was continually raised, it was noted that the volumes cut increased dramatically from a very low level over the planning horizon. In fact, decade 1 volumes were as low as 120,000 m^3, which rapidly increases to around 300,000 m^3 by decade 3. This same trend occurred in trial runs with the ILP's, but the drop occurred in decade 4, and increased by decade 6.

As proposed earlier, this high variance in volume production happens because low valued stands cannot be cut in early periods without causing the volume to decline. The model therefore cuts a low volume at the start (the high valued stands), and increases the cut as it makes up the necessary revenue from the lower valued stands. It was for this reason that the ILP's were formulated with a sequential volume constraint that overcomes the problem. Volumes still rise steadily over time under the ILP formulations, and this is probably because the stands on high sites need to be cut early so that these hectares can provide regenerated stands as soon as possible. The high growth sites tend to support high volume and high net revenue stands, so the early cuts are somewhat lower than subsequent harvests.

Discussion of area-based plans and MCIP

Focussing on the area-based plans now, this study has demonstrated that the MCIP algorithm is an effective way to generate integer solutions. The MCIP program has about 800 statements (includes input data and print statements). It takes about 1.5 seconds to find alternatives that satisfy adjacency and volume constraints. This average time per solution remained constant for the sample problem (20 units) and for the study problem (45 units), suggesting that the MCIP technique is not very sensitive to the number of integer variables. When the net revenue constraint was added, solution time increased to about 8 minutes, which is a clear indication that there was a major reduction of the feasible region of the problem. The results of the sample problem in Appendix 1 were excellent, but there is no way of knowing how close the MCIP came to the true optimum for the 45 unit problem in this study. This problem has almost 300 integer variables, which exceeds the limit of 200 allowed for in Hyper-LINDO/PC, so there is no way to find the MIP solution without resorting to a mainframe computer integer program. The difficulties that Moore and Nielson (1987) documented when they used IRPM on a smaller problem was deemed sufficient reason not to continue searching for the optimal solution.

The idea of using a linear programming solution as an upper bound on the objective function value of the area-based plan was rejected. The splits that occur in road and harvest unit variables are meaningless, and the value of the objective function is grossly overstated. This was the case in the sample problem found in Appendix 1. The LP solution was valued at $1,125,140 and the MIP solution was $805,000 (71% of the LP). Jones (1988) has also come to the same conclusion after examining integer solutions using IRPM and heuristic methods.

Regardless of what the optimum really is, the MCIP algorithm is a major improvement over manually identifying feasible alternatives. It is also a simple algorithm requiring less expertise than MIP. How well it will perform on more complex planning problems where wildlife cover, sediment and road budget constraints are imposed is a problem identified for further research. The MCIP technique could be applied to logging scheduling problems. For example, once the first decade schedule has been set, the annual schedule must be developed using settings within the harvest units.

Another project that should be undertaken is to determine if better results could be obtained by maximizing the area-based plan period by period. This approach would find the best solution for period 1 only, then using this solution find the best solution for period 2, and finally examine period 3 with periods 1 and 2 fixed. It is similar to the selective searches used in this study that generally found better solutions over the random search approach. Whether this new approach would find better alternatives or just "highgrade" the harvest units in the early periods remains to be seen.

Two other concerns regarding the selective searches have been observed. First, one of the objectives of doing the selective searches was to identify alternatives that allow flexibility for change in the future. By selecting only the high valued solutions, it is implicitly assumed that all the problem coefficients and parameters have not changed, which is really a contradiction to the objective. This is especially true for economic data which tends to be the most difficult to predict. As a defense to this argument, it is proposed that the selective searches have identified other options that meet adjacency and volume requirements, and even though economic factors may change, the physical alternatives still exist for adapting a revised plan. The second concern is that not all the alternatives identified in the selective search were tested for their long-term feasibility. It is noted that 3 very different area-based plans were used in the ILP's, and all proved to be feasible over the planning horizon. Likewise, during the preliminary work with ILP's several other quite different area plans were tested and found to be acceptable over the long-term. It is therefore argued that the selective search alternatives, which share a common first decade harvest pattern with the area-based plans actually used, would also be feasible when tested over the entire 15 decades.

Figure 12 and table 19 summarize the random search MCIP solutions, and figure 13 illustrates the results of the entire MCIP procedures. It is interesting to note the number of alternatives that exist with PNW's at least as large as $5 million (figure 12).

Discussion of the integrated plans

The ability of FORPLAN to handle area-based solutions through coordinated allocation choices (CAC's) certainly eased the difficulty involved in generating the ILP's. Specific portions of stands can be forced into the solution and local costs (rather than averages) can be included. The resulting plans are spatially feasible in the short-term and they are also capable of supporting long-term harvests. All 3 ILP's are very similar in terms of PNW and also in terms of the type of stands harvested in decades 4 through 15 (see figures in Appendices 9-11). The similarity comes from the homogeneity of the existing second-growth forest, and the large percentage of high site hectares. The high sites rapidly produce regenerated stands following cutting, thus providing consistent inventories in the latter decades. In a more heterogenous forest, the ILP's would be less similar.

Based on the results of this study, the best plan to implement is ILP1. It has a slightly higher PNW than the other two integrated plans. It also has the highest valued alternative area-based plans that were found with selective searches (see figure 13). It is stressed that this decision is based on the data used, and as previously cautioned, many assumptions were used, especially regarding the existing inventory and growth projections. It has been demonstrated that the procedures used in this study are useful in creating better forest plans, and it would be worthwhile to spend more time collecting accurate data to use in the model.

The ILP's had approximately 1900 variables and 140 rows. It takes about 20 minutes to generate the ILP matrix and about 1 hour for LINDO to solve the ILP.

One of the most perplexing problems relating to this study and forest planning in general, is how useful is the strata-based portion of the plan. We know that it will not be spatially feasible, but it does give some strategic goals to work with. It would be interesting to investigate what would happen if the entire 15 decades were solved as an area-based plan. An argument against this approach is that no one knows what technology will prevail in the future, so it is not possible to specify future harvest units based on current practices. Conversely, the basic principles of harvest planning are likely to prevail, and with growing environmental concerns, it is unlikely that harvest unit size will increase. This suggests that small units will be scheduled for cutting in a pattern that must conform to the adjacency restrictions used in this study.

MCIP may be an effective technique for solving this difficult problem. It is possible to partition the entire forest into zones that contain the specific harvest units. MCIP could generate area-based plans for these zones, and these could in turn be combined to create a spatially feasible plan for the entire forest. One important difference in this approach as compared to the ILP method is that specific rotations would be needed for the harvest units. A regenerated stand would not be cut independently of the other stands that make up the harvest unit. In other words, the cutting pattern for existing stands would repeat itself on the regenerated stands. Solving the entire forest plan using an area-based approach is a project identified for further research.

CONCLUSIONS AND RECOMMENDATIONS

Procedures were developed for integrating short-term, area-based plans with long-term, strata-based harvest schedules. These procedures were tested on a 4000 hectare tract of forest land in British Columbia. It was shown that a combination of these two approaches to forest planning provides a spatially feasible short-term solution that is also feasible in terms of strategic harvest goals over the long-term. All the models used were implemented on a microcomputer, which allows this type of planning to be done at the logging division level. By decentralizing planning, more realistic plans can be developed because divisional foresters and engineers are more familiar with the potential and limitations of their local forests.

Three basic steps are used to develop integrated area and strata-based plans. First, a 15-decade strata-based linear program is used to determine strategic volume and net revenue targets needed for area-based planning. Second, Monte-Carlo integer programming is used to randomly select harvest units in a search for feasible solutions to a three decade area-based plan. The highest valued area-based plans are then forced in as the first three-decade solution in a 15-decade linear program. The linear programs are solved using FORPLAN.

The conclusions drawn from this study are:

1. Strata-based linear programs are useful for establishing strategic harvest goals, but they do not provide a spatially feasible plan that can be implemented on the ground. These linear programs overstate the long term sustained yield and the present net worth of the harvest schedule.

2. Constraints that prevent net revenues from declining over time can be added to the linear program. Under this formulation, the discount rate is not a factor in determining the optimal harvest schedule. The discount rate is used only to calculate the present net worth of the cash flows generated from the schedule.

3. Monte-Carlo integer programming is an effective technique for generating feasible solutions to large integer problems encountered in area-based planning. It was tested on two problems, one with 132 integers and one with 280 integer variables. Over this range, solution time did not appear to be very sensitive to the number of integer variables. While MCIP does not guarantee an optimal solution, the technique is a major improvement over manual methods. It is also a practical alternative to mixed-integer programming, where the cost of finding

the true optimum is prohibitive.

4. Flexibility is built into the area-based plans though the selective search MCIP's that identified alternative cutting patterns.

5. Through random and selective MCIP searches, a total of 21 area-based solutions with PNW's greater than $5 million were found. The best solution had a PNW of $5.302 million.

6. Three integrated plans were prepared, with ILP1 having the highest PNW equal to $7.74 million. The two other ILP's were quite similar in terms of PNW and the stands that were harvested in decades 4 through 15, a situation caused by the homogeneity of the second-growth forest and a large proportion of high growth sites. IlP1 also had the highest valued alternative area-based plans as identified in the selective searches. It is therefore the logical plan to implement, however, caution is warranted because the inventory data is not precise.

The recommendations of this study are:

1. The procedures developed for generating integrated

plans are practical, and it would be worthwhile to examine the same problem with more accurate data.

2. A test should be made to determine if better results can be obtained with the MCIP technique by selectively searching period by period, rather than randomly searching all three periods.

3. Further research is needed to evaluate the MCIP algorithm on more complex planning problems, such as those with wildlife cover, sediment and specific budget constraints. Application of MCIP to the scheduling of individual settings, as required in 5-year development plans, should be investigated.

4. Further research is needed to determine if MCIP could solve the entire forest plan using an area-based approach, and what advantages, if any, this would offer forest managers.

BIBLIOGRAPHY

Arney, J.D. 1985. A modeling strategy for the growth projection of managed stands. Canadian Journal of Forest Research, Vol. 15, No. 3:511-518

Bullard, H.S, H.D. Sherali and W.D. Klemperer. 1985. Estimating optimal thinning and rotation for mixed-species timber stands using a random search algorithm. Forest Science 31:303-315.

Conley, W. 1980. Computer optimization techniques. Petrocelli Books Inc., New York. 266p.

Conley, W. 1981. Optimization: A simplified approach. Petrocelli Books Inc., New York. 248p.

Curtis, R.O., G.W. Clenden and D.J. DeMars. 1981. A new stand simulator for coast Douglas-fir: DFSIM Users Guide, U.S. Forest Service General Technical Report PNW-128.

Davis, L.S. and K.N. Johnson. 1987. Forest Management, Third Edition. McGraw-Hill, Inc. New York. 790p.

Eldred, P. 1987. Evaluation of a shadow price search heuristic as an alternative to linear programming or binary search for timber harvest scheduling. Unpublished Masters thesis, Dept. of Forest Management, Oregon State University. 64p.

Hokans, H.H. 1983. Evaluating spatial feasibility of harvest schedules with simulated stand-selection decisions. Journal of Forestry, Sept:601-603, 613.

Johnson, K.N. 1987. FORPLAN VERSION 11. Dept. of Forest Management, Oregon State University, in cooperation with USDA Forest Service, Land Management Planning.

Johnson, K.N., and S. Crim. 1981. Integrating long-term and short-term scheduling in forest planning. Unpublished paper. 20p.

Johnson, K.N. and H.L. Scheurman. 1977. Techniques for prescribing optimal timber harvest and investment under different objectives-Discussion and synthesis. Forest Science Monograph 18.

Johnson, K.N., and T.W. Stuart. 1987. FORPLAN Version 2: Mathematical programmer's guide. USDA Forest Service, Land Management Planning Systems Section, Washington, D.C. 158p.

Johnson, K.N., T.W. Stuart and S.A. Crim. 1986. FORPLAN Version 2:an overview. USDA Forest Service, Land management planning Systems Section, Washington D.C. 98p.

Jones, J.G., J.F.C. Hyde and M.L. Meacham. 1986. Four analytical approaches for integrating land management and transportation planning on forest lands. Res. Pap. INT-361, USDA Forest Service, Intermountain Res. Sta. 32p.

Jones, J.G., A. Weintrab, A. Magendzo and M.L. Meacham. March 1988. A heuristic approach for solving IRPM and FORPLAN mixed-integer programming formulations. Paper presented at the Soc. of American Foresters' Symposium on Systems Analysis in forest Resources. Pacific Grove. CA.

Kirby, M.W., P. Wong, W.A. Hager and M.E. Huddleston. 1980. A guide to the integrated resources planning model. USDA For. Serv., Berkeley California. 211p.

Law, A.M., and W.D. Kelton. 1982. Simulation modeling and analysis. McGraw-Hill, Inc., New York. 400p.

MacDonald, J. 1987. Productivity and profitability of grapple yarding B.C. coastal second growth timber. Forest Engineering Research Institute of Canada, Special Report SR-48. 35p.

Magnanti, T.L., and R.T. Wong. 1984. Network design and transportation planning: Models and algorithms. Transportation Science. 18(1):1-55.

McQuillan, A.G. 1986. The declining even flow effect - non sequitur of national forest planning. Forest Science 32:960-969

Moore, T.L., and R. Nielson. 1987. An evaluation of timber sale scheduling using Tranship computer model. USDA Forest Service, Resources Transportation Eng. Program, Oregon State Univ. 201p.

Morrison, P., R. Gasson, G. Armstrong and D. Williams. 1985. The recovery cost of the merchantable timber in coastal British Columbia. Forest Economics and Policy Analysis Project, Information report 85-8. 48p.

Schuster, E.G. and J.G. Jones. 1985. Below-cost timber sales: analysis of a forest policy issue. Gen. Tech. Report INT-183. USDA, Forest Service, Intermountain Res. Sta. 17p.

Schrage, L. 1979. A more portable Fortran random number generator. ACM Trans. Math. Software 5:132-138

Schrage, L. 1981. Linear, Integer, and Quadratic Programming with LINDO. The Scientific Press. 274 p.

Sessions, J. December, 1987. User's Guide for Scheduling and Network Analysis Program (SNAP). Draft. U.S.D.A. Forest Service, Division of Timber Management, Portland, Oregon. 145 p.

Row, C., H.F. Kaiser and J. Sessions. June, 1981. Discount rate for long-term Forest Service investments. Journal of Forestry:367-369:376.

Steinberg, D.I. 1970. The fixed charge problem. Naval Research Logistics Quarterly. 17:217-235.

Tanke, W.C. 1985. PASS - A tool for analyzing alternative harvest schedules, in Proceedings of Society of American Foresters Symposium on System Analysis in Forest Resources. The Georgia Center for Continuing Education, Athens, Georgia. pp.303-314

U.S. Department of Agriculture, Forest Service, Management Sciences Staff. 1983. Procedure for obtaining a heuristic solution to IRPM/TRANSHIP problems. USDA Forest Service, Berkeley, CA. (number of pages unknown).

Williams, D. and R. Gasson. 1986. The economic stock of timber in the coastal region of British Columbia. Forest Economics and Policy Analysis Project, Report 86-11, Vol. 1 and 11. 22p. and 78p.

Zanakis, S.H. and J.R. Evans. 1981. Heuristic "optimization": why, when, and how to use it. Interfaces 11:84-91.

APPENDICES

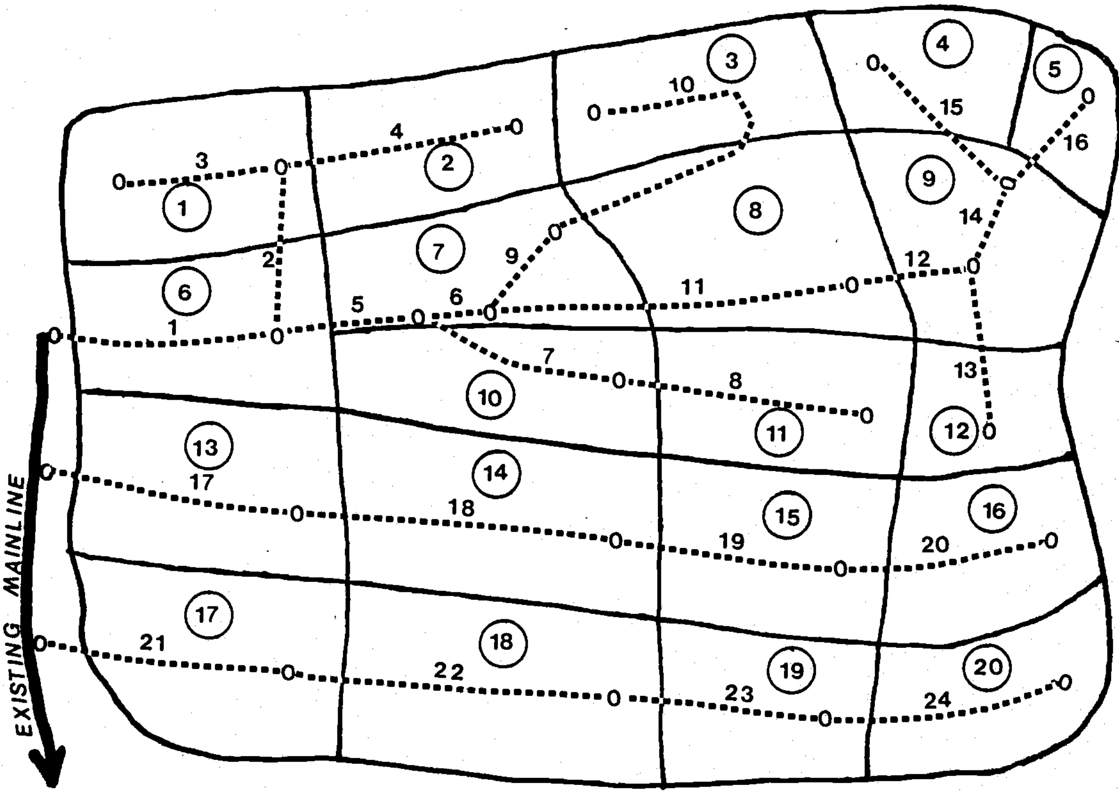
APPENDIX 1

A sample problem solved with MIP and MCIP

A small sample problem was created to test how well the Monte-Carlo integer program algorithm performed in comparison to mixed integer programming. The problem consisted of 20 harvest units and 24 road projects (see figure 21), all of which were defined as 0/1 integers. The objective was to maximize the present net worth of harvests over 3 decades. Adjacency constraints were added so that no two adjacent units (any two units sharing a common boundary) could be cut in the same decade. The volume cut per decade had to be at least 2000 Mcf. A real discount rate of 4% was used. There was no growth in stand volumes during the 3 decades, however, this could be easily added without complicating the problem.

The mixed integer program had 132 integer variables ((20 units + 24 roads) X 3 periods = 132) and 3 continuous variables to measure the total volume cut in each decade. With adjacency constraints, road project linkages, and volume restrictions, there was a total of 333 rows in the formulation. The MIP was solved using Hyper-LINDO on a Compaq Deskpro 386 computer. The optimal solution was found after 10,224 pivots, which required 90 minutes of computing time (provided the variables in the objective function are placed in descending order according to their coefficients). The optimal solution to this problem (Z=$805.35) is given in table 5. Harvest unit variables begin with the letter S, followed by a digit representing the decade, followed by digits for the unit number. Road variables begin with the letter R, followed by a letter denoting the project, followed by a digit representing the decade. The road project letters correspond to the road project numbers on figure 21. For example A=1, B=2, C=3,....X=24.

The Monte-Carlo integer program was about 400 statements in length, and was written and compiled with TURBO BASIC. 5000 feasible solutions (not all unique on this small problem) were found in approximately 45 minutes using the same Compaq computer. Only those solutions that were within 10% of the MIP optimum were recorded. These solutions are found in table 6. Of the 15 solutions recorded, 8 were unique, and the optimum was found (Z=$805.35).



