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Forest management zone design with a tabu search algorithm

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Abstract

Increased conflicts between timber production and environmental protection led some analysts to advocate land-use segregation, often referred to as forest management zoning. The objective of zoning is to create ecologically desirable non-fragmented forest reserves and group timber production areas. We formulate an integer programming model of forest zoning that explicitly addresses clustering of spatial units allocated to timber production and reserve zones while also promoting separation of these zones. A tabu search algorithm is developed, implemented and tested using a case study. The case study results indicate that up to 5% of the net financial return is sacrificed with a 'satisfactory' grouping of units within each zone. A 'good' separation between the reserves and timber production zone is achieved at the cost of further decline of the net financial return up to 11% relative to the unconstrained case.

Keywords: forest planning; integer programming; reserves; tabu search; timber production; zoning

1. **INTRODUCTION**

In response to increased pressure to protect forests through reservation and tighter regulations on timber harvest and other activities in non-reserved areas, some analysts have advocated the spatial segregation of forest uses (Vincent and Binkley 1993; Hunter and Calhoun 1996). In this paper, we refer to this segregation of land uses as zoning. A forest management zoning consists of selecting and allocating spatially defined forest cells (units) to different uses according to specific criteria. Required criteria for cell selection in forest zoning at the strategic planning level typically deal with the zone size, its location and shape. The forest zoning design is a special case of a more general spatial cell allocation problem, which includes various applications from urban planning to design of natural reserves (Shirabe 2005).

In forest planning, the importance of spatial land allocation for both timber and non-timber values has been widely recognized. The size, shape, and distribution of forest patches left for conservation determine the availability and quality of wildlife habitat. Less fragmented reserves are generally preferred (Hunter 2001). Likewise, geographical location and relative position of cells allocated to timber production affect the production cost. Widely dispersed production cells are more expensive to harvest than spatially concentrated ones (Baskent and Jordan 1991; Rose and Chapman 2003).

One of the most frequently required criteria in spatial cell allocation problem is continuity or connectivity of a group of cells. Because of the complexity to operationalize continuity, many models in the literature addressed grouping or clustering of an allocation as opposed to its spread. A variety of modeling approaches has been developed using mathematical optimization (Shirabe 2005; Fischer and Church 2003; Williams 2002), heuristics (Baskent and Jordan 2002; Nalle et al. 2002; Ohman 2000; Boston and Bettinger 1999) and simulation techniques (Gustafson 1998).

To improve forest management both ecologically and economically, Seymour and Hunter (1992) suggested a three-zone framework, which included an intensive timber production zone in addition to reserves and multiple-use zone. Questions posed by policy makers, forest managers and academics include not only how to model zoning, but also the impact of zoning on forestry outputs. Only few studies in forest literature address the spatial land allocation to multiple uses. Davis and Johnson (1987) were among the first to discuss allocation of spatially defined forest cells to different uses. They formulated the land allocation problem as a mixed-integer linear program, but did not impose spatial requirements to zones. Adding a spatial land allocation component to the harvest scheduling model resulted in a decline of both net present worth and total harvest volume (Davis and Johnson 1987). Bos (1993) studied the allocation of forestland among timber production, nature conservation and recreation, formulating the zoning problem as a quadratic assignment model. The model objective function constructed with the suitability indices does not allow the tradeoff analysis. Gustafson (1998) examined effects of clustering timber harvest areas on forest fragmentation over different temporal and spatial scales. The study results indicate that clustering of harvests produces less forest fragmentation than dispersed harvesting. However, the harvest simulation model used in the study cannot provide quantitative tradeoffs between several outputs.

Using solutions to mixed-integer linear programs, Krcmar et al. (2003) compared the traditional two-zone land allocation framework, which included reserves and the multiple-use zone, with a three-zone scheme by adding a timber production zone. The idea was to offset increased reserve area with intensively managed timber production. Because of an 'a priori' aggregation of cells into larger units, testing different spatial configurations by this approach was not possible.

In this paper, we extend the results of previous studies by developing a model and a solution approach to a forest zone design problem that decreases fragmentation of both the reserves and production zone while also encourages their spatial separation. We analyze the impact of such zoning on financial benefits of timber harvest. The paper is organized as follows. The next section describes the forest zoning problem and model developed. Section 3 presents the solution methodology. In Section 4, the results of an empirical study in northeast Ontario are analyzed. The conclusions follow in Section 5.

2. PROBLEM DESCRIPTION AND MODEL FORMULATION

We formulate the strategic model of forest zoning for land allocation and scheduling of management treatments in such a way that, once an optimal land allocation is determined, it does not change over the planning horizon, which leads to a static zoning design. The model starts with a number of candidate forest cells (units) from which subsets are to be assigned to reserves and intensive timber production, with remaining cells assigned to the multiple-use zone. Each cell is given a unique zoning assignment and a unique treatment schedule. It is assumed that the cells are raster-type, e.g., uniformly sized and square shaped.

The zoning problem is modeled so that financial benefits from timber harvest are maximized, while protecting environmental values that are expressed as requirements for clustering cells within the reserves and timber production zone and spatial separation of these zones. Ecological constraints are expressed in terms of the minimum area set aside for reserves and the minimum proportion of area that should remain in old-growth conditions. For ecological reasons, the maximum size of the production zone is also introduced. A model solution consists of a zoning assignment and treatment schedule for each forest cell.

This section presents a non-linear 0-1 mathematical programming formulation of the zoning problem. It is a spatially explicit optimization model for selecting forest cells for reserves and intensive production in order to maximize cumulative discounted net financial returns, while satisfying a minimum reserve area requirement and limiting the production area. The model promotes but does not guarantee clustering of forest cells allocated to reserve and intensive production. To avoid conflicts between ecological protection and intensive production, the model attempts to locate reserves as far away from the production zone as possible.

The model elements are defined as follows. Each cell $c \in C$ is defined in terms of species, site quality, age class, its geographic (spatial) location and relationships to other cells (adjacency and distance), distance to the secondary road network, and distance to a processing facility. A cell can be assigned to one of three zones – timber production (P), reserves (R) and multiple-use (M). Let $T(c)$ be the set of management treatments appropriate to cell c. A treatment assigned to a cell consists of the series of silviculture activities performed over the planning horizon and depends on the silviculture regime chosen. Three silviculture regimes – extensive, basic and intensive – are considered in this study. The extensive regime assumes natural regeneration of harvested stands, while the basic regime assumes artificial regeneration. Neither the basic nor extensive regimes include silvicultural activities after regeneration. The intensive regime includes several activities after artificial regeneration of denuded stands, the timing of which is fixed relative to the harvest period. For each silvicultural regime we consider one treatment with a ‘no harvest’ activity. Other treatments include a ‘harvest’ activity that can take place in several time periods over the planning horizon.

Decision variables x_{cm}, y_{cm} and z_c are to be associated to each cell c such that: x_{cm} equals 1 if cell c is assigned to the production zone and managed by treatment m, and 0 otherwise; y_{cm} equals 1 if cell c is assigned to the multiple-use zone and managed by treatment m, and 0 otherwise; and z_c equals 1 if cell c is assigned to nature reserve, and 0 otherwise, as no management is assumed for the reserve zone.

Let parameter npv_{cm} represent the discounted net financial benefits of managing cell c by treatment m if the cell is in the multiple-use or production zone. This parameter includes timber value and production cost. The timber value (TV) is defined as the price ($\$/m^3$) paid for timber at the mill gate and depends upon species, grade and log size, where the latter is a function of the silvicultural regime that is applied. The production costs consist of five components: silviculture (SC), logging (LC), spur road building (SRC), hauling (HC), and transportation (TC).

SC ($\$/m^3$) includes the costs of several phases: site preparation, acquiring new stock, planting, tending, pre-commercial (PCT) and commercial thinning (CT), and monitoring. LC ($\$/m^3$) consists of direct logging costs (felling, delimbing and bucking of trees) and indirect costs that include carrying and administrative costs, operational overhead, contribution to a silvicultural trust and so on. We assume that main and branch roads are already in place, so road construction is not a consideration except for spur roads. Construction of spur roads (SRC) is assumed to occur at the time of harvest. The cost of hauling (HC) depends on the cell’s distance to the secondary road network. The hauling cost is calculated for each cell by multiplying the hauling distance (km) by an average hauling cost ($\$/m^3/km$). The transportation cost (TC) depends on the cell’s distance from the processing facility. Similar to hauling, the transportation cost is calculated for each cell by multiplying the cell's distance from the mill by the average transportation cost.