DATA FOR SAMPLE PROBLEM				
HARVEST UNIT NUMBER	VOLUME MCF	NET REVENUE X(1000)	ROAD LINK NUMBER	CONST'N COST X(1000)
1	318	80	1	170
2	696	174	2	8.5
3	370	92	3	19.3
4	675	169	4	10
5	285	71	5	18.7
6	528	132	6	7.6
7	530	133	7	14.5
8	446	112	8	14.6
9	700	175	9	19.4
10	680	170	10	21.5
11	447	112	11	18.9
12	459	115	12	12.2
13	359	90	13	9.5
14	78	20	14	1.7
15	993	98	15	27.8
16	646	162	16	17.9
17	486	121	17	150
18	307	77	18	13.3
19	1066	267	19	8.2
20	511	128	20	29.8
			21	90
			22	14
			23	28.2
			24	8.2

LEGEND

UNIT BOUNDARY....

ROAD PROJECT..... 0······3······0

UNIT NUMBER .... (8)

Figure 21. Harvest units and road projects for the sample problem.

Table 6. The optimal solution for the sample problem found with MIP.

OBJECTIVE FUNCTION VALUE

1) 805.350000

VARIABLE	VALUE	REDUCED COST
S119	1.000000	-219.500000
S12	1.000000	-143.000000
S110	1.000000	-139.700000
S14	1.000000	-138.900000
S117	1.000000	-99.450000
S112	1.000000	-94.500000
S26	1.000000	-75.000000
S220	1.000000	-69.500000
S39	1.000000	-65.600000
S211	1.000000	-61.000000
S316	1.000000	-60.800000
S37	1.000000	-49.900000
S23	1.000000	-51.000000
S218	1.000000	-43.000000
S25	1.000000	-39.300000
S313	1.000000	-33.800000
RA1	1.000000	170.000000
RU1	1.000000	90.000000
RQ3	1.000000	68.500000
RB1	1.000000	8.500000
RD1	1.000000	10.000000
RE1	1.000000	18.700000
RF1	1.000000	7.600000
RG1	1.000000	14.500000
RK1	1.000000	18.900000
RL1	1.000000	12.200000
RM1	1.000000	9.500000
RN1	1.000000	1.700000
RO1	1.000000	27.800000
RV1	1.000000	14.000000
RW1	1.000000	28.200000
RH2	1.000000	9.860000
RI2	1.000000	13.100000
RJ2	1.000000	14.500000
RP2	1.000000	12.100000
RX2	1.000000	5.530000
RR3	1.000000	6.070000
RS3	1.000000	3.740000
RT3	1.000000	13.600000
H1	40.620000	.000000
H2	24.480000	.000000
H3	22.350000	.000000

Table 7. Solutions for the sample problem found with MCIP.

	UNITS PERIOD 1	UNITS PERIOD 2	UNITS PERIOD 3	UNITS PERIOD 1	UNITS PERIOD 2	UNITS PERIOD 3	UNITS PERIOD 1	UNITS PERIOD 2	UNITS PERIOD 3
	2	3	7	2	1	7	2	3	1
	4	5	9	4	3	9	4	5	9
	10	6	13	10	5	13	10	6	13
	12	11	16	12	11	15	12	11	15
	19	17		17	18		17	18	
		20		19	20		19	20	
VOL	35.76	26.27	22.35	40.62	22.38	25.82	40.62	24.48	23.7
PNW	731.33			754.03			767.25		
FREQ	SOL'N	CHOSEN	1			4			1

	UNITS PERIOD 1	UNITS PERIOD 2	UNITS PERIOD 3	UNITS PERIOD 1	UNITS PERIOD 2	UNITS PERIOD 3	UNITS PERIOD 1	UNITS PERIOD 2	UNITS PERIOD 3
	2	3	1	2	1	7	2	1	6
	4	5	8	4	3	9	4	3	9
	10	6	13	10	5	16	10	5	16
	12	11	15	12	11	18	12	11	18
	17	18		17	13		17	13	
	19	20		19	20		19	20	
VOL	35.76	24.48	21.16	40.62	22.9	21.83	40.62	22.9	21.81
PNW	743.62			733.9			733.52		
FREQ	SOL'N	CHOSEN	2			2			3

	UNITS PERIOD 1	UNITS PERIOD 2	UNITS PERIOD 3	UNITS PERIOD 1	UNITS PERIOD 2	UNITS PERIOD 3
	2	3	7	2	3	1
	4	5	9	4	5	9
	10	6	13	10	6	13
	12	11	16	12	11	16
	17	18		17	18	
	19	20		19	20	
VOL	35.76	24.48	22.35	40.62	24.48	20.23
PNW	805.35			777.66		
FREQ	SOL'N	CHOSEN	1			1

APPENDIX 2

Inventory data used in the study

Assumptions regarding inventory data:

1. Existing and regenerated stands grow at the same rate (normal yield tables in the SPS model).

2. High sites include site indices of 30-37 metres at 50 years (34 metres was used in the SPS model). Medium sites include site indices of 21-27 metres at 50 years (24 metres was used in the SPS model). Low sites include site indices of 15-18 metres at 50 years (16.5 metres was used in the SPS model).

3. Utilization factors are a 15 cm. top, 30 cm. stump height, 17.5 cm. minimum dbh, and a minimum log length of 5 metres.

4. Stands were assumed to be either pure Douglas-fir, pure hemlock or pure cedar.

Codes used to define timber strata (analysis areas):

1. Site, species and age code: These codes are made up of 4 alphanumeric characters. The first character is the site class (H=high, M=medium, L=low), the second character is the species group (F=fir, H=hemlock, C=cedar), the third and fourth characters are the 10 year age classes (J1=10, J2=20, J3=30, J4=40, J5=50, J6=60, J7=70, J8=80, J9=90, JA=100, JB=110, JC=130,

JO=200+).

2. Zone, logging system code: This code is made up of two letters, the first gives the zone (A or B), and the second is the logging system (S=skidder , Y=grapple yarding).

Table 8. Description of the analysis areas.

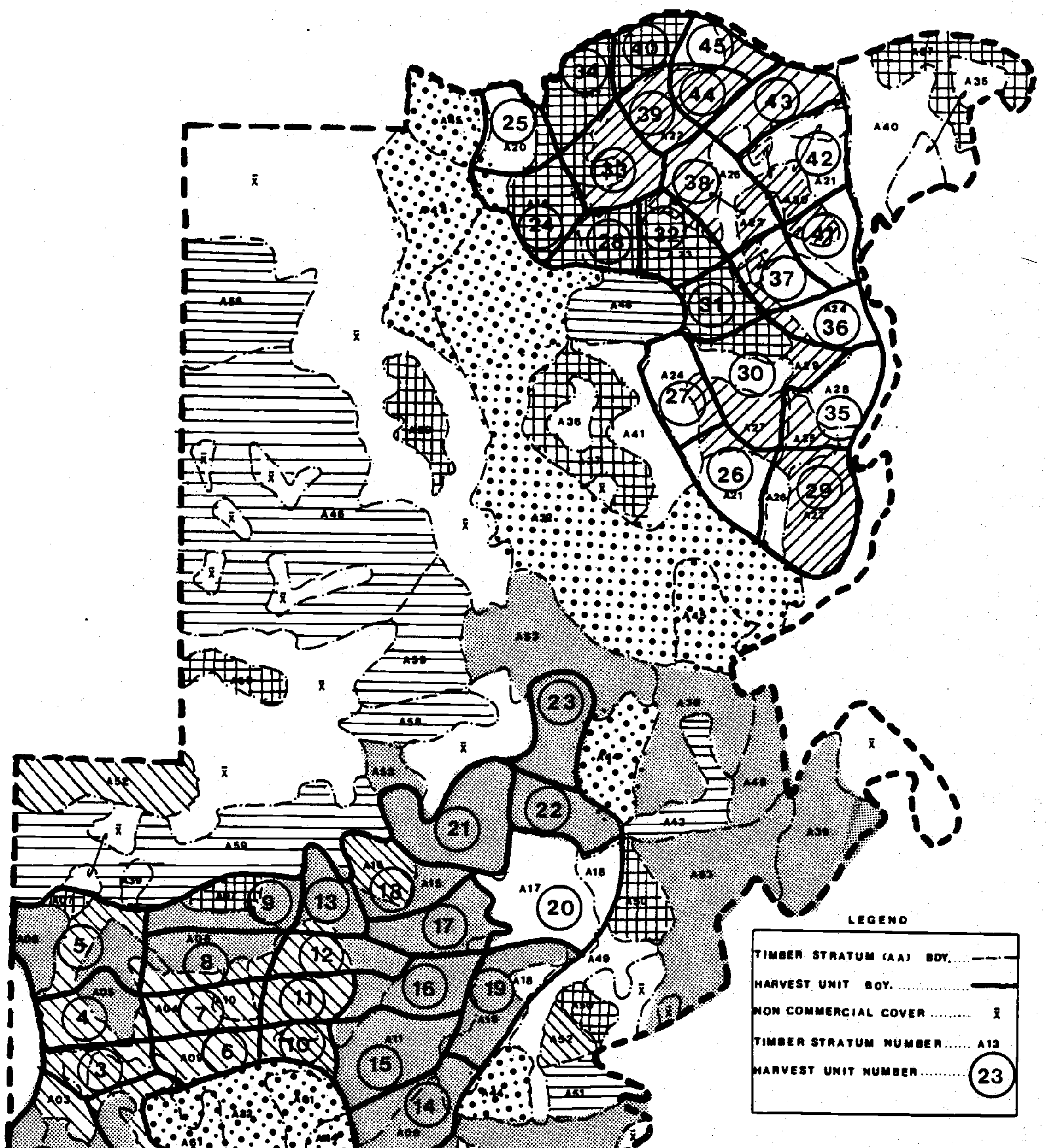
ANALYSIS AREA	SITE SPECIES AGE	ZONE LOG. SYS.	HA	VOL/HA (m^3)	TOTAL VOL (m^3)
1	HCJ7	AS	45	690	31050
2	MCJ7	AS	13	400	5200
3	MFJ6	AS	40	330	13200
4	HHJ6	AY	120	610	73200
5	HCJ8	AY	36	760	27360
6	MFJ8	AY	19	470	8930
7	LCJO	AY	17	440	7480
8	HHJ8	AY	67	800	53600
9	HHJ6	AS	55	610	33550
10	LFJ6	AY	12	100	1200
11	MFJ7	AY	95	410	38950
12	LFJ6	AS	17	100	1700
13	MFJ7	AS	28	410	11480
14	MFJO	AS	37	710	26270
15	MHJ7	AY	233	410	95530
16	LHJ6	AY	18	90	1620
17	MFJO	AY	137	710	97270
18	MFJC	AY	21	620	13020
19	LFJ7	AY	45	200	9000
20	MFJC	AS	31	620	19220
21	HHJB	AS	71	970	68870
22	MHJA	AY	202	570	115140
23	HFJO	AS	82	1170	95940
24	HHJC	AS	80	1010	80800
25	HHJA	AY	39	930	36270
26	HHJB	AY	29	970	28130
27	HHJA	AS	16	930	14880
28	HHJC	AY	28	1010	28280
29	HCJ9	AS	20	840	16800
30	MHJA	AS	44	570	25080
32	HFJ1	BY	368	0	0
34	HFJ7	BS	15	680	10200
35	HFJB	BY	35	940	32900
36	HFJC	BS	12	990	11880
37	HFJO	BS	92	1170	107640
38	HHJ7	BY	59	720	42480
39	HHJ8	BY	56	800	44800
40	HHJB	BS	70	800	56000
41	HHJC	BS	40	1010	40400
43	HCJ4	BY	26	330	8580
44	MFJ1	BY	148	0	0
45	MFJ2	BY	64	0	0
46	MFJ3	BY	295	14	4130
47	MFJ7	BS	65	410	26650
48	MFJ8	BY	27	470	12690
49	MFJC	BS	33	615	20295
50	MFJO	BY	58	710	41180
51	MHJ4	BS	20	125	2500
52	MHJ6	BS	62	330	20460
53	MHJ7	BY	270	410	110700
54	MHJ8	BS	60	480	28800
58	MCJ3	BY	99	20	1980
59	MCJ4	BY	205	120	24600
60	MCJO	BY	14	750	10500
61	LFJ1	BS	47	0	0
62	LFJ6	BS	46	100	4600
		TOTAL	3983		1742985

Table 9. Harvest unit areas and volumes (000 m^3) for decades 1-3.

BLOCK	HA	VOL1	VOL2	VOL3
1	62	33970	38450	42740
2	67	24040	29080	32340
3	23	10670	12840	14440
4	39	26340	30120	32900
5	58	34500	38660	41800
6	28	16520	19540	21740
7	28	13000	16000	17760
8	42	28400	31970	34570
9	41	23800	25830	27330
10	18	28720	31590	33570
11	25	15250	18000	20000
12	32	16720	19680	21680
13	26	11460	13440	14640
14	47	27130	29840	32350
15	49	19902	23003	25386
16	39	16590	19180	21120
17	36	15360	17690	19100
18	36	9000	11160	12960
19	41	11140	12120	13650
20	76	50480	50880	51200
21	53	21730	25440	27560
22	32	13120	15360	16640
23	41	16810	19680	21320
24	34	23510	23650	23720
25	29	18430	18910	19150
26	33	31850	33170	34470
27	34	33540	34900	36020
28	24	25780	25780	25780
29	58	38500	40380	42260
30	62	61490	63630	65400
31	24	28080	28080	28080
32	30	32700	32820	32940
33	43	26330	27230	28130
34	30	21300	21300	21300
35	41	38530	40130	41500
36	29	28100	29400	30340
37	30	27460	28700	29740
38	51	34670	36340	38010
39	27	15390	16200	17010
40	23	16330	16330	16330
41	31	26310	27450	28530
42	47	35190	36810	38430
43	37	23090	24250	25410
44	18	10260	10800	11340
45	23	14930	15230	15530
BLKS 1-23	939	484652		
BLKS 24-45	758	611770		
TOTAL	1697	1096422		

Table 10. Description of the existing inventory by site, species group, logging system, zones and age classes.

EXISTING	INVENTORY	
SITE	HA	VOL1
HIGH	1461	943600
MEDIUM	2320	773800
LOW	202	25600
TOTAL	3983	1743000
SPECIES		
CEDAR	475	133600
FIR	1869	608300
HEMLOCK	1639	1001100
TOTAL	3983	1743000
LOGGING	SYSTEM	
SKID	1141	773500
YARD	2842	969500
TOTAL	3983	1743000
ZONES		
ZONE A	1697	1079000
ZONE B	2286	664000
TOTAL	3983	1743000
AGE	CLASSES	
1	563	0
2	64	0
3	394	6000
4	251	35500
5	0	0
6	370	148000
7	868	380000
8	265	176000
9	20	16500
10	301	190000
11	205	184500
12	245	230500
20	437	385000
TOTAL	3983	1752000



AGE IN YEARS	CODES	COLOR
10 &20	J1, J2	(dotted)
30 & 40	J3, J4	(horizontal lines)
50 & 60	J5, J6	(diagonal hatching, \\)
70 & 80	J7, J8	(stippled grey)
90 &100	J9, JA	(diagonal hatching, //)
110 & 120	JB, JC	(blank)
200 +	JO	(cross-hatched grid)

Figure 22. Map showing the distribution of age classes.

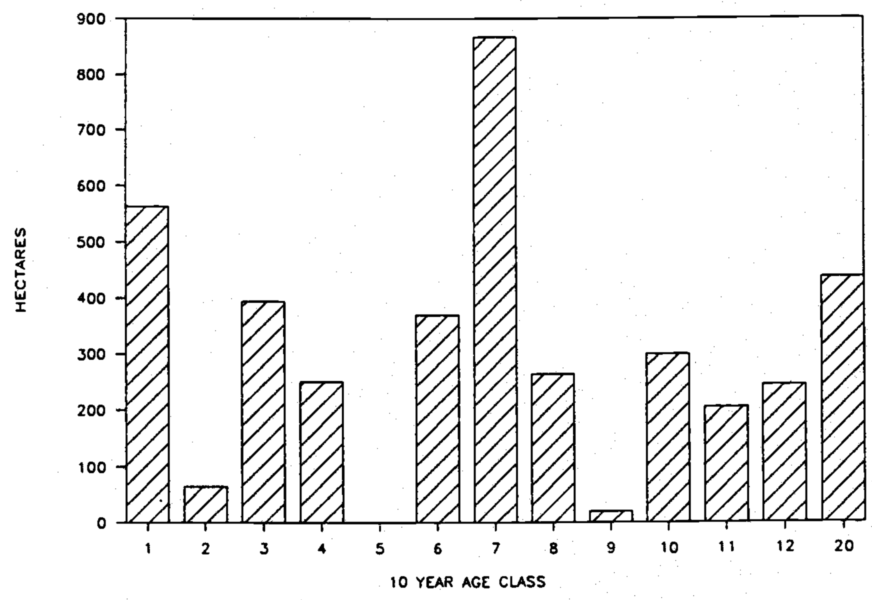


Figure 23. Distribution of total area by age classes.

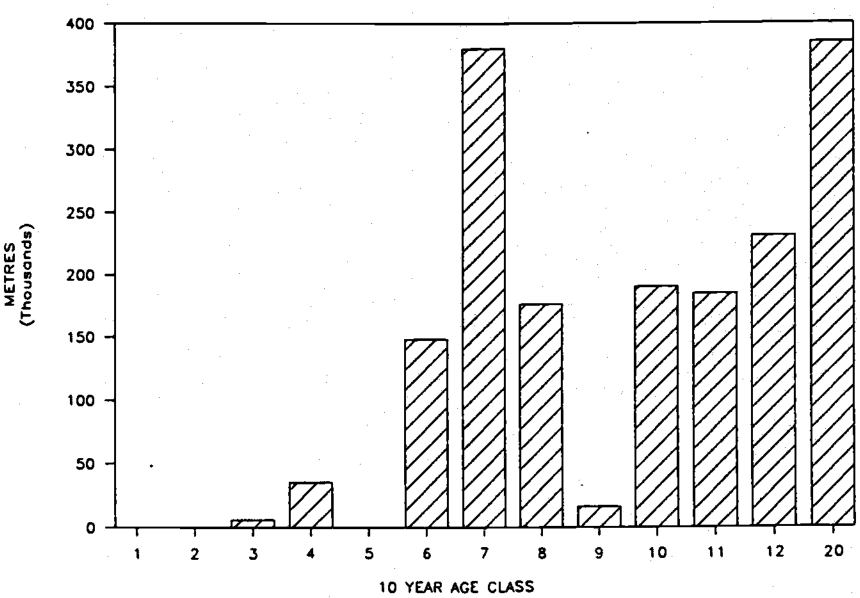


Figure 24. Distribution of total volume by age classes.

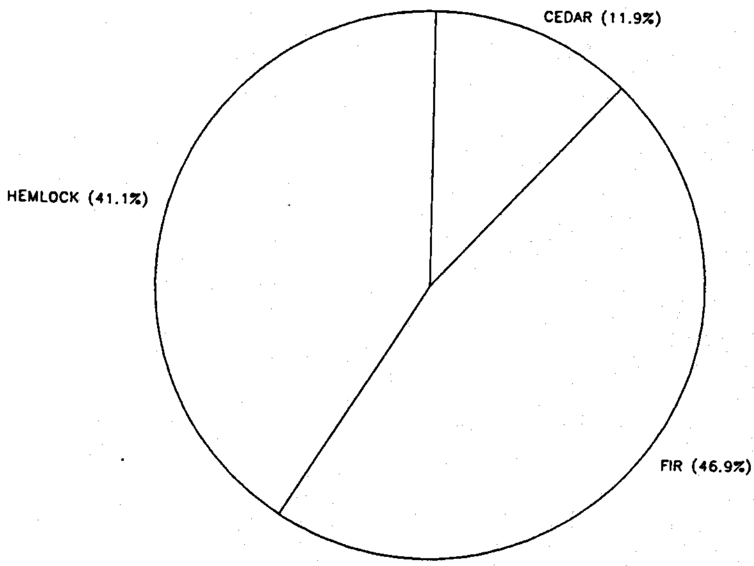


Figure 25. Distribution of total area by species.

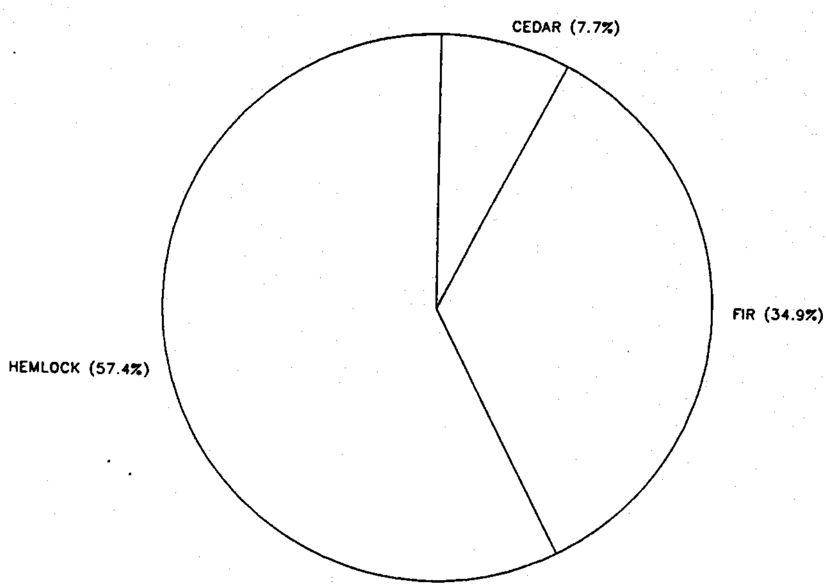


Figure 26. Distribution of total volume by species.

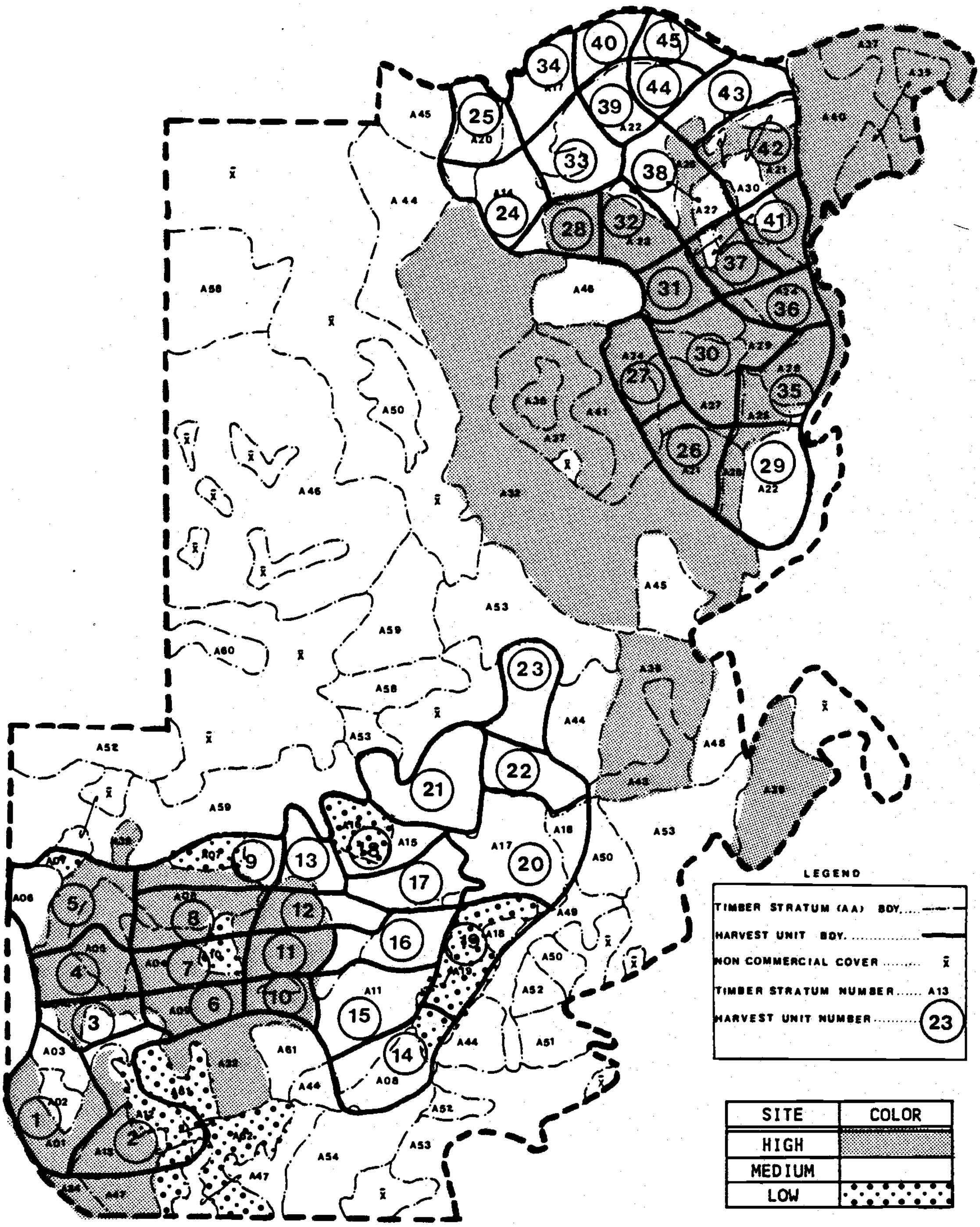


Figure 27. Map showing the distribution of site classes.

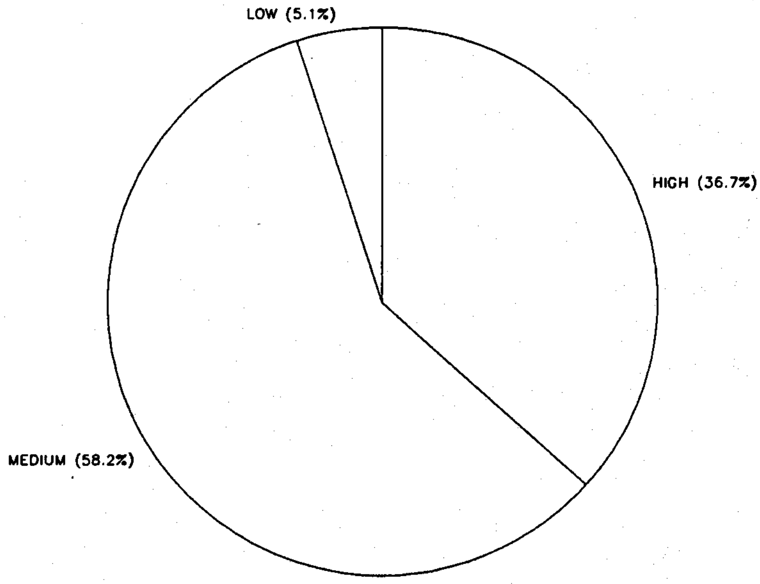


Figure 28. Distribution of total area by site classes.

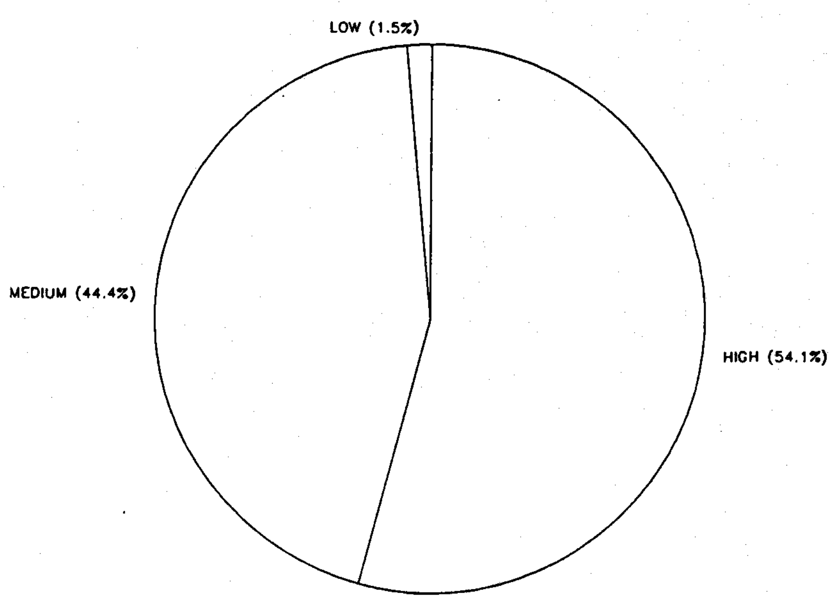


Figure 29. Distribution of total volume by site classes.

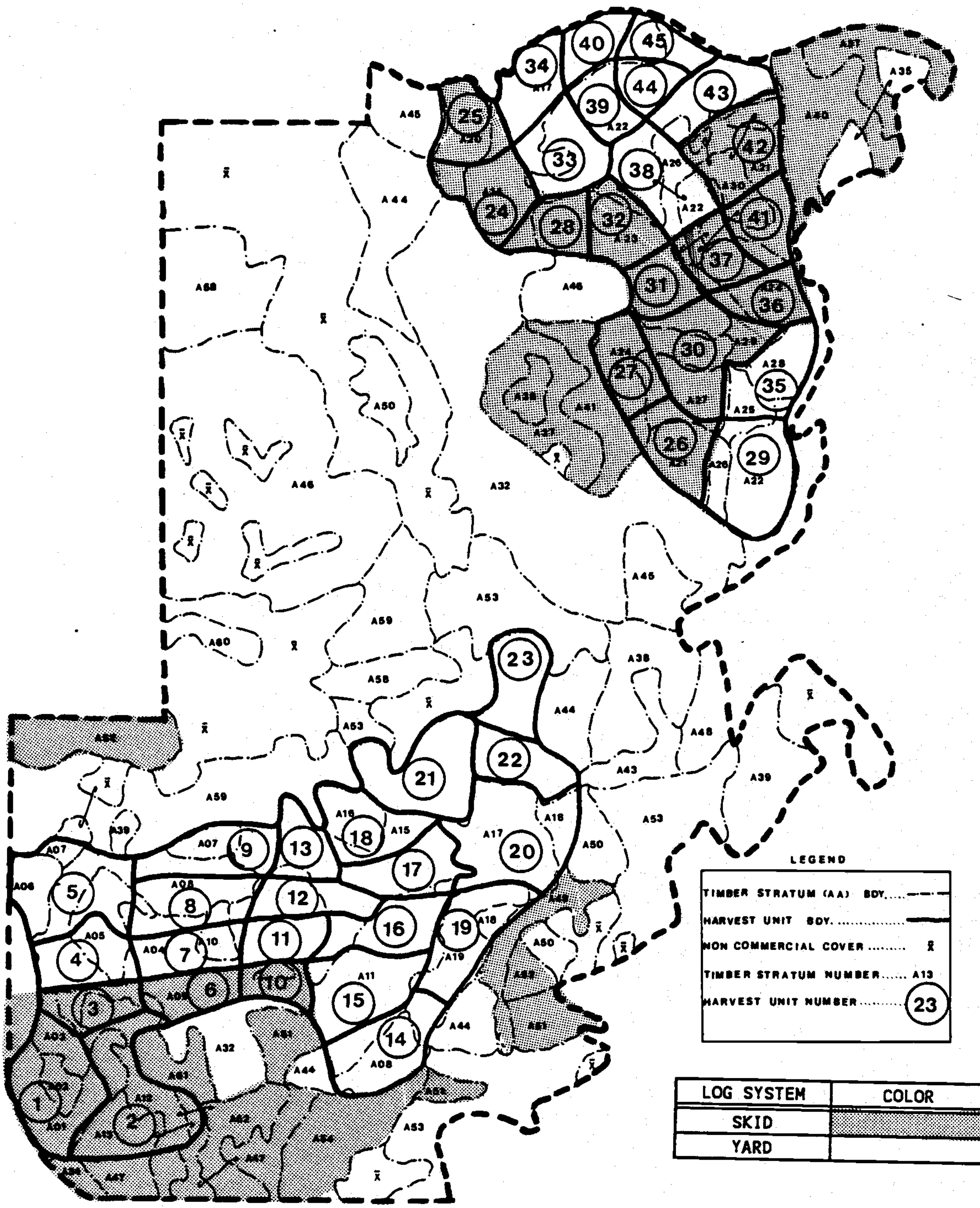


Figure 30. Map showing the distribution of logging systems.

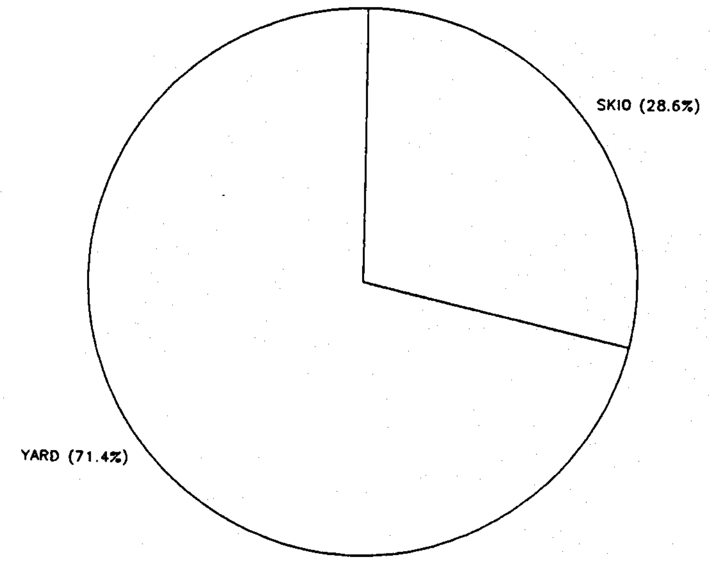


Figure 31. Distribution of total area by logging system.

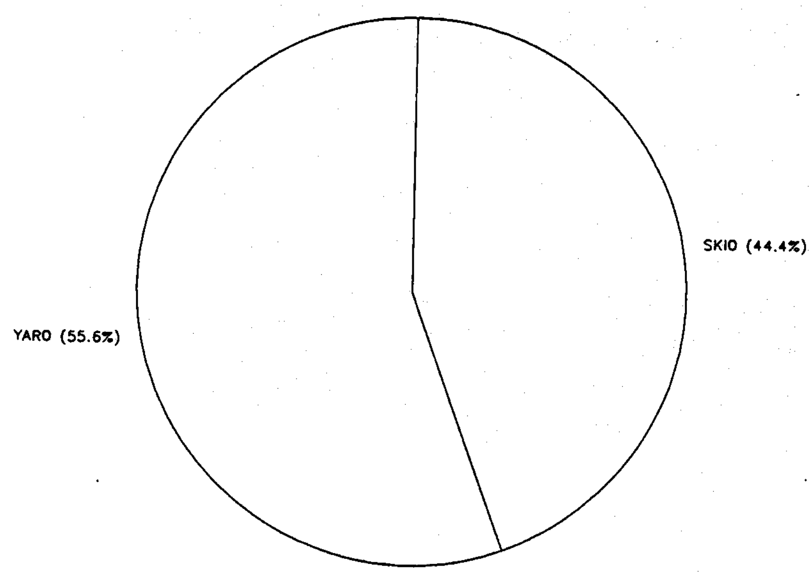


Figure 32. Distribution of total volume by logging system.

APPENDIX 3

Economic data used in the study

Table 11. Summary of prices, costs and net revenues for each species by dbh (expressed in inches). All figures are in $\$/m^3$. Only the harvesting costs from felling through transport to the dump site are included.

DBH	NET FIR		NET HEM		NET CED		FIR	HEM	CED	COST	COST
	YARD	SKID	YARD	SKID	YARD	SKID	PRICE	PRICE	PRICE	YARD	SKID
7	8.3	11.3	2.0	5.0	0.1	1.8	32	25	22	23.3	20.3
8	10.5	13.5	3.9	6.9	0.6	3.6	33	26	23	22.4	19.4
9	12.6	15.6	5.7	8.7	2.3	5.3	34	28	24	21.8	18.8
10	14.7	17.7	7.5	10.5	5.7	8.7	36	29	27	21.3	18.3
11	17.1	20.1	9.5	12.5	7.6	10.6	38	30	28	20.8	17.8
12	19.5	22.5	11.5	14.5	9.5	12.5	40	32	30	20.4	17.4
13	22.0	25.0	13.6	16.6	17.8	20.8	42	34	38	20.1	17.1
14	24.6	27.6	15.7	18.7	20.2	23.2	44	36	40	19.8	16.8
15	27.5	30.5	18.1	21.1	22.8	25.8	47	38	42	19.5	16.5
16	30.4	33.4	20.5	23.5	30.4	33.4	50	40	50	19.3	16.3
17	33.6	36.6	23.1	26.1	33.6	36.6	53	42	53	19.0	16.0
18	36.8	39.8	25.7	28.7	42.4	45.4	56	45	61	18.8	15.8
19	42.1	45.1	30.3	33.3	48.0	51.0	59	47	65	16.8	13.8
20	43.9	46.9	31.4	34.4	50.1	53.1	62	50	69	18.4	15.4
21	47.6	50.6	34.4	37.4	60.7	63.7	66	53	79	18.3	15.3
22	51.6	54.6	37.7	40.7	65.6	68.6	70	56	84	18.0	15.0

Administration, operational overhead, and additional phase costs needed to transport logs to the mill was set at $\$15.00/m^3$.

Table 12. Summary of harvest unit net revenues per m^3 for decades 1-3 .

BLOCK	PERIOD 1	PERIOD 2	PERIOD 3
1	20.4	23.0	28.9
2	21.2	24.2	27.5
3	17.2	20.5	22.8
4	17.1	21.4	22.8
5	16.8	21.4	22.4
6	24.6	27.0	30.3
7	13.6	15.8	17.9
8	17.3	19.8	21.9
9	14.1	15.9	17.3
10	16.9	19.2	21.5
11	13.9	16.2	18.5
12	11.6	14.0	15.5
13	10.2	12.6	13.1
14	18.3	20.4	22.6
15	19.2	21.5	23.7
16	16.4	18.7	20.4
17	12.6	14.5	15.0
18	8.2	9.7	10.1
19	17.9	18.1	18.2
20	29.8	29.8	32.3
21	9.2	11.6	11.6
22	9.2	11.6	11.6
23	9.2	11.6	11.6
24	33.1	33.1	35.8
25	31.1	31.1	31.7
26	26.0	26.2	28.6
27	26.0	28.3	28.3
28	47.4	47.5	47.9
29	17.1	17.1	19.3
30	32.9	33.8	34.1
31	50.7	50.7	50.7
32	48.3	48.2	48.3
33	19.8	19.6	22.1
34	30.7	30.7	34.0
35	22.5	24.4	24.5
36	27.6	30.2	30.9
37	26.2	27.6	29.3
38	17.5	17.4	20.1
39	13.9	13.9	16.2
40	30.7	30.7	34.0
41	24.0	24.7	27.0
42	20.9	20.9	23.6
43	18.1	18.1	20.5
44	13.9	13.9	16.2
45	23.4	23.4	26.3

Table 13. Description of the major road projects.

ROAD NUMBER	LINK NUMBER	CONST'N COST	TOTAL $	KM	$/KM
1	1	11000		1.1	10000
1	2	3000		0.3	10000
1	3	3000		0.3	10000
1	4	2200		0.22	10000
1	5	2200		0.22	10000
1	6	10000		0.4	25000
1	7	6750		0.27	25000
1	8	8750		0.35	25000
1	9	23500		0.94	25000
1	10	6250		0.25	25000
1	11	12500		0.5	25000
1	12	24000		0.96	25000
	TOTAL		113150	5.81	
2	1	10000		0.5	20000
2	2	25500		1.02	25000
2	3	21250		0.85	25000
	TOTAL		56750	2.37	
3	1	3450		0.23	15000
3	2	8000		0.32	25000
3	3	20000		0.8	25000
3	4	18250		0.73	25000
3	5	31250		1.25	25000
	TOTAL		80950	3.33	
4	1	16500		0.55	30000
4	2	22500		0.75	30000
4	3	20100		0.67	30000
4	4	24000		0.8	30000
4	5	36900		0.82	45000
	TOTAL		120000	3.59	
5	1	28500		0.95	30000
5	2	16250		0.65	25000
5	3	30000		1.2	25000
	TOTAL		74750	2.8	
6	1	14800		0.37	40000
6	2	55000		1.1	50000
	TOTAL		69800	1.47	
7	3	8750		0.35	25000
7	4	6250		0.25	25000
7	5	3000		0.12	25000
7	6	14500		0.58	25000
7	7	19750		0.79	25000
7	8	17500		0.7	25000
7	9	7750		0.31	25000
7	10	6250		0.25	25000
7	11	15000		0.6	25000
7	12	11000		0.44	25000
	TOTAL		164750	4.39	

Table 13. continued.