If we denote by vol_{cm} the volume (m^3) harvested from cell *c* managed by treatment *m*, then the net present value of timber benefits ($) is calculated as:

$$npv_{cm} = (TV - SC - LC - SRC - HC - TC)vol_{cm}.$$

Economic values – benefits and costs – are in constant dollars. Several phases of silviculture, road construction, transportation and harvesting take place at different times. Rather than lumping together all the costs to get an average cost per cubic meter of timber harvested, we keep track of the costs along with when they occur, and discount them accordingly. A real discount rate of 4% is assumed.

In addition, og_c is an indicator of the old-growth status of cell *c*; og_c equals 1 if cell *c* is in the old-growth condition, and 0 otherwise. A distance between cells *c* and *f* is denoted by d_{cf}, while b_R denotes the minimum number of cells to be allocated to the reserve zone; b_{OG} is the minimum portion of the reserve zone in old-growth condition, and b_P is the maximum number of cells to be allocated to the intensive production zone.

The zone design problem consists of assigning each cell to one of the three zones and selecting the cell management treatment (the regime and harvest schedule) to maximize the overall objective function. The 0–1 optimization model follows:

Maximize
$$\alpha \sum_{c \in C} \sum_{m \in T(c)} npv_{cm}(x_{cm} + y_{cm}) + \beta \sum_{c \in C} \sum_{f \in C} \sum_{m \in T(c)} x_{cm} d_{cf} z_f$$
$$- \chi \sum_{c \in C} \sum_{f \in C, f > c} \sum_{m \in T(c)} \sum_{n \in T(f)} x_{cm} d_{cf} x_{fn} - \delta \sum_{c \in C} \sum_{f \in C, f > c} z_c d_{cf} z_f \qquad (1)$$

subject to:

$\sum_{c \in C} z_c \geq b_R$ Minimum area of reserves (2)

$\sum_{c \in C} og_c z_c \geq b_{OG} \sum_{c} z_c$ Minimum area of old growth forest within reserves (3)

$\sum_{c \in C} \sum_{m \in T(c)} x_{cm} \leq b_P$ Maximum area in the intensive production zone (4)

$\sum_{m \in T(c)} (x_{cm} + y_{cm}) + z_c = 1, \quad \forall c \in C$ Each cell allocated to only one zone and treatment (5)

$x_{cm} \in \{0,1\}, \; y_{cm} \in \{0,1\}, \; z_c \in \{0,1\}$ Non-negativity and integrality (6)

The first term in the objective function (1) represents the net present value of forest management activities over the intensive production and multiple-use zones. The second term measures the distance between reserve and production zones, while the third and fourth terms are measures of clustering of the cells within the reserve and production zone, respectively. Since the objective is maximization, terms that refer to clustering are subtracted. The parameter α>0 scales net present value (NPV), while β>0, χ>0, and δ>0 scale distances to make NPV and distance measures comparable. Constraints (2) and (3) ensure that the minimum required area of the reserve and old-growth forest are met, and constraint (4) limits the production area. Constraint (5) ensures that each cell is assigned to only one zone and one treatment. The last constraint provides for non-negativity and integrality of decision variables.

3. SOLUTION METHOD: A TWO-PHASE TABU SEARCH PROCEDURE

Tabu search is a local search algorithm that has the ability to continue exploring the solution space after a local optimum has been reached (Glover 1989; 1990). It includes a method that enables escape from a local optimum (current solution) to the best solution in its neighborhood by exploring larger portions of the search space. To avoid cycling through the same solutions, any previously visited solutions are declared to be 'tabu' for a certain number of iterations. The tabu search procedure starts with an initial solution that consists of a set of zone-treatment pairs for each forest cell. The initial solution is determined by assigning the cells to the zones according to the cells' labels. First, cells are assigned in succession to the reserves until all constraints related to the minimum reserve size and minimum old-age portion within the reserve zone are satisfied. Then, the remaining cells are assigned to the production zone until the maximum allowable area of this zone is reached. The remains is allocated to the multiple-use zone. In the initial solution, all cells assigned to either timber production or multiple uses are treated extensive silviculture while harvest period is determined randomly.

A neighboring solution to the current solution is obtained by switching the zoning assignment of any two cells. The size of the neighborhood is $n(n–1)$, where n is the number of cells. However, not the whole neighborhood is explored as two cells within the same zone are not considered because this would result in the same solution. As one of the objectives is to group cells belonging to the P and R zones, eligible moves include: (a) switching a cell in P zone with either a cell in R or cell in M zone, or (b) switching a cell in R zone with either a cell in P or cell in M zone.