8	1	16250		0.65	25000
9	1	30000		0.75	40000
9	2	22000		0.55	40000
	TOTAL		52000	1.3	
10	1	10750		0.43	25000
10	2	15000		0.6	25000
	TOTAL		25750	1.03	
11	1	3000		0.1	30000
11	2	33000		1.1	30000
11	3	10500		0.35	30000
	TOTAL		46500	1.55	
12	1	8750		0.35	25000
12	2	43750		1.25	35000
	TOTAL		52500	1.6	
	GRAND	TOTAL	856900	29.89	

Table 14. Description of the secondary roads.

SEC. RD. NUMBER	LINK NUMBER	CONST'N 'COST	RD&LAND TOTAL	KM	$/KM	NO. OF LAND
1	1	23250	35750	0.93	25000	5
2	1	6300		0.42	15000	
2	2	17500		0.7	25000	
2		17500				7
	TOTAL		41300	1.12		
3		10000	10000			4
4	1	3750		0.15	25000	
4	2	5000		0.25	20000	
4		12500				5
	TOTAL		21250	0.4		
5	1	12900		0.43	30000	
5	2	1200		0.12	10000	
5		12500				5
	TOTAL		26600	0.55		
6		7500	7500			3
7		7500	7500			3
8		7500	7500			3
9	1	17500		0.5	35000	
9		12500				5
	TOTAL		30000	0.5		
10		5000	5000			2
11		5000	5000			2
12		7500	7500			3
13	1	16800		0.42	40000	
13		10000				4
	TOTAL		26800	0.42		
14	1	27500		1.1	25000	
14	2	4500		0.15	30000	
14	3	6600		0.22	30000	
14	4	2500		0.1	25000	
14		17500				7
	TOTAL		58600	1.57		
15	1	12900		0.43	30000	
15		10000				4
	TOTAL		22900	0.43		
16		10000	10000			4
17	1	33300		1.11	30000	
17		17500				7
	TOTAL		50800	1.11		
18		15000				6
	TOTAL		15000			

Table 14. continued.

19	1	3750		0.15	25000	
19		17500				7
	TOTAL		21250	0.15		
20	1	16250		0.65	25000	
20	2	18000		0.6	30000	
20		25000				10
	TOTAL		59250	1.25		
21	1	23450		0.67	35000	
21	2	5000		0.2	25000	
21	3	12300		0.41	30000	
21	4	18000		0.4	45000	
21		25000				10
	TOTAL		83750	1.68		
22	1	17600		0.44	40000	
22		10000				4
	TOTAL		27600	0.44		
23		12500				5
24		10000	10000			4
25		5000	5000			2
26		7500	7500			3
27		7500	7500			3
28	1	10000		0.4	25000	
28		7500				3
	TOTAL		17500	0.4		
29	1	7250		0.29	25000	
29		10000				4
	TOTAL		17250	0.29		
30	1	14250		0.57	25000	
30		12500				5
	TOTAL		26750	0.57		
31		5000	5000			2
32	1	5000		0.2	25000	
32	2	3750		0.15	25000	
32		12500				5
	TOTAL		21250	0.35		
33	1	12000		0.48	25000	
33	2	8250		0.33	25000	
33		15000				6
	TOTAL		35250	0.81		
34	1	17500		0.7	25000	
34	2	5000		0.2	25000	
34		7500				3
	TOTAL		30000	0.9		

Table 14. continued.

35	1	27600		0.92	30000	
35		10000				4
	TOTAL		37600	0.92		
36	1	19500		0.65	30000	
36		7500				3
	TOTAL		27000	0.65		
37		7500	7500			3
38	1	6250		0.25	25000	
38	2	6250		0.25	25000	
38		15000				6
	TOTAL		27500	0.5		
39	1	10500		0.3	35000	
39		10000				4
	TOTAL		20500	0.3		
40		5000	5000			2
41	1	10500		0.35	30000	
41		10000				4
	TOTAL		20500	0.35		
42	1	5000		0.2	25000	
42		7500				3
	TOTAL		12500	0.2		
43	1	18250		0.73	25000	
43		10000				4
	TOTAL		28250	0.73		
44		7500	7500			3
45		5000	5000			2
			KM			
TOTAL	MAIN	ROADS	29.89			
TOTAL	SEC	ROADS	17.52			
TOTAL	ALL	ROADS	47.41			

APPENDIX 4

Summary of LP1 solution

Table 14. Volumes, net revenues, and hectares harvested under LP1.

DECADE	VOLUME (000) METRES	NET REVENUE ($000)	NET REV ($/M)	EXIST. HA. CUT	REGEN. HA. CUT	TOTAL HA. CUT
1	285.02	833.76	29.25	278	0	278
2	285.02	415.89	14.59	312	0	312
3	285.02	411.96	14.45	326	0	326
4	285.02	239.69	8.41	334	0	334
5	285.02	253.53	8.90	381	0	381
6	285.02	210.45	7.38	456	0	456
7	285.02	225.85	7.92	364	151	515
8	285.02	199.48	7.00	373	35	408
9	285.02	157.91	5.54	353	112	465
10	285.02	135.9	4.77	67	346	413
11	285.02	82.67	2.90	83	333	416
12	285.02	130.89	4.59	0	459	459
13	285.02	231.03	8.11	0	463	463
14	285.02	122.73	4.31	236	209	445
15	285.02	53.69	1.88	420	35	455

PNW=	$ 12,416,100	LTSY=	28500	METRES	PER	YEAR

APPENDIX 5

Summary of LP2 solution

Table 16. Volumes, net revenues, and hectares harvested under LP2.

DECADE	VOLUME (000) METRES	NET REVENUE ($000)	NET REVENUE ($/M)	EXIST. HA. CUT	REGEN. HA. CUT	TOTAL HA. CUT
1	294.24	594.17	20.19	355	0	355
2	294.24	282.47	9.60	319	0	319
3	294.24	180.55	6.14	432	0	432
4	296.97	724.49	24.40	298	0	298
5	296.97	256.28	8.63	342	0	342
6	296.97	212.58	7.16	477	0	477
7	296.97	238.01	8.01	466	52	518
8	296.97	57.84	1.95	433	30	463
9	296.97	120.07	4.04	430	72	502
10	296.97	258.65	8.71	12	486	498
11	296.97	94.87	3.19	337	83	420
12	296.97	243.99	8.22	5	392	397
13	296.97	280.88	9.46	0	441	441
14	296.97	226.28	7.62	0	405	405
15	296.97	96.03	3.23	77	375	452

PNW=	$10,049,400	LTSY=	28000	PER YEAR

APPENDIX 6

Summary of LP3 solution

Table 17. Volumes, net revenues and hectares harvested under LP3.

DECADE	VOLUME (000) METRES	NET REVENUE ($000)	NET REVENUE ($/M)	EXIST. HA. CUT	REGEN. HA. CUT	TOTAL HA. CUT
1	263.01	564.73	21.47	319	0	319
2	263.01	252.6	9.60	285	0	285
3	263.01	250	9.51	360	0	360
4	272.32	572.03	21.01	290	0	290
5	275.81	250	9.06	314	0	314
6	275.81	250	9.06	365	0	365
7	275.81	250	9.06	433	0	433
8	275.81	250	9.06	369	19	388
9	275.81	250	9.06	410	0	410
10	275.81	250	9.06	200	237	437
11	275.81	250	9.06	233	143	376
12	275.81	250	9.06	44	296	340
13	275.81	250	9.06	53	313	366
14	275.81	250	9.06	169	215	384
15	275.81	250	9.06	139	314	453

PNW=	$9,733,300	LTSY=	27600	PER YEAR	

Table 18. Analysis areas harvested in decades 1-3 under LP3.

ANALYSIS AREA	DECADE HARVESTED	HECTARES HARVESTED
1	3	45
3	3	40
5	2	36
6	2	19
8	3	67
11	3	95
13	3	27
14	1	37
17	1	137
18	1	12
18	2	9
20	1	31
21	2	38
21	3	34
23	1	82
24	2	80
25	2	39
26	3	29
27	2	16
28	2	28
29	1	20
30	2	21
30	3	23

APPENDIX 7

Temporary solutions found with the random search MCIP

Table 19. Present net worth of 200 temporary solutions found with the random search MCIP ($000).

5189	4943	4870	4811	4759	4696	4627	4570
5168	4937	4868	4810	4758	4692	4626	4569
5043	4936	4867	4810	4755	4691	4626	4567
5043	4934	4865	4804	4754	4691	4624	4566
5038	4933	4855	4796	4750	4690	4623	4565
5030	4932	4853	4793	4748	4690	4623	4564
5019	4931	4850	4792	4747	4685	4619	4564
5008	4929	4850	4792	4744	4683	4618	4563
5001	4928	4848	4792	4740	4681	4618	4559
4999	4923	4847	4789	4740	4680	4617	4556
4993	4920	4846	4787	4739	4677	4613	4555
4986	4914	4845	4784	4738	4674	4613	4553
4980	4912	4840	4782	4737	4672	4611	4544
4978	4912	4836	4781	4732	4668	4609	4542
4977	4909	4832	4780	4725	4657	4608	4539
4976	4906	4829	4777	4720	4656	4602	4538
4974	4904	4828	4773	4720	4656	4599	4538
4967	4904	4826	4773	4716	4654	4597	4533
4966	4898	4826	4771	4716	4646	4590	4532
4954	4888	4826	4768	4713	4642	4589	4529
4954	4884	4825	4767	4712	4640	4588	4528
4949	4884	4823	4765	4709	4636	4588	4520
4948	4883	4820	4765	4703	4631	4584	4511
4948	4875	4820	4764	4701	4631	4580	4509
4943	4871	4812	4762	4700	4627	4578	4502

Table 20. Temporary solution 1.

```
**************************FEASIBLE SOLUTION********************
FNW= 5167.77                    SEED= 1661568940
UNITS PERIOD  1  4  9  20  30  32  34  42  45
UNITS PERIOD  2  1  5  6  12  14  18  22  24  26  31  39  41
UNITS PERIOD  3  2  7  15  27  28  29  36  38  40
HECTARES                  348         444         363
VOLUMES                   266         301         264
NET REVENUES              3187        2672        2838
MAIN ROAD COSTS           245         199         162
SEC. ROAD COSTS           206         242         173

            MAIN ROADS

ROADS 1        ROADS 2          ROADS 3
---------------------------------------
 1    1
 1    2
 1    3
 1    4
 1    5
 1    6
 1    7
 1    8
 1    9
                 1    10
                 2    1
                 2    2
                 2    3
 3    1
 3    2
                                 3    3
                 4    1
                 4    2
                                 4    3
                                 4    4
 5    1
 5    2
                 6    1
 7    1
 7    2
 7    3
 7    4
 7    5
 7    6
                                 7    7
 7    8
 7    9
 7    10
 7    11
 7    12
                                 8    1
                 9    1
                                 10   1
                                 10   2
                                 11   1
                                 11   2
                 12   1
                 12   2

*****************************************************************
```

<u>Table 21. Temporary solution 2.</u>

```
****************************FEASIBLE SOLUTION**********************
FNW= 5189.28                   SEED= 1233823428
UNITS PERIOD  1   2   7   13   14   20   23   25   26   28   31   41   43
UNITS PERIOD  2   4   11   17   24   27   29   32   36   40   42
UNITS PERIOD  3   1   6   9   15   18   30   34   38   45
HECTARES                   463          355          382
VOLUMES                    296          280          270
NET REVENUES              3029         2991         2769
MAIN ROAD COSTS            289          138          201
SEC. ROAD COSTS            290          178          200

            MAIN ROADS

ROADS 1      ROADS 2        ROADS 3
---------------------------------
 1   1
 1   2
 1   3
 1   4
 1   5
 1   6
 1   7
 1   8
 1   9
 1   10
 1   11
              1   12
 3   1
 3   2
 3   3
              3   4
                                4   1
                                4   2
                                4   3
                                4   4
 5   1
 5   2
 6   1
 6   2
 7   1
              7   2
                                7   3
                                7   4
                                7   5
                                7   6
              7   7
              7   8
 7   9
 7   10
 7   11
 7   12
                                8   1
                                10   1
                                10   2
              11   1
              11   2
 12   1
                                12   2

*****************************************************************
```

Table 22. Temporary solution 3.

```
***************************FEASIBLE SOLUTION*******************
FNW= 5043.17                    SEED= 1336312261
UNITS PERIOD  1   3   5   12   18   20   24   30   32   41   45
UNITS PERIOD  2   1   4   9    15   21   25   26   31   40   42
UNITS PERIOD  3   2   8   14   22   27   28   35   37   43
HECTARES                   405         400          354
VOLUMES                    280         276          274
NET REVENUES              3104        2588         2813
MAIN ROAD COSTS            375          85           72
SEC. ROAD COSTS            213         207          233

              MAIN ROADS

ROADS 1        ROADS 2        ROADS 3
----------------------------------
 1   1
 1   2
 1   3
 1   4
 1   5
 1   6
 1   7
 1   8
 1   9
 1   10
 2   1
 2   2
 2   3
                3   1
                3   2
 4   1
 4   2
 4   3
                4   4
 5   1
 5   2
                5   3
                               6   1
 7   1
 7   2
                7   7
 7   8
 7   9
 7   10
 7   11
 7   12
                               10   1
                               11   1
                               11   2
                               11   3
 12   1
 12   2

***************************************************************
```

APPENDIX 8

Permanent solutions found with selective search MCIP's

Table 23. Results of selective search 1 (SS1).

	TS1			SS1-1		SS1-2		SS1-3		SS1-4		SS1-5	
	HARVEST UNITS PERIOD 1	HARVEST UNITS PERIOD 2	HARVEST UNITS PERIOD 3	HARVEST UNITS PERIOD 2	HARVEST UNITS PERIOD 3	HARVEST UNITS PERIOD 2	HARVEST UNITS PERIOD 3	HARVEST UNITS PERIOD 2	HARVEST UNITS PERIOD 3	HARVEST UNITS PERIOD 2	HARVEST UNITS PERIOD 3	HARVEST UNITS PERIOD 2	HARVEST UNITS PERIOD 3
	4	1	2	1	2	2	1	1	2	1	2	2	2
	9	5	7	5	7	5	6	5	8	5	7	5	1
	20	6	15	6	13	12	15	10	15	6	14	10	6
	30	12	27	12	25	14	18	13	18	12	21	12	8
	32	14	28	15	27	21	22	14	22	15	25	18	14
	34	18	29	24	28	24	25	24	25	18	27	19	21
	42	22	36	26	29	26	27	26	27	24	28	22	24
	45	24	38	31	36	31	28	31	28	26	29	25	27
		26	40	39	38	40	29	41	35	31	36	26	36
		31		41	40	41	37	43	37	39	40	28	38
		39					44		44	41		31	
		41										39	
												41	
VOLUME (000)	266	301	264	268	273	271	284	270	286	279	280	289	287
NET REV.($000)	319	267	284	286	292	276	287	279	280	273	285	288	263
PNW ($000)	5168			5302		5229		5217		5207		5203	

Table 24. Results of selective search 2 (SS2).

	TS2			SS2-1		SS2-2		SS2-3		SS2-4		SS2-5	
	HARVEST UNITS PERIOD 1	HARVEST UNITS PERIOD 2	HARVEST UNITS PERIOD 3	HARVEST UNITS PERIOD 2	HARVEST UNITS PERIOD 3	HARVEST UNITS PERIOD 2	HARVEST UNITS PERIOD 3	HARVEST UNITS PERIOD 2	HARVEST UNITS PERIOD 3	HARVEST UNITS PERIOD 2	HARVEST UNITS PERIOD 3	HARVEST UNITS PERIOD 2	HARVEST UNITS PERIOD 3
	2	4	1	4	1	4	1	3	1	3	1	3	1
	7	11	6	11	5	9	6	5	6	8	5	5	4
	13	17	9	17	6	10	8	10	9	10	6	10	9
	14	24	15	22	15	18	15	12	15	17	12	17	15
	20	27	18	24	18	22	17	22	17	24	30	24	18
	23	29	30	27	30	24	27	24	27	27	34	27	22
	25	32	34	29	34	30	29	30	33	29	38	29	30
	26	36	38	32	38	32	34	32	35	32	45	32	34
	28	40	45	36		40	37	39	37	36		36	38
	31	42		40		42		42	45	39		39	45
	41			42						42		42	
	43												
VOLUME (000)	296	280	270	295	269	269	273	273	287	302	268	296	298
NET REV.($0000)	303	299	277	291	285	308	253	295	251	256	300	275	267
PNW ($000)	5189			5175		5147		5071		5035		5017	

Table 25. Results of selective search 3 (SS3).

	TS3			SS3-1		SS3-2		SS3-3		SS3-4		SS3-5	
	HARVEST UNITS PERIOD 1	HARVEST UNITS PERIOD 2	HARVEST UNITS PERIOD 3	HARVEST UNITS PERIOD 2	HARVEST UNITS PERIOD 3	HARVEST UNITS PERIOD 2	HARVEST UNITS PERIOD 3	HARVEST UNITS PERIOD 2	HARVEST UNITS PERIOD 3	HARVEST UNITS PERIOD 2	HARVEST UNITS PERIOD 3	HARVEST UNITS PERIOD 2	HARVEST UNITS PERIOD 3
	3	1	2	4	1	2	1	2	1	1	4	2	1
	5	4	8	9	6	4	6	4	8	6	9	4	6
	12	9	14	10	8	10	8	9	14	8	11	9	16
	18	15	22	14	15	14	15	10	16	15	14	14	21
	20	21	27	17	27	17	21	17	27	27	22	17	27
	24	25	28	22	29	28	25	22	29	28	25	22	28
	30	26	35	25	34	29	26	25	34	29	26	25	29
	32	31	37	26	36	31	36	26	36	34	31	26	34
	41	40	43	28	38	34	40	28	43	37	40	31	36
	45	42		31		42	43	31		43	42	40	43
				39				39				42	
				42				42					
VOLUME (000)	280	276	274	291	292	272	278	290	286	288	266	281	294
NET REV.($0000)	310	259	281	292	282	287	271	298	253	278	277	256	305
PNW ($000)	5043			5230		5163		5153		5133		5125	

Table 26. Permanent solution 1.

```
**************************FEASIBLE SOLUTION*******************
PNW= 5301.66                       SEED= 601318397
UNITS PERIOD  1   4   9   20   30   32   34   42   45
UNITS PERIOD  2   1   5   6   12   15   24   26   31   39   41
UNITS PERIOD  3   2   7   13   25   27   28   29   36   38   40
 HECTARES                    348          378          369
VOLUMES                     266          268          273
NET REVENUES                3187         2860         2916
MAIN ROAD COSTS             245          170          145
SEC. ROAD COSTS             206          164          182

           MAIN ROADS

ROADS 1       ROADS 2         ROADS 3
---------------------------------------
 1   1
 1   2
 1   3
 1   4
 1   5
 1   6
 1   7
 1   8
 1   9
                                1    10
                                1    11
                  2    1
                  2    2
                  2    3
 3   1
 3   2
                                3    3
                  4    1
                  4    2
                  4    3
                  4    4
 5   1
 5   2
 7   1
 7   2
 7   3
 7   4
 7   5
 7   6
                                7    7
 7   8
 7   9
 7   10
 7   11
 7   12
                                8    1
                  9    1
                                10   1
                                10   2
                                11   1
                                11   2
                                12   1

**************************************************************
```

Table 27. Permanent solution 2.

```
**************************FEASIBLE SOLUTION*******************
FNW= 5189.28              SEED= 1233823426
UNITS PERIOD  1  2  7  13  14  20  23  25  26  28  31  41  43
UNITS PERIOD  2  4  11  17  24  27  29  32  36  40  42
UNITS PERIOD  3  1  6  9  15  18  30  34  38  45
HECTARES                463          355          382
VOLUMES                 296          280          270
NET REVENUES           3029         2991         2769
MAIN ROAD COSTS         289          138          201
SEC. ROAD COSTS         290          178          200

              MAIN ROADS

ROADS 1        ROADS 2         ROADS 3
---------------------------------------
 1   1
 1   2
 1   3
 1   4
 1   5
 1   6
 1   7
 1   8
 1   9
 1   10
 1   11
                1   12
 3   1
 3   2
 3   3
                3   4
                                4   1
                                4   2
                                4   3
                                4   4
 5   1
 5   2
 6   1
 6   2
 7   1
                7   2
                                7   3
                                7   4
                                7   5
                                7   6
                7   7
                7   8
 7   9
 7   10
 7   11
 7   12
                                8   1
                                10   1
                                10   2
                11   1
                11   2
 12   1
                                12   2

****************************************************************
```

Table 28. Permanent solution 3.

```
***************************FEASIBLE SOLUTION********************
PNW= 5230.32                    SEED= 1160323092
UNITS PERIOD  1   3   5   12   18   20   24   30   32   41   45
UNITS PERIOD  2   4   9   10   14   17   22   25   26   28   31   39   42
UNITS PERIOD  3   1   6   8   15   27   29   34   36   38
HECTARES                 405          397          383
VOLUMES                  280          291          292
NET REVENUES            3104         2920         2820
MAIN ROAD COSTS          375          102          126
SEC. ROAD COSTS          213          240          183

           MAIN ROADS

ROADS 1        ROADS 2          ROADS 3
----------------------------------
 1    1
 1    2
 1    3
 1    4
 1    5
 1    6
 1    7
 1    8
 1    9
 1    10
               1    11
               1    12
 2    1
 2    2
 2    3
               3    1
               3    2
 4    1
 4    2
 4    3
                                4    4
 5    1
 5    2
               6    1
 7    1
 7    2
               7    3
                                7    4
                                7    5
                                7    6
 7    8
 7    9
 7    10
 7    11
 7    12
                                8    1
               9    1
                                10    1
                                10    2
                                11    1
                                11    2
12    1
12    2

*************************************************************
```

APPENDIX 9

Solution to ILP1

Table 29. Summary of ILP1 solution (R= regenerated stands).

AA	Z/LS	S/S	AGE	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15
1	AS	HC	7		30	15								R30	R12			
2	AS	MC	7		13												R13	
3	AS	MF	6		16	12			12							R16	R12	R12
4	AY	HH	6	22	36	24					38			R22	R36	R24		
5	AY	HC	8	14	18				4								R14	R22
6	AY	MF	8		19											R19		
7	AY	LC	20	12	5													
8	AY	HH	8	17	2				32	17				R17	R2			
7	AS	HH	6		26						29				R26			
10	AY	LF	6			8											4	
11	AY	MF	7		47			23			25					R47	R23	
12	AS	LF	6			17												
13	AS	MF	7			28									R15		R13	
14	AS	MF	20		27	10										R27	R10	
15	AY	MH	7	12	16	21	102							41		37	4	
16	AY	LH	6														18	
17	AY	MF	20	99		23		15							R99		R38	
18	AY	MF	12	16				5							R16		R5	
19	AY	LF	7	4				41										
20	AS	MF	12		7	24									R24	R7		
21	AS	HH	11	21	40					10				R21	R40			
22	AY	MH	10	10	26	81	20	53			11							
23	AS	HF	20	39	24	19								R49	R14	R19		
24	AS	HH	12	19	8	46			7					R19	R8	R46	R7	
25	AY	HH	10	21		4					14			R21		R4		
26	AY	HH	11			24				5						R24		
27	AS	HH	10		6	10									R6	R10		
28	AY	HH	12							28								
29	AS	HC	9	9					11				R9					R11
30	AS	MH	10	30	10						4					R30		
32	BY	HF	1								160	82	98		28			R242
34	BS	HF	7						12	3								R15
35	BS	HF	11					19	16								R17	R18
36	BS	HF	12					12									R12	
37	BS	HF	20				90		1							R63	R27	R1
38	BY	HH	7							59								
39	BY	HH	8						56									
40	BS	HH	11							70								R65
41	BS	HH	12						40								R40	
43	BY	HC	4										26					
44	BY	MF	1											148				
45	BY	MF	2								64							
46	BY	MF	3									295						
47	BS	MF	7					65									R65	
48	BY	MF	8							27								
49	BS	MF	12					33									R33	
50	BY	MF	20					58									R58	
51	BS	MH	4														20	
52	BS	MH	6							62								
53	BY	MH	7				145		82						43			
54	BS	MH	8					60										
58	BY	MC	3										99					
59	BY	MC	4									49	137				19	
60	BY	MC	20					14										
61	BS	LF	1															47
62	BS	LF	6						46									
TOTAL	EXIST	HA.	CUT	345	376	366	357	398	319	281	345	426	360	189	71	37	65	47
TOTAL	REGEN	HA.	CUT										9	179	301	335	388	386
	TOTAL	HA.	CUT	345	376	366	357	398	319	281	345	426	369	368	372	372	453	433
	TOTAL	VOL.	CUT	266	268	273	260	263	265	268	271	273	276	279	282	284	287	290
	NET	REVEN.		319	286	292	311	311	311	311	311	311	311	311	311	311	311	311
		PNW	=	771														

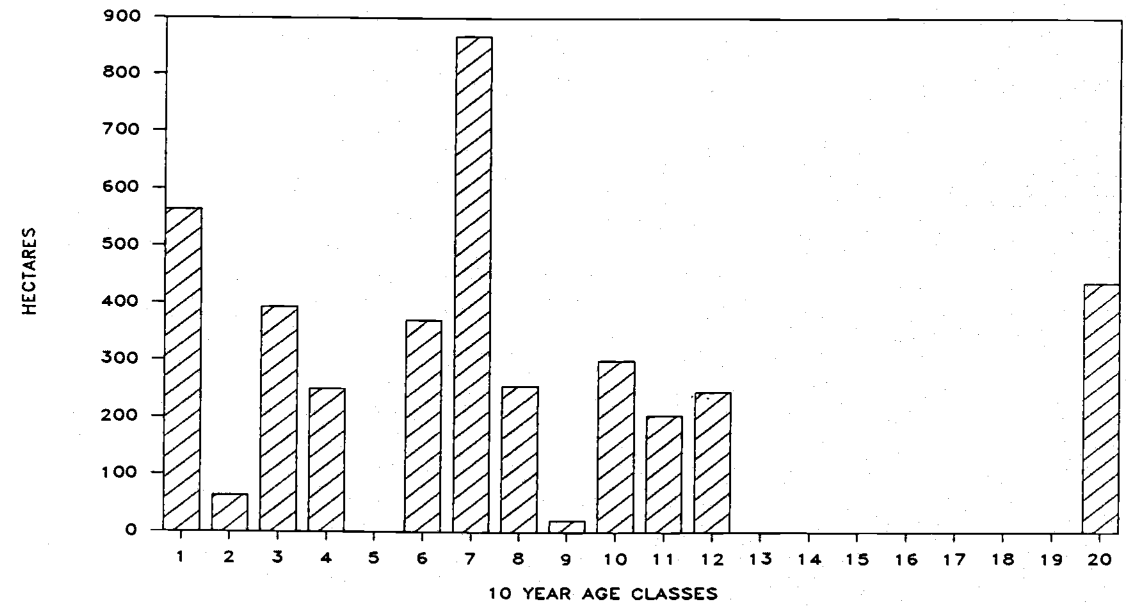


Figure 33. Initial age class distribution.

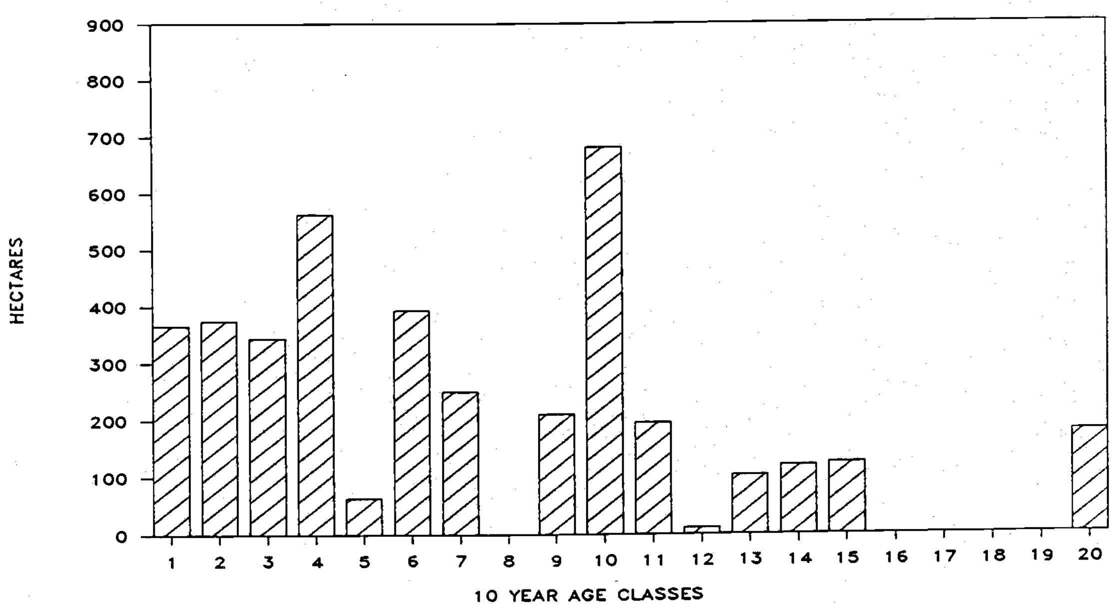


Figure 34. ILP1: Age class distribution at the start of decade 4.

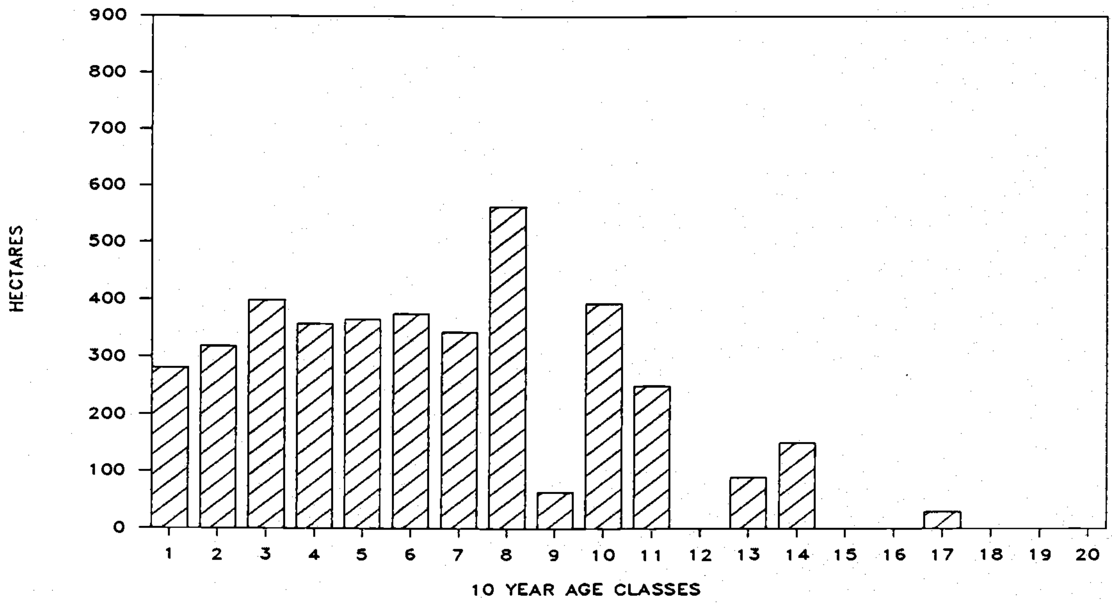


Figure 35. ILP1: Age class distribution at the start of decade 8.

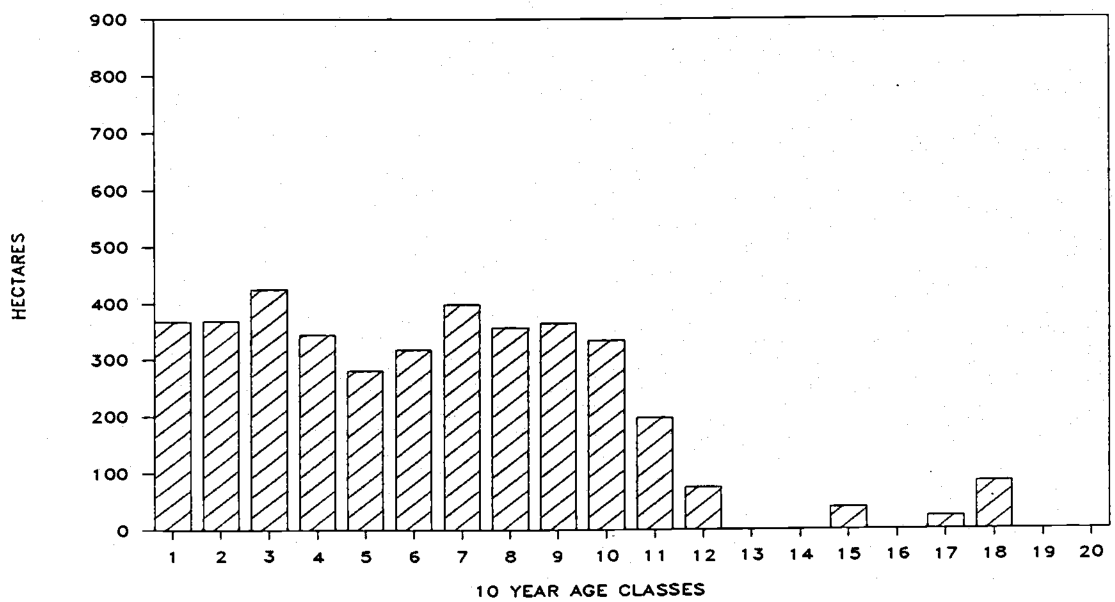


Figure 36. ILP1: Age class distribution at the start of decade 12.

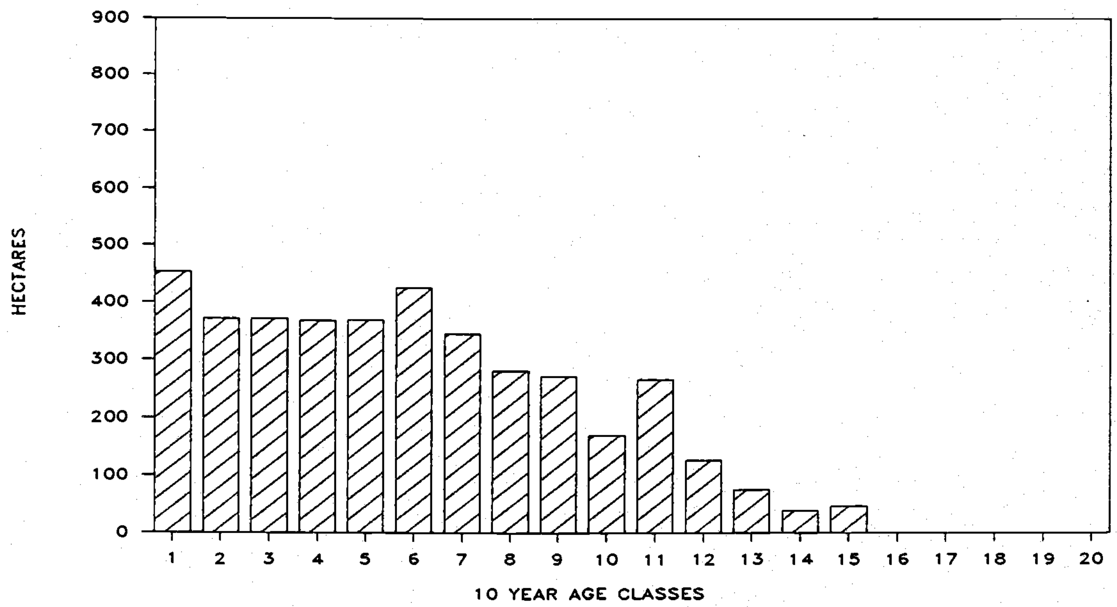


Figure 37. ILP1: Age class distribution at the start of decade 15.

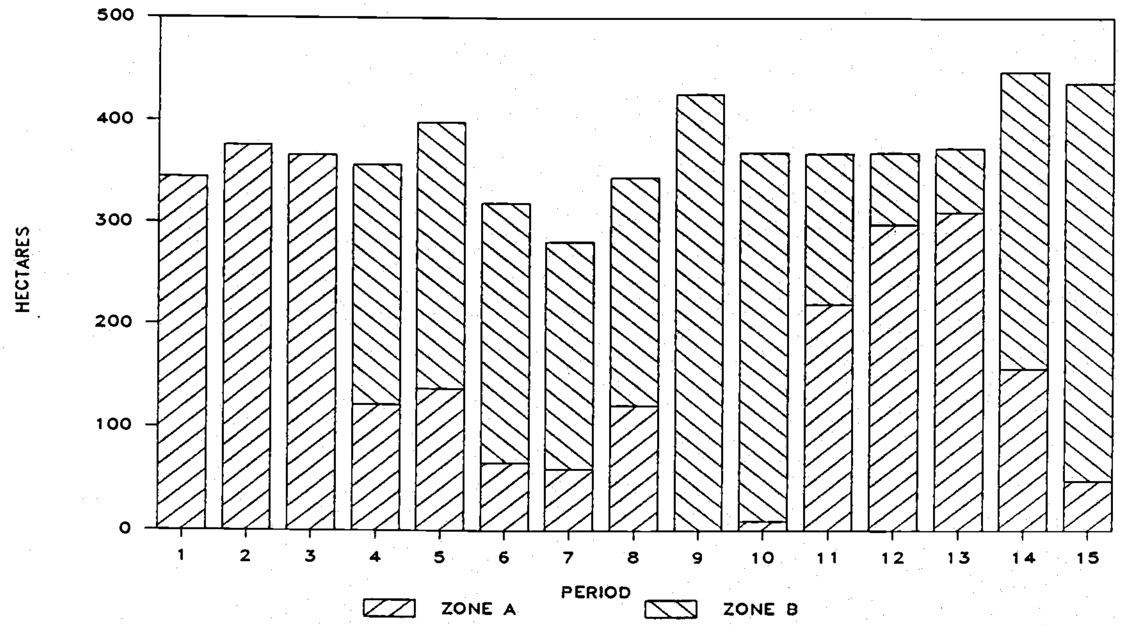


Figure 38. Distribution of ILP1 solution by zones.