The tabu search procedure explores only feasible solutions. For instance, in the case of old-growth forest cells, only a 'switch' with another old-growth cell is permitted in order to satisfy the minimum size of old-growth forest in the R zone. Due to zone switching mechanism, the remaining two constraints on the maximum allowable P zone and minimum R zone areas are satisfied, providing the move results in a feasible solution.

Two-phase tabu search algorithm

We solve the zoning problem using a two-phase tabu search method. The phases differ in terms of the corresponding objective functions. In the *first phase*, we explore neighborhoods by maximizing the *NPV* portion of the model objective function. The stopping criterion for the first phase is set using the number of iterations (*N1*) within which the 'best' solution no longer improves the objective function. The *second phase* of the tabu search procedure maximizes the sum of normalized *NPV* plus a term that measures the spatial features of a particular zoning assignment:

$$z = NPV + ZD \tag{6}$$

where *ZD* is a distance between zones, *ZD* = *avgPR* - *avgPP* – *avgRR*. Value *avgPR* is the average distance between two cells, one in the *P* zone and the other in the *R* zone. Similarly, *avgPP* and *avgRR* are the average distances between two production and reserve cells, respectively. The objective is to minimize *avgRR* and *avgPP*, and to maximize *avgPR*.

We apply the following stopping criteria for the second phase:

1) the maximum percentage (*PCNT*) decrease of the *NPV* at the current solution relative to the best *NPV*, where the best *NPV* is that found in the first phase of the tabu search procedure; or
2) no more improvements of the objective function can be achieved after the number of iterations (*N2*).

An outline of our tabu search procedure follows:

```
tabuSearchProc() {
     // First phase
     ONLY_NPV = true;
     while (number of iterations without the best solution improvement < N1){
            findBestInNeighborhood();  // by switching R and (P or M)
            updtBestSoln();
     }
     // Second phase - Start to consider zone distances
     ONLY_NPV = false;
     largestNPV = bestSoln.getNpv();
```

```
        while (currSoln.getNpv() > largestNPV*(1-PCT/100)) {
        //while (number of iterations without the best solution improvement < N2){
              findBestInNeighborhood(P);  // by switching P with R or M
              updtBestSoln();
              findBestInNeighborhood(R);  // by switching R with P or M
              updtBestSoln();
        }
}
```

Finally, we also tested variations of the procedure where the neighborhood exploration stops when a non-tabu solution better than the current one is found. To improve the algorithm's time to reach a solution, only the change in the objective function value is calculated for each neighbor being explored.

Tabu list and aspiration criterion

The tabu list represents a short-term memory of the algorithm. Tabu moves are stored in the tabu list by means of the cell index and its zoning assignment. Once a zoning assignment (denoted z) of cell j is changed, pair (j, z) is added to the tabu list. The assignment z to cell j remains tabu for a certain number of iterations, referred to as the tabu *tenure*. In our tabu search procedure, the tabu tenure is a random number between *MIN_TABU* and *MAX_TABU*.

The aspiration criterion defines when to override the tabu status of a move. Our algorithm implements a simple aspiration criterion that allows a tabu move to be accepted if it leads to a solution better than the best solution obtained so far. A diversification is implicitly present in this algorithm by the use of random tabu tenures. The random tabu tenures imply a variable tabu list length, which may be seen as the simplest form of the diversification mechanism.

4. COMPUTATIONAL STUDY

The modeling and solution approach is applied to a case study within the Romeo Malette forest near Timmins, Ontario. The 4,824 ha study area is rasterized into 300 meters by 300 meters cells, organized into 17 rows and 31 columns. The cell labeling starts with 0, which is assigned to the cell in the upper left (north-west) corner of the area and continues row by row.

In Ontario, current forest legislation requires 10-20% of the forest area to be maintained in old-growth conditions to provide habitat for marten. Accordingly, the minimum amount of reserve area (*R*) in each period is set to 20% of the total area under consideration, while a minimum 60% of the reserve area should remain in old-growth conditions (age 120 years or older). The intensive timber production zone (*P*) cannot exceed 50% of the total area under consideration.