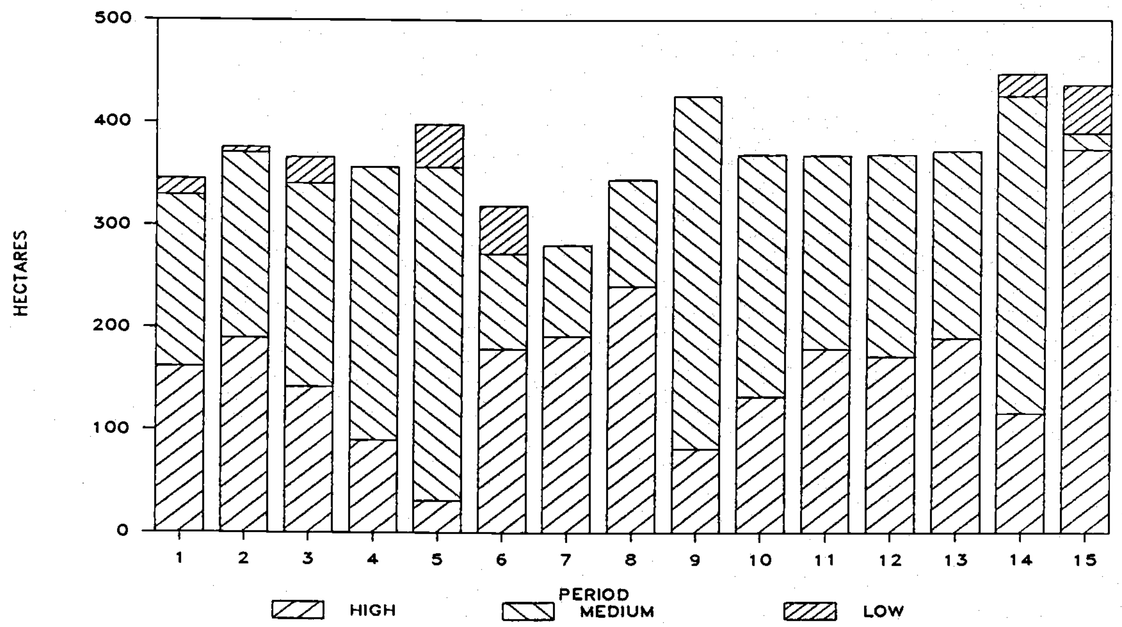


Figure 39. Distribution of ILP1 solution by site class.

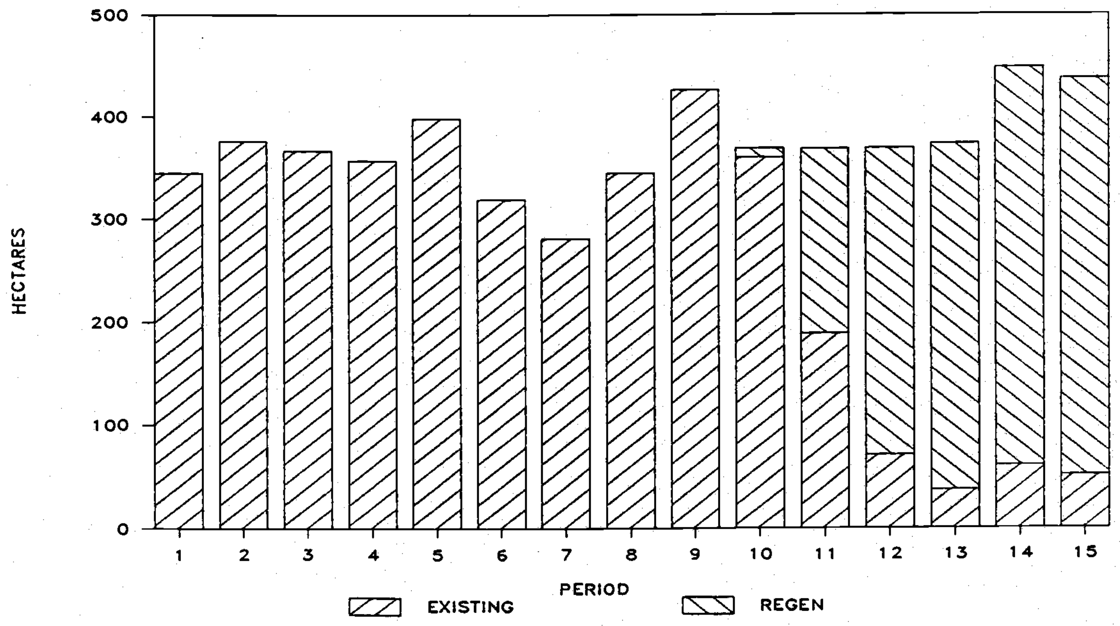


Figure 40. Distribution of ILP1 solution by existing and regenerated stands.

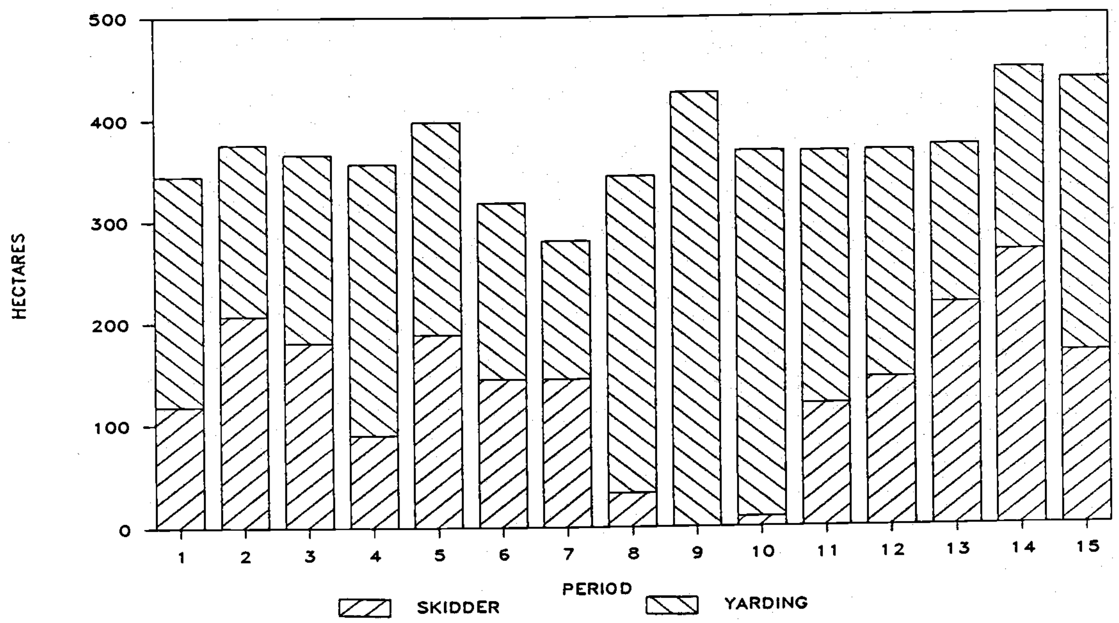


Figure 41. Distribution of ILP1 solution by logging system.

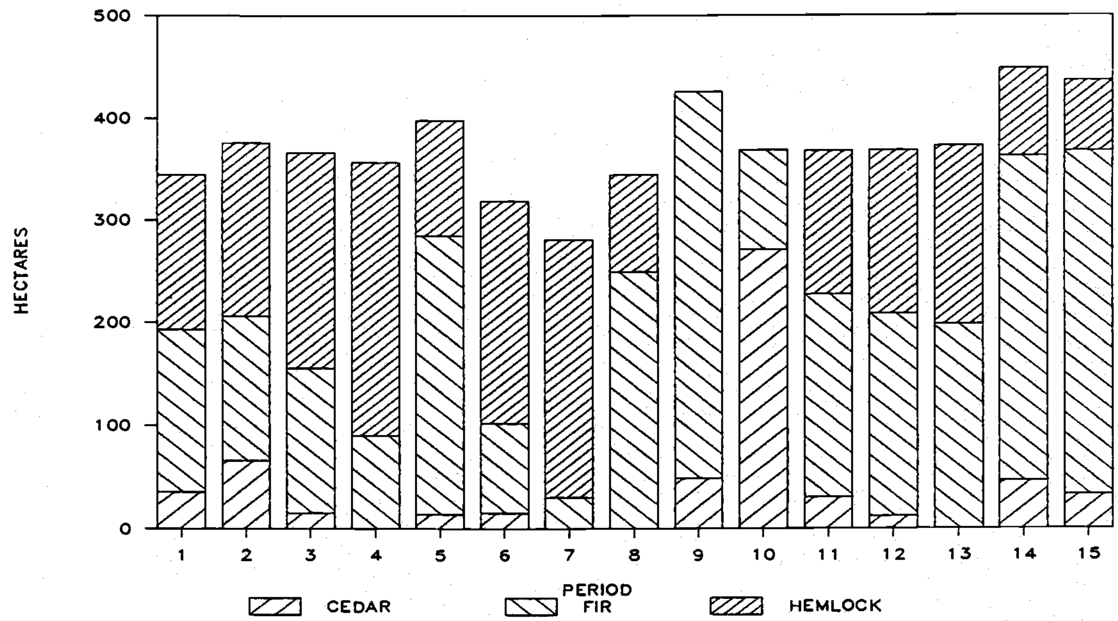


Figure 42. Distribution of ILP1 solution by species group.

APPENDIX 10

Solution to ILP2

Table 30. Summary of ILP2 solution (R= regenerated stands).

AA	Z/LS	S/S	AGE	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15
1	AS	HC	7	8		37									R12	R25	R8	
2	AS	MC	7			13										R13		
3	AS	MF	6	12		16			12						R12		R16	R12
4	AY	HH	6	24	47						49			R24	R47			
5	AY	HC	8		17				19									R36
6	AY	MF	8							19								
7	AY	LC	20			12											5	
8	AY	HH	8	25		17			25					R25		R17		
9	AS	HH	6			26					29					R26		
10	AY	LF	6	8									4					
11	AY	MF	7	13	5	47					30				R13	R5	R47	
12	AS	LF	6	17														
13	AS	MF	7	28											R28			
14	AS	MF	20	10	27										R10	R27		
15	AY	MH	7	63	28	33	54							25		31		
16	AY	LH	6			18												
17	AY	MF	20	56	25	44		12							R56	R25	R56	
18	AY	MF	12	16				5							R16		R5	
19	AY	LF	7	13				32										
20	AS	MF	12	24	7										R24	R7		
21	AS	HH	11	40	19	3				10				R40	R19	R3		
22	AY	MH	10	32	44	46	19	60										
23	AS	HF	20	43	26	13								R67		R13	R2	
24	AS	HH	12	8	46	18			7					R8	R46	R18		R7
25	AY	HH	10		4	21					14				R4	R21		
26	AY	HH	11	5	10	14								R5	R10	R14		
27	AS	HH	10	6	10									R6	R10			
28	AY	HH	12							28								
29	AS	HC	9		7	1			12					R7	R1			R12
30	AS	MH	10	10	30			4								R10		
32	BY	HF	1								146	86	105		31			R232
34	BS	HF	7						9	6								R15
35	BS	HF	11					26	8								R23	R11
36	BS	HF	12					12									R12	
37	BS	HF	20				90		1							R72	R18	R1
38	BY	HH	7							59								
39	BY	HH	8						56									
40	BS	HH	11							70								R30
41	BS	HH	12						40								R15	R25
43	BY	HC	4										26					
44	BY	MF	1											148				
45	BY	MF	2								51		13					
46	BY	MF	3									295						
47	BS	MF	7					56			9						R56	
48	BY	MF	8							27								
49	BS	MF	12					33									R33	
50	BY	MF	20					58									R58	
51	BS	MH	4														20	
52	BS	MH	6							62								
53	BY	MH	7				181		74						15			
54	BS	MH	8					60										
58	BY	MC	3										99					
59	BY	MC	4									30	112				62	
60	BY	MC	20					14										
61	BS	LF	1													47		
62	BS	LF	6						46									
TOTAL EXIST HA. CUT				461	352	379	344	372	309	281	328	411	359	173	46	78	87	0
TOTAL REGEN HA. CUT														181	309	296	350	391
TOTAL HA. CUT				461	352	379	344	372	309	281	328	411	359	354	355	374	437	391
TOTAL VOL CUT				296	280	270	252	255	257	260	262	265	268	270	273	276	279	281
NET REV				303	299	277	313	313	313	313	313	313	313	313	313	313	313	313

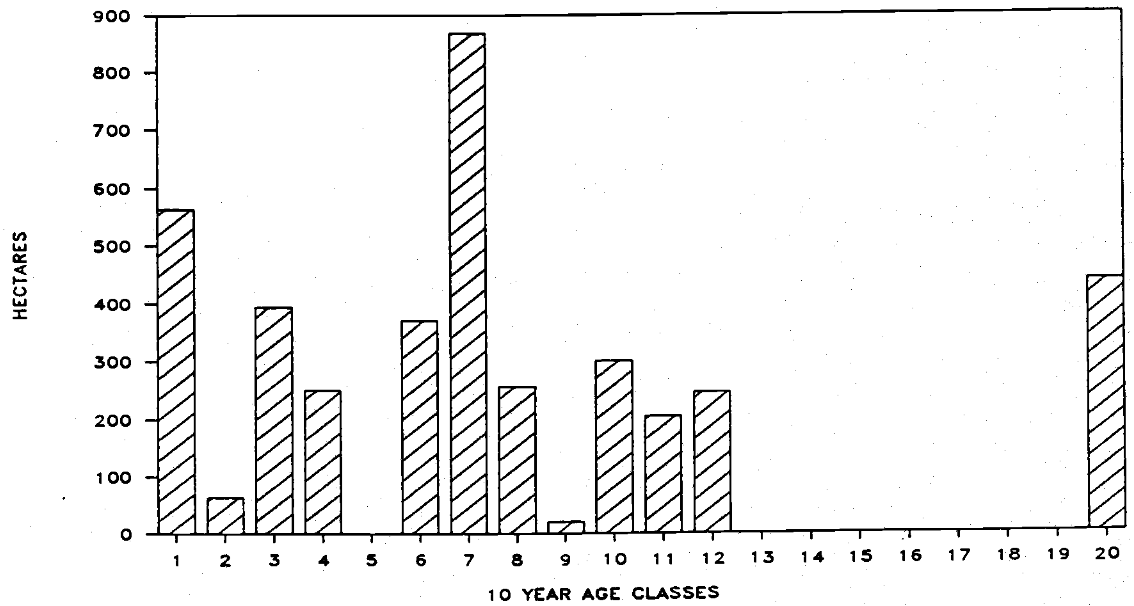


Figure 43. Initial age class distribution.

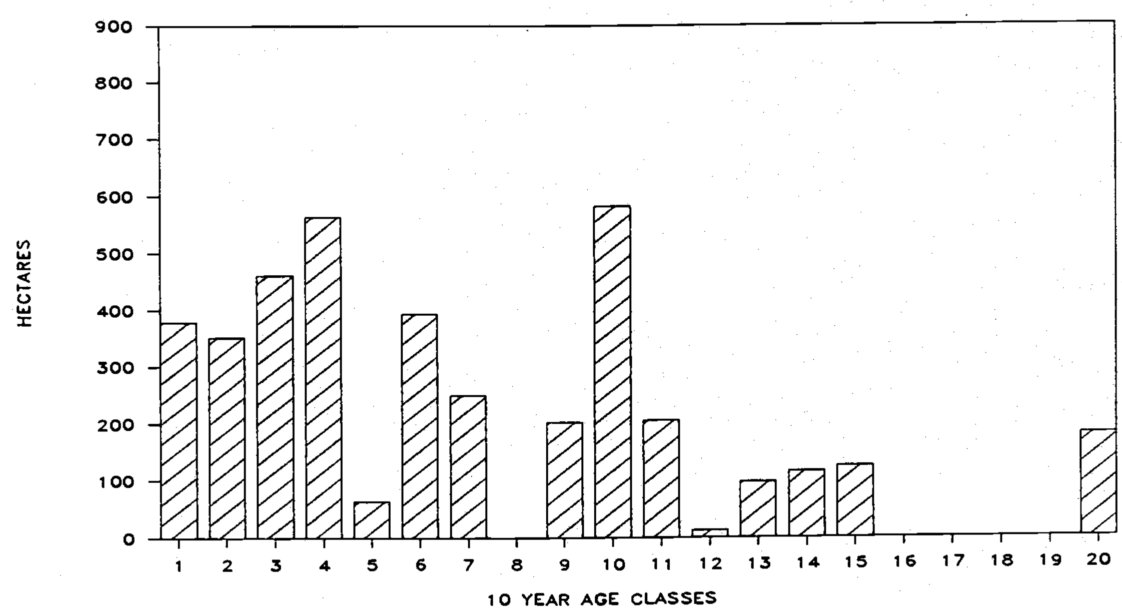
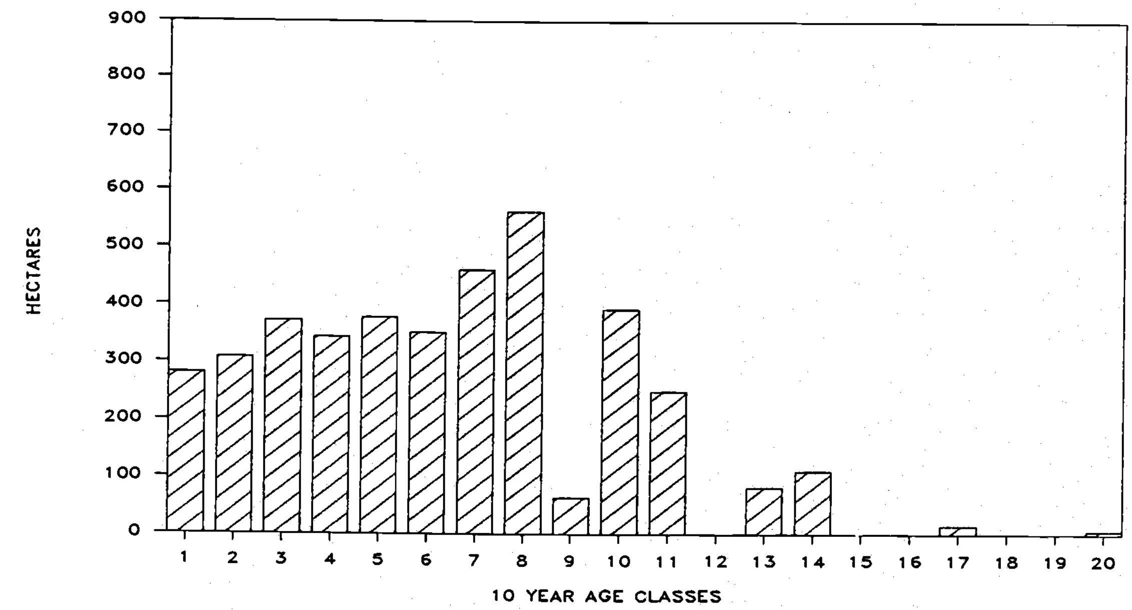
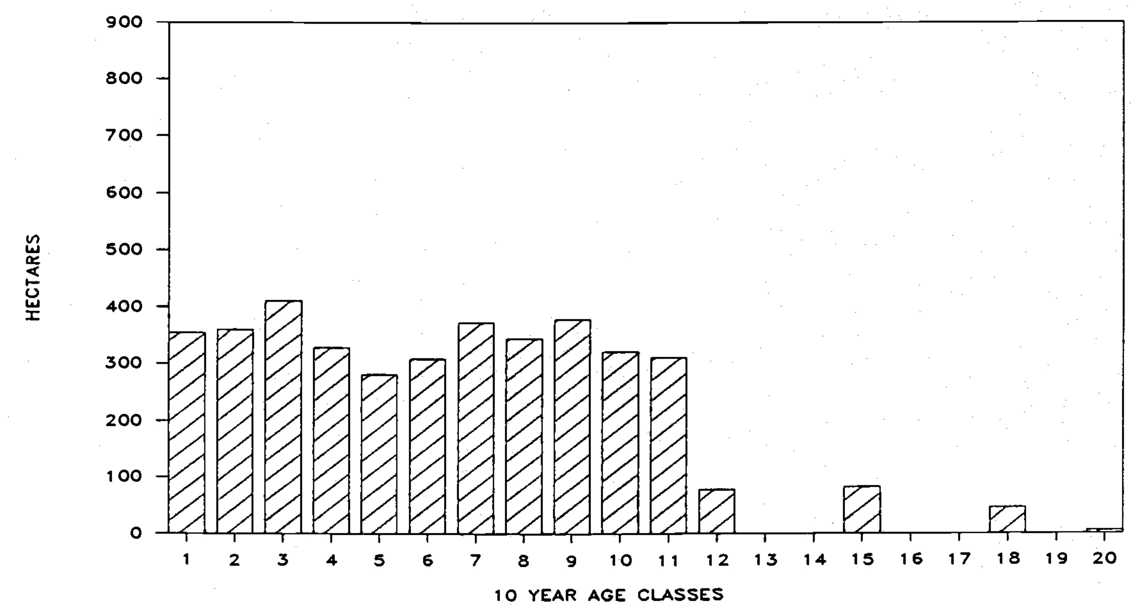


Figure 44. ILP2: Age class distribution at the start of decade 4.