The 100-year planning horizon is divided in ten decadal periods. The three silvicultural regimes considered are extensive, basic and intensive. Figure 1 represents the case study area in terms of the forest types and age distributions of trees at the beginning of the planning horizon. The forest types are Birch Poplar (BW1), Lowland Conifer (LC1), Jack-Pine Mixed (MW1), Spruce Mixed (MW2), Jack Pine (PJ1), Pine Spruce (PJ2), Poplar (PO1), Black Spruce Lowland (SB1), Spruce Fir (SF1), and Spruce Pine (SP1). The location of the horizontal black line within the cell represents the initial stand age. Higher the line is within a square, older the stand is.

<Insert Figure 1 about here>

Solution procedure and solutions

The solution procedure is tested with parameter values *N1*=100, *N2* =50, and *PCNT* $\in$ {3%, 5%, 10%}. If the *PCNT* criterion is not reached within 20 minutes of the second phase, the algorithm is artificially halted. As for the tabu tenure, preliminary experiments (not reported in the paper) were performed with [5, 15] values for [MIN_TABU, MAX_TABU]. The values were then increased to [20, 50]. Outcomes of the algorithm with the latter tabu tenure values are reported in Table 1.

<Insert Table 1 about here>

The values reached in Phase I (Table 1, row 2) serve as benchmarks for the Phase II procedure. The values of the objective *z*, grouping indicators *avgPP* and *avgRR*, and separation indicator *avgPR* in the last three rows of Table 1 all improved relative to their benchmarks. This was made possible by the reduction of NPV (Table 1, column 2).

The case study solutions are graphically represented by coloring each cell in one of three colors depending on the current zoning assignment: green indicates the reserve zone (*R*), red indicates the timber production zone (*P*), and yellow indicates the multiple use zone (*M*). In addition, a black horizontal line within a cell indicates the timing of harvest. If the line is placed lower within the cell, harvesting occurs in the near future, while higher positions of the line indicate later harvest periods.

Figures 2(a) and 2(b) illustrate the spatial distributions of zones and harvest schedules for the initial solution and the Phase I solution, respectively. The spatial distribution of zones in Figure 2(a) illustrates how the initial solution was generated. The green band of cells (representing reserves) is located in the upper portion of the study area and is only interrupted by non-forested cells (rivers and lakes). The mid, large section of the study area is assigned to the production zone, followed by the multiple-use zone in the lower part of the figure. The production zone is not fully continuous as both the reserve and non-forest cells are located within its boundaries. The only almost continuous zone is the multiple-use one.

The solution to the Phase I assignment is shown in Figure 2(b). In sharp contrast to the zoning structure of the initial solution, the cells allocated to reserves and multiple uses are scattered all over the study area.

<Insert Figure 2 about here>

Figures 3(a)-(c) illustrate the spatial distributions of zoning assignment for the three solutions of Phase II, when the *PCNT* stopping criterion is applied. The three solutions presented in Figure 3 are obtained for *PCNT* values of 3%, 5% and 10%, respectively. As *PCNT* increases, gradual grouping of cells assigned to the reserve and production zones occurs (Figure 3). There is only a slight difference between grouping in Figure 3(b) and that in Figure 3(a). Several reserve cells located in the south-east part of the region (Figure 3(a)) switch from reserves to timber production or multiple uses (Figure 3(b)). This allows for better grouping of the reserve cells located in the western part of the region (Figure 3(b)). Stronger grouping of the timber production cells and those of the reserves happens for the PCNT value of 10% as illustrated in Figure 3(c). In this case, zones come in large continuous patches.

<Insert Figure 3 about here>

Separation between the reserves and production zone was not reached until the best NPV achieved in Phase I is permitted to decline by 10%. Figure 3(c) shows the reserve zone located mostly at the west side of the region and separated from the production zone by the multiple-use cells. In this final figure, the production zone is moved to the eastern part of the region. Such location has several benefits: closeness to the secondary road and the mill located east of the study region. The graphical illustration presented in Figure 3 suggests that, under the current weights applied in the overall objective function, grouping of the single-use cells occurs earlier than their spatial separation. Another conclusion is that grouping is somewhat less costly than the separation property.

The results are not sensitive to variation in the number of iterations *N2* used in Phase II, at least within the range examined here. The spatial distribution of zones was similar to that presented in Figure 3(c). The maximum observed reduction of the NPV achieved in Phase II relative to Phase I was slightly above 11%. After reaching an 11% tolerable sacrifice in NPV, the combined objective value could not be improved further. The latter result suggests that, for this case study, the costs of grouping the cells assigned to single-use zones and the separation of these two zones does not exceed 11% of the best NPV achieved in Phase I.