<u>Figure 45. ILP2: Age class distribution at the start of decade 8.</u>



<u>Figure 46. ILP2: Age class distribution at the start of decade 12.</u>

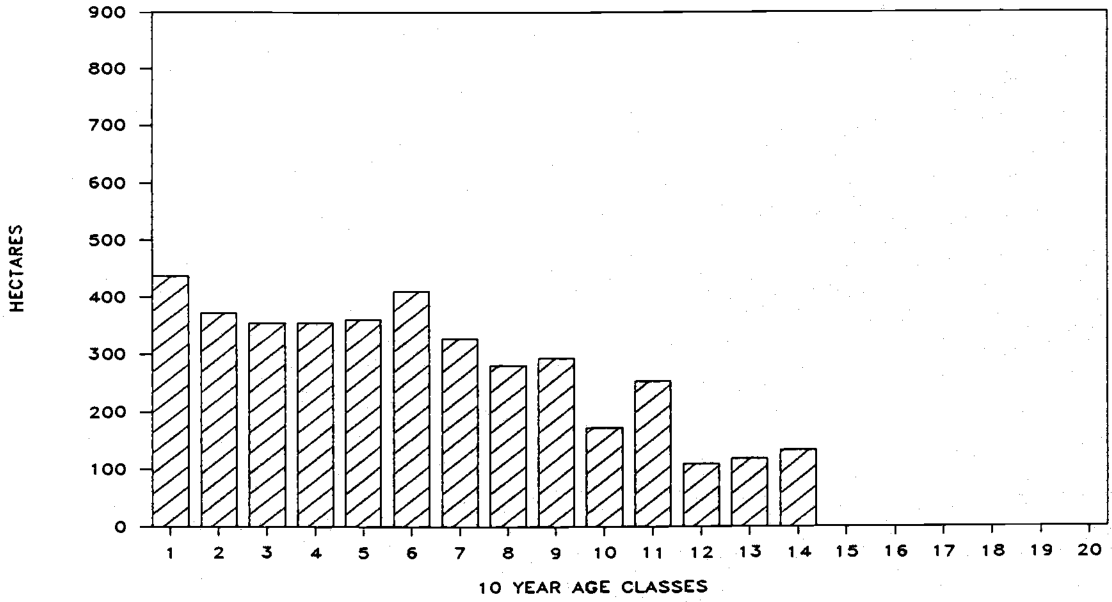


Figure 47. ILP2: Age class distribution at the start of decade 15.

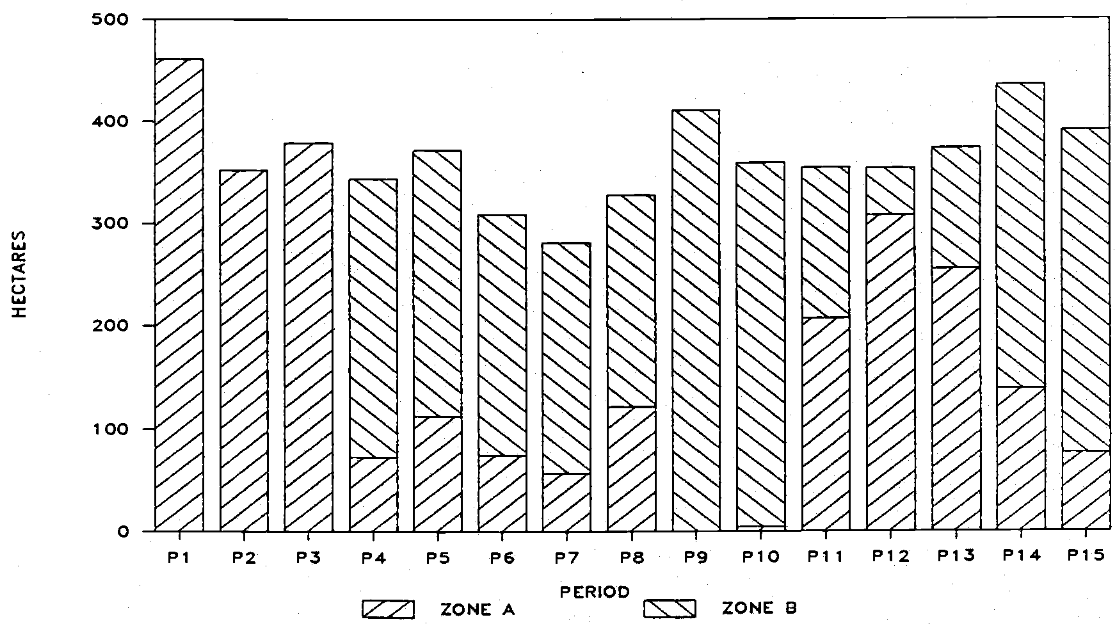


Figure 48. Distribution of ILP2 solution by zones.

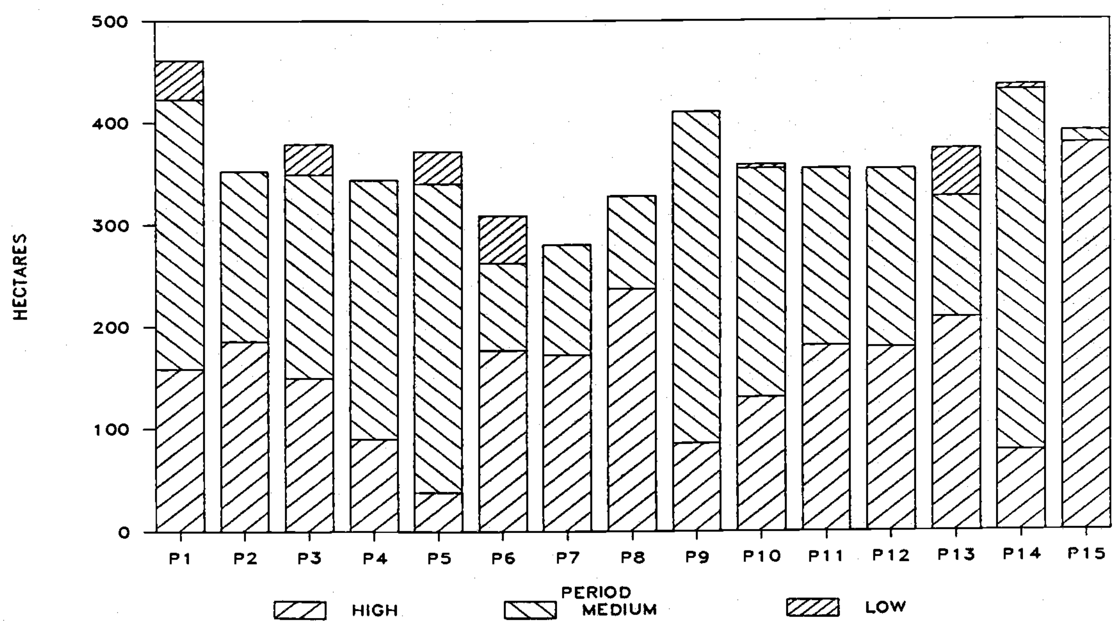


Figure 49. Distribution of ILP2 solution by site class.

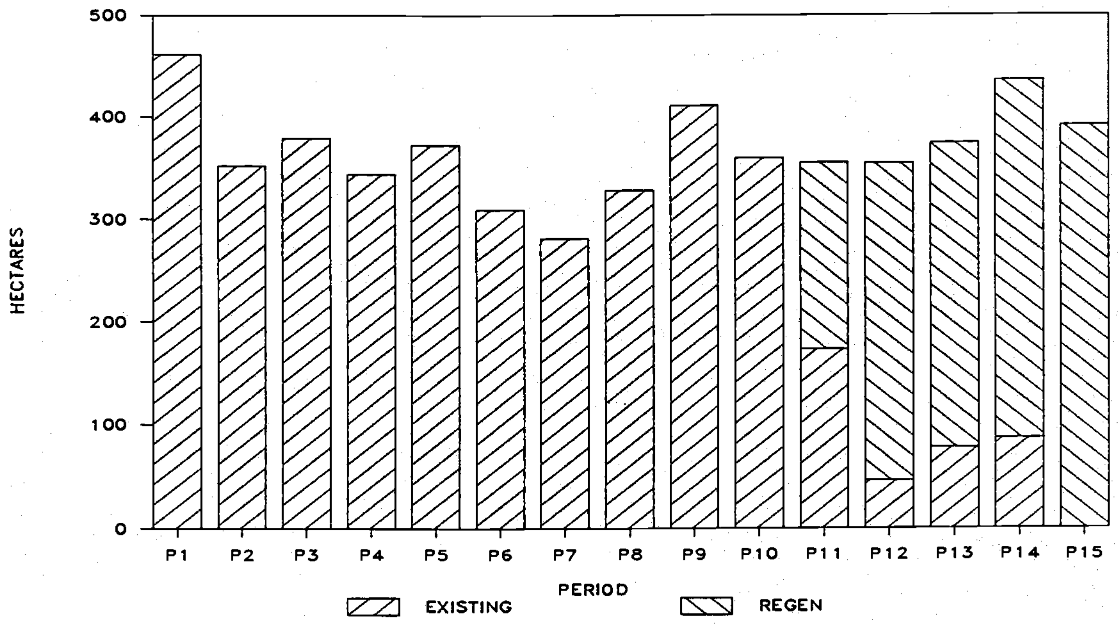


Figure 50. Distribution of ILP2 solution by existing and regenerated stands.

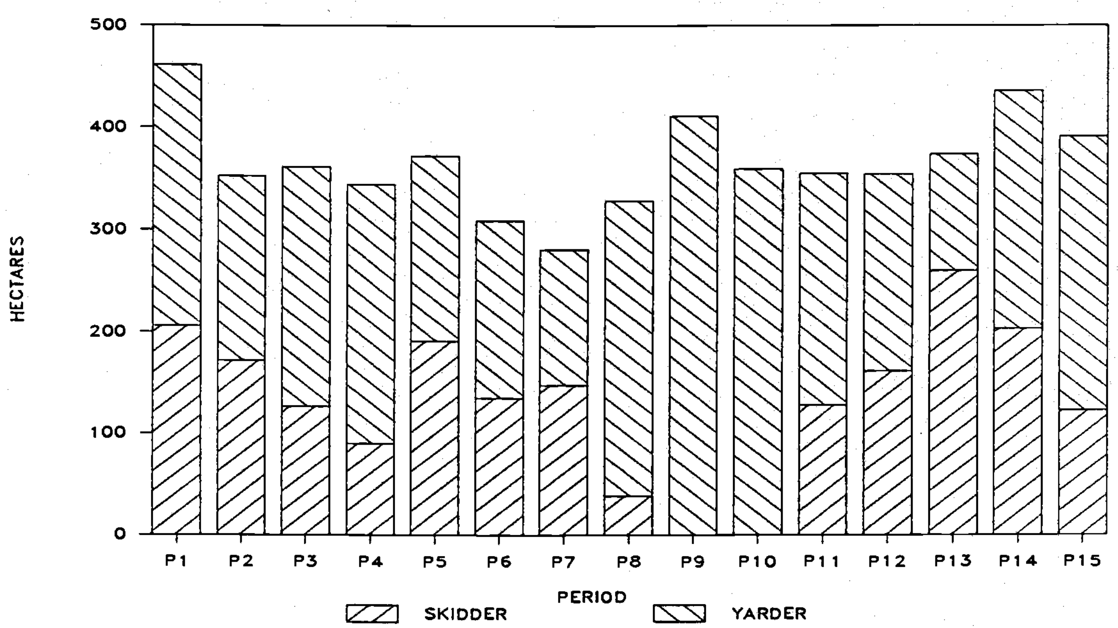


Figure 51. Distribution of ILP2 solution by logging system.

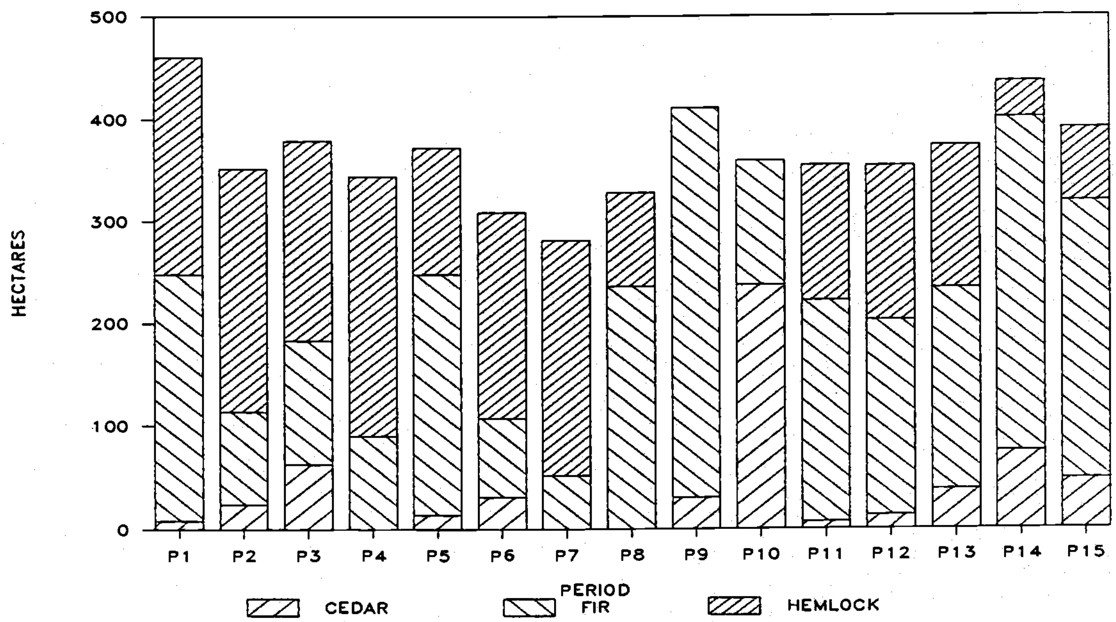


Figure 52. Distribution of ILP2 solution by species group.

APPENDIX 11

Solution to ILP3

Table 31. Summary of ILP3 solution (R= regenerated stands).

AA	Z/LS	S/S	AGE	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15
1	AS	HC	7			35				10					R35			R10
2	AS	MC	7			13										R13		
3	AS	MF	6	12		16			12						R12		R16	R12
4	AY	HH	6	35	23	12					50			R35	R23	R12		
5	AY	HC	8	13	19				4								R13	R23
6	AY	MF	8	19											R19			
7	AY	LC	20	5	12													
8	AY	HH	8	2	42	23								R2	R42	R23		
9	AS	HH	6	11	18	26								R11	R18	R26		
10	AY	LF	6			4							8					
11	AY	MF	7		18	47					30					R18	R47	
12	AS	LF	6						17									
13	AS	MF	7					28									R28	
14	AS	MF	20	27	10										R27	R10		
15	AY	MH	7	33	72	2	81							28		17		
16	AY	LH	6	18														
17	AY	MF	20	69	3	30		36							R69	R3	R66	
18	AY	MF	12	16				5							R16		R5	
19	AY	LF	7	4	9			32										
20	AS	MF	12	7	24										R7	R24		
21	AS	HH	11	15	40	6				10				R15	R40	R6		
22	AY	MH	10	10	26	81	32	48			5							
23	AS	HF	20	39	43									R73	R9			
24	AS	HH	12	25	2	46			7					R25	R2	R46		R7
25	AY	HH	10	21		4					14			R21		R4		
26	AY	HH	11			24				5						R24		
27	AS	HH	10		6	10									R6	R10		
28	AY	HH	12						15	13								
29	AS	HC	9	9		2			9							R2	R9	R9
30	AS	MH	10	14	26						4					R14		
32	BY	HF	1								161	83	108		16			R244
34	BS	HF	7						15								R11	R4
35	BS	HF	11					13	22								R13	R22
36	BS	HF	12					12									R12	
37	BS	HF	20				90		2							R90		R2
38	BY	HH	7							59								
39	BY	HH	8						35	21								
40	BS	HH	11							70								R26
41	BS	HH	12						40								R23	R17
43	BY	HC	4										26					
44	BY	MF	1											148				
45	BY	MF	2								64							
46	BY	MF	3									295						
47	BS	MF	7					47			18						R47	
48	BY	MF	8							27								
49	BS	MF	12					33									R33	
50	BY	MF	20					58									R58	
51	BS	MH	4														20	
52	BS	MH	6							62								
53	BY	MH	7				143		111						16			
54	BS	MH	8					60										
58	BY	MC	3										99					
59	BY	MC	4									37	122				47	
60	BY	MC	20					14										
61	BS	LF	1															47
62	BS	LF	6						46									
TOTAL	EXIST	HA.	CUT	404	393	381	346	386	335	277	346	415	363	176	32	17	67	47
TOTAL	REGEN	HA.	CUT											182	325	324	381	376
TOTAL	HA.	CUT		404	393	381	346	386	335	277	346	415	363	358	357	341	448	423
TOTAL	VOL	CUT		280	291	292	254	257	259	262	264	267	270	272	275	278	281	283
NET	REV			310	292	282	310	310	310	310	310	310	310	310	310	310	310	310
PNW			763.39															

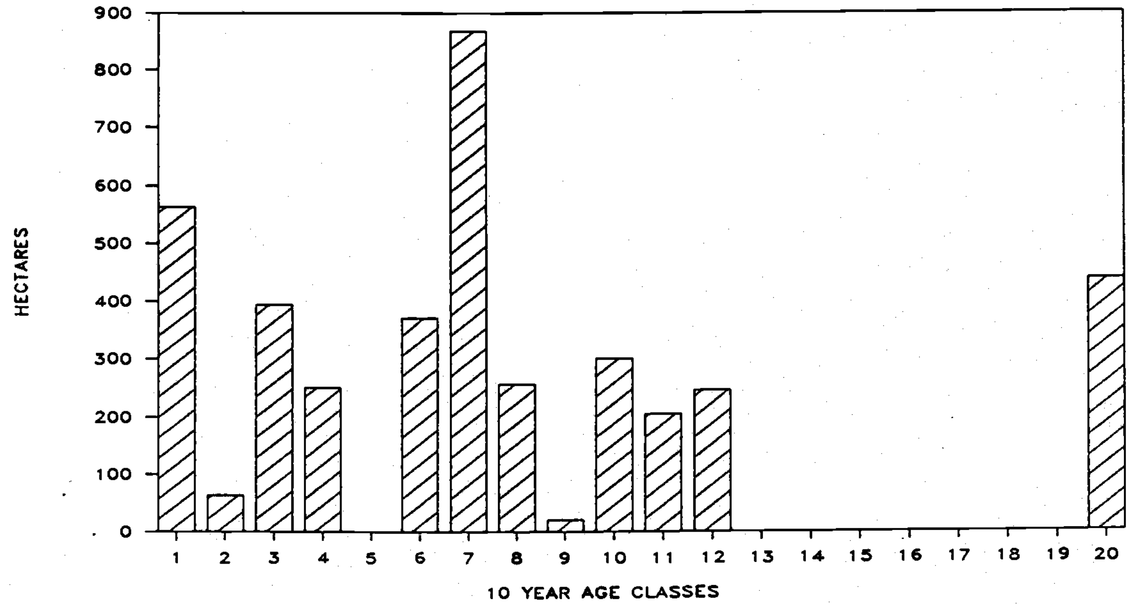


Figure 53. Initial age class distribution.

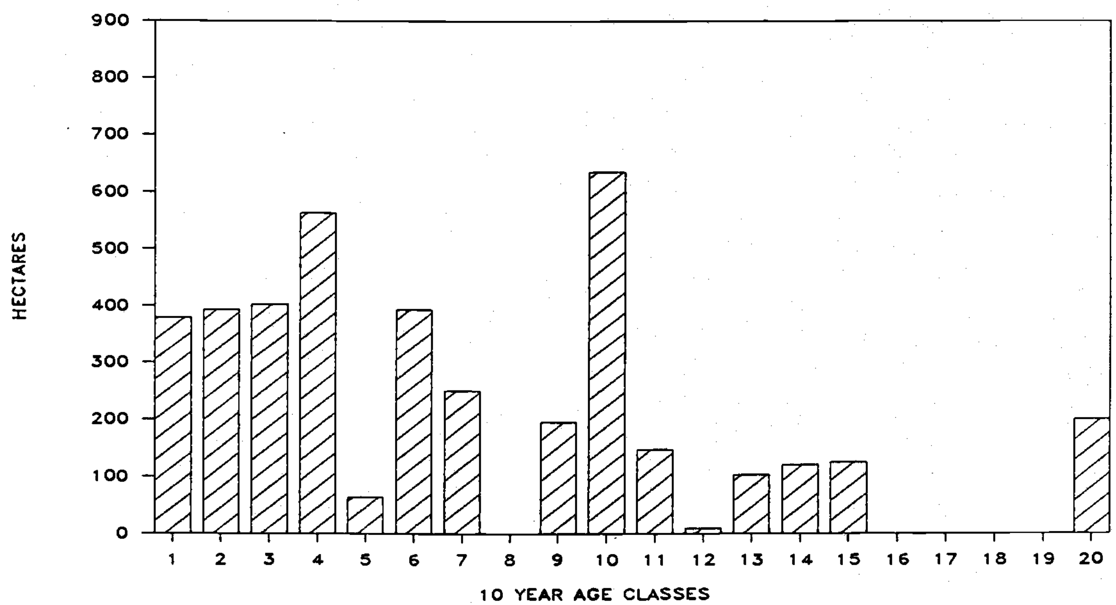


Figure 54. ILP3: Age class distribution at the start of decade 4.

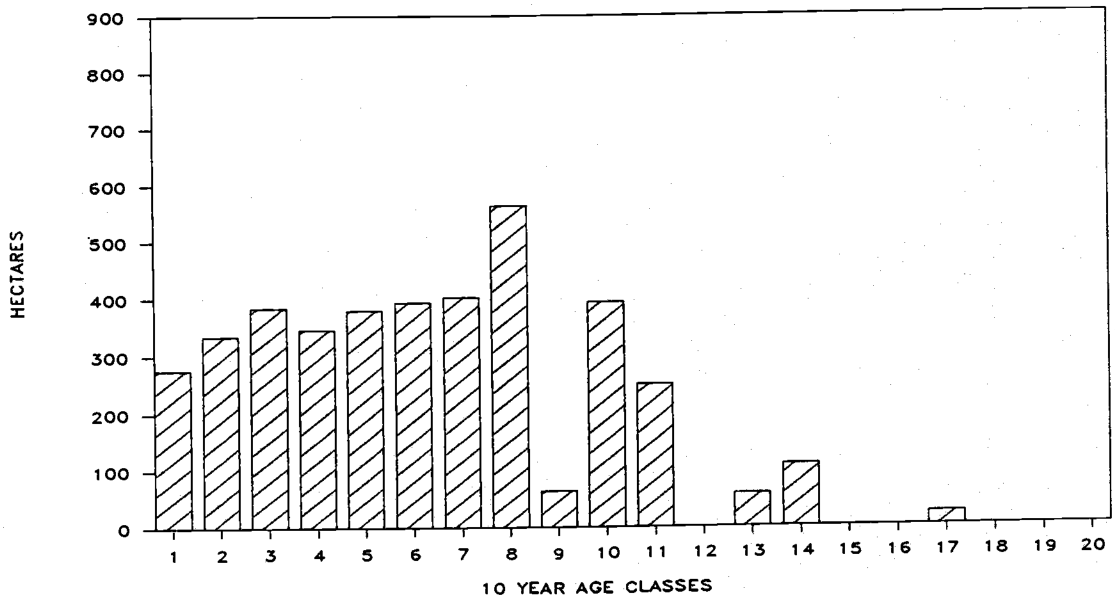


Figure 55. ILP3: Age class distribution at the start of decade 8.

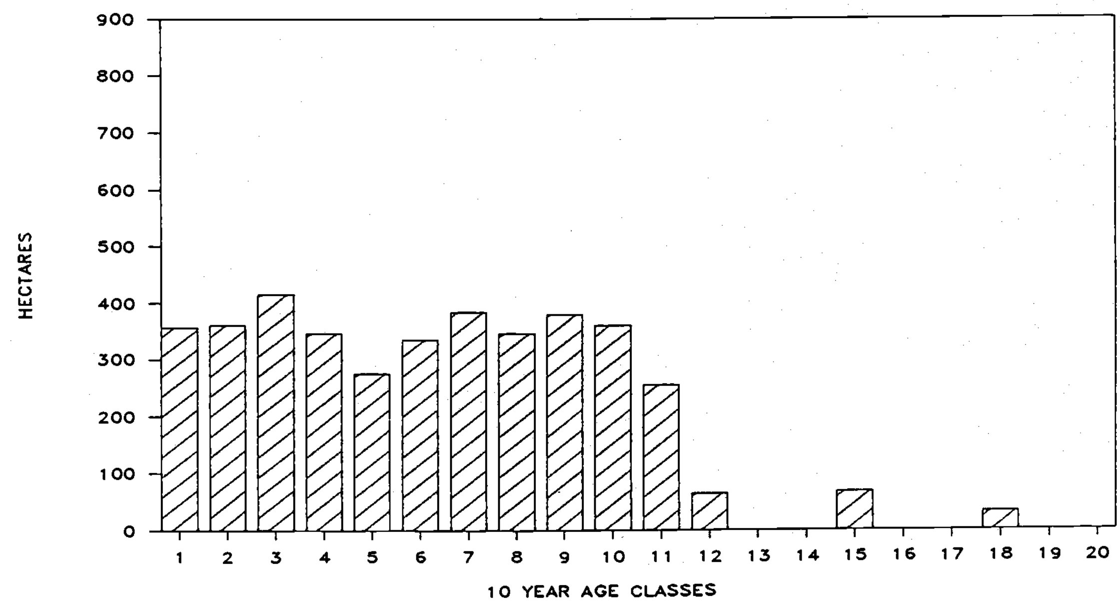


Figure 56. ILP3: Age class distribution at the start of decade 12.

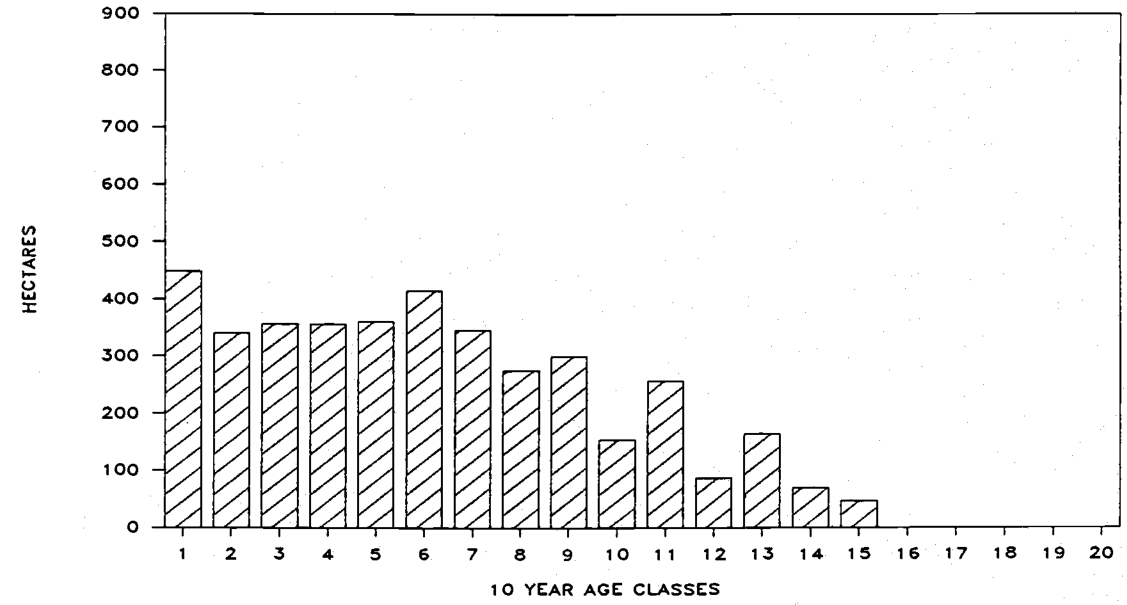


Figure 57. ILP3: Age class distribution at the start of decade 15.

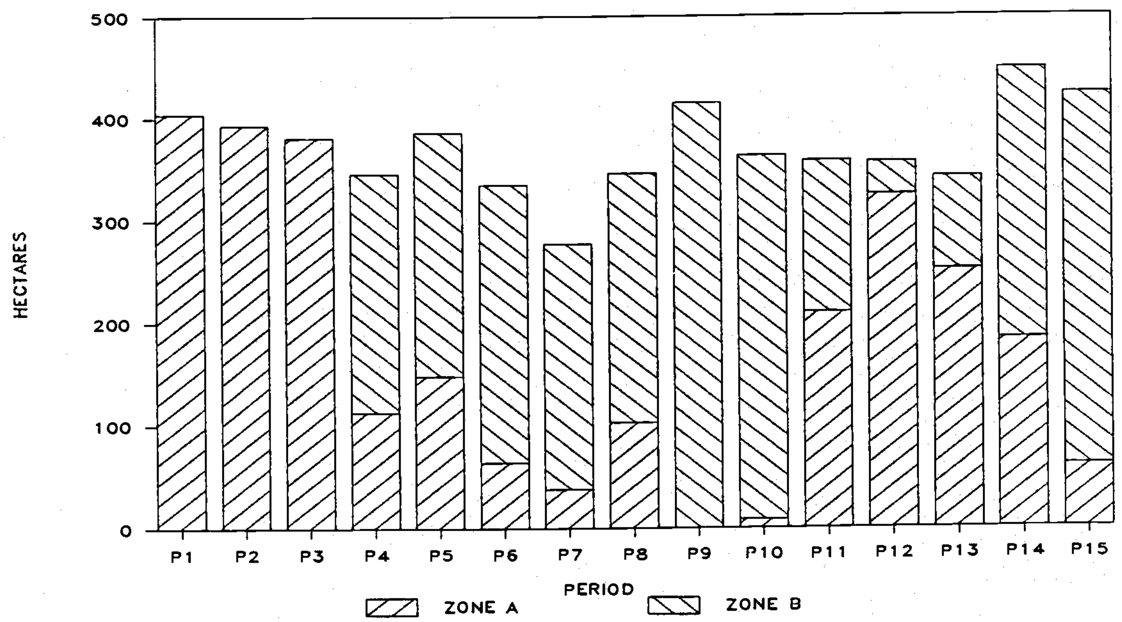


Figure 58. Distribution of ILP3 solution by zones.

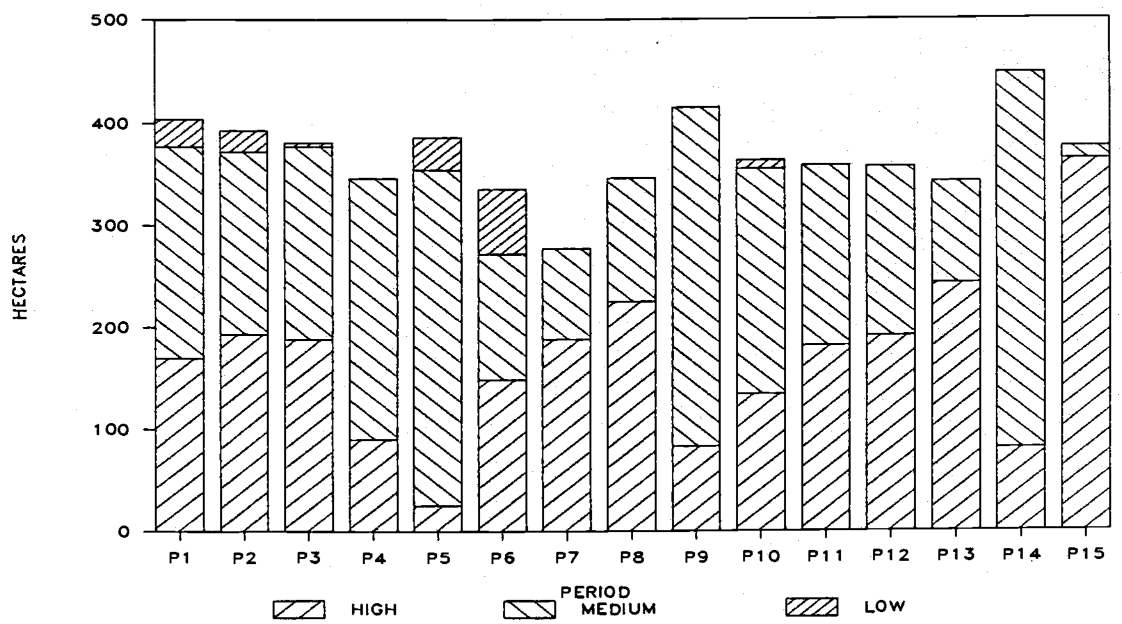


Figure 59. Distribution of ILP3 solution by site class.

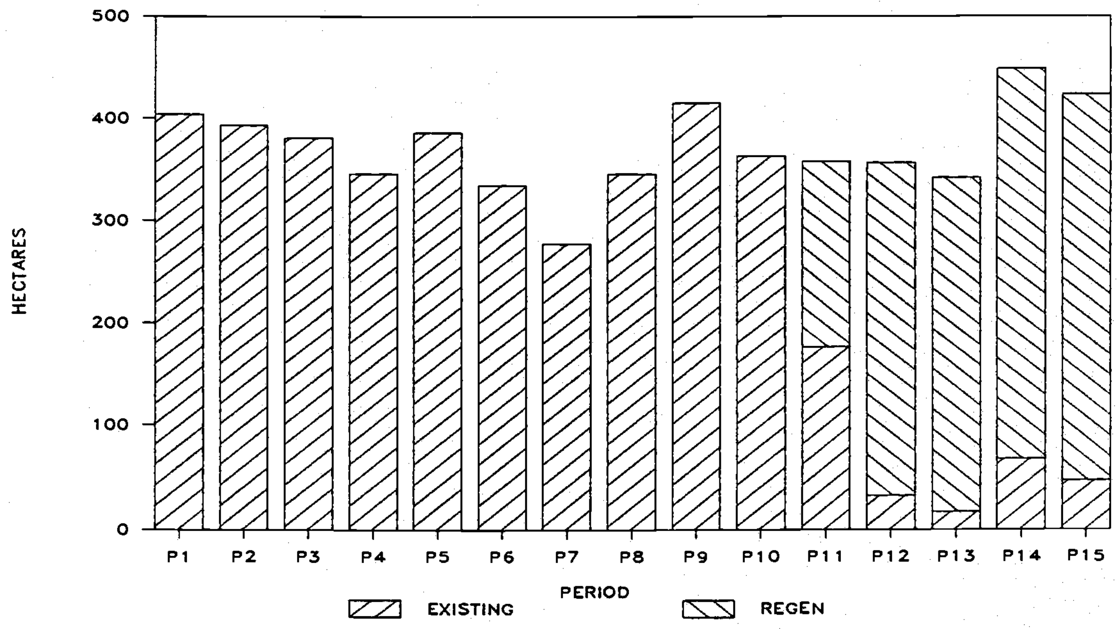


Figure 60. Distribution of ILP3 solution by existing and regenerated stands.

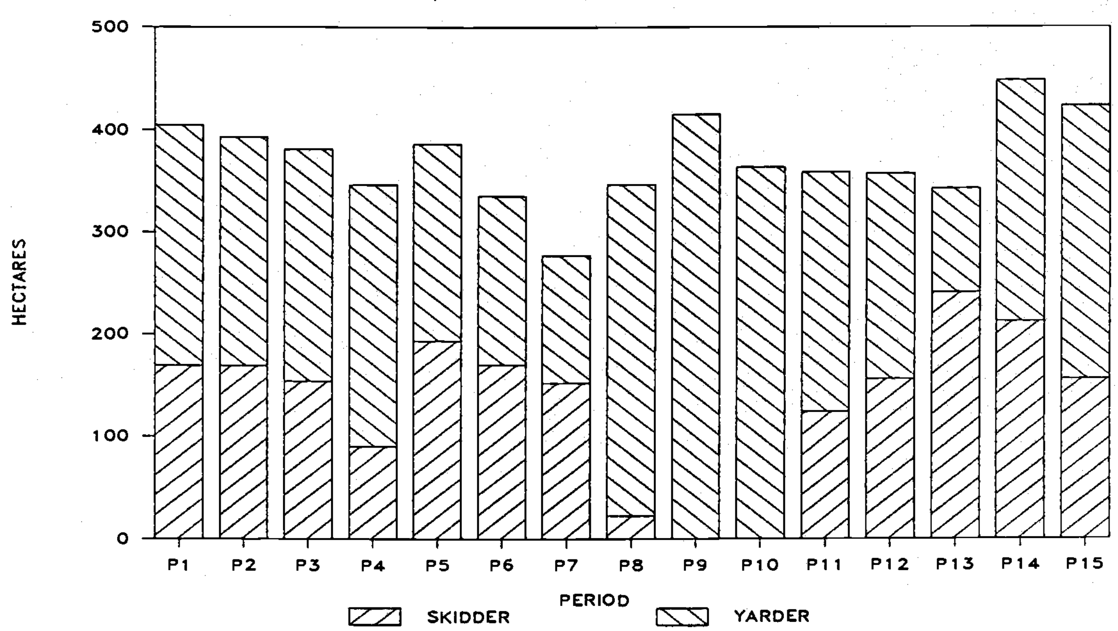


Figure 61. Distribution of ILP3 solution by logging system.

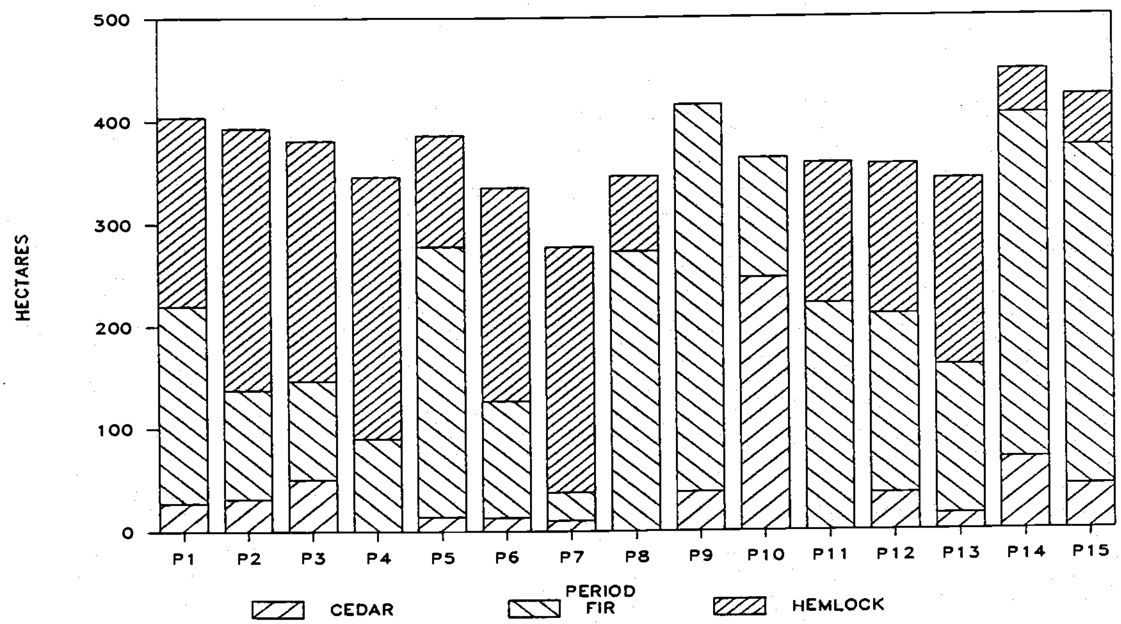


Figure 62. Distribution of ILP3 solution by species group.