In this study, we assumed that reserves do not provide economic benefits or that they bear management costs. Further, we do not account for the cost savings due to grouping of the production cells. If additional costs savings from the 'tighter' groupings of the reserve and production zones were added, the relative loss in NPV in Phase II of the algorithm might be significantly lower.

Computational performance

With continual improvements in computer technology, the speed at which the zoning problem with 476 cells reaches a solution is relative to the computer employed. Computational tests were performed on a Sun Sparc Ultra 5. The best solution in the first phase of the tabu search procedure was reached after 50 iterations or about 30 seconds, with remaining iterations not able to improve the solution. The second phase of tabu search procedure lasted four minutes when *PCNT* was 3%, six minutes when *PCNT* was 5%, and 20 minutes when *PCNT* was 10%. We tested an alternative to our tabu search procedure that stopped exploring the neighborhood whenever a solution better than the current one was found. The alternative procedure did not reduce the search speed significantly.

5. CONCLUSIONS

In this paper we explored a forest zoning problem using a tabu search procedure that we developed to determine the ‘best’ allocation of forest cells to the reserves and intensively managed timber production zone. One of the objectives of the research was to determine sensitivities pertaining to grouping of forest cells into single-use zones and separation of nature reserves from intensive production by multiple-use areas. Results of a computational study indicate that our algorithm can be used to obtain a ‘satisfactory’ grouping of cells within each zone, a good separation between the reserve and production zones, and complete satisfaction of the imposed zone size and old-growth constraints. However, the extent to which this occurs comes about at some sacrifice in financial returns. As cells keep grouping more tightly within the zones, our computations indicate that NPV decreases gradually up to 5% of its best value in Phase I. A ‘good’ separation between the reserves and timber production zone is achieved at the cost of further decline of NPV up to 11% relative to the unconstrained case.

The major rationale for grouping cells within a production zone is to take advantage of decreasing production costs due to reduced road building, transportation, administrative, monitoring and other costs. These ‘savings’ are not included in the objective function. Therefore, whether our results hold more generally, and whether the ‘tighter’ grouping leads to offsetting financial benefits, are subjects that future research needs to address.

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List of figures

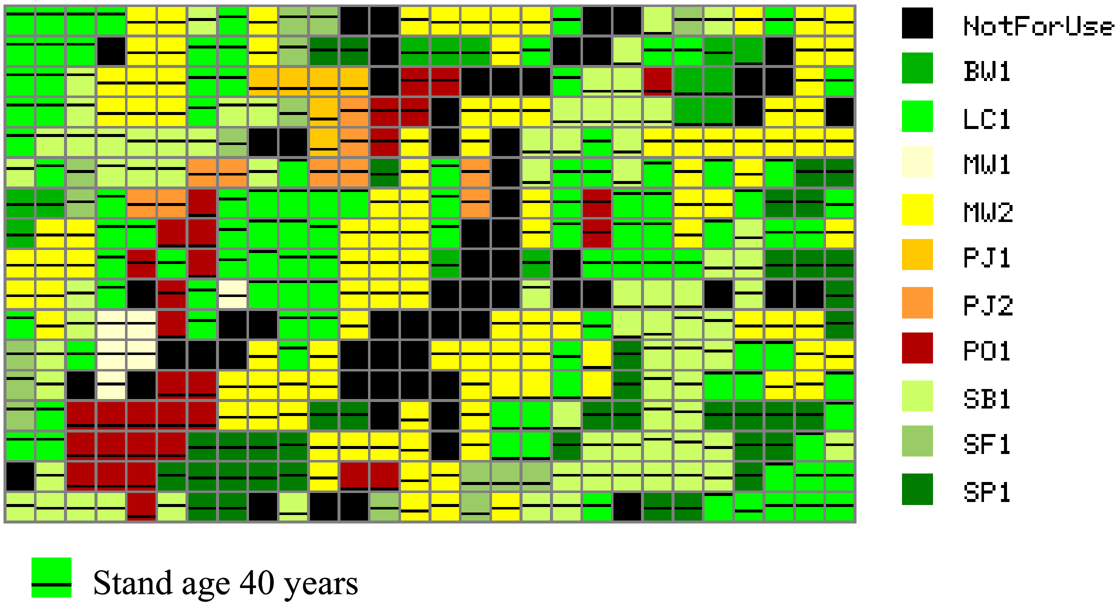

Figure 1. Study area in terms of forest type and age.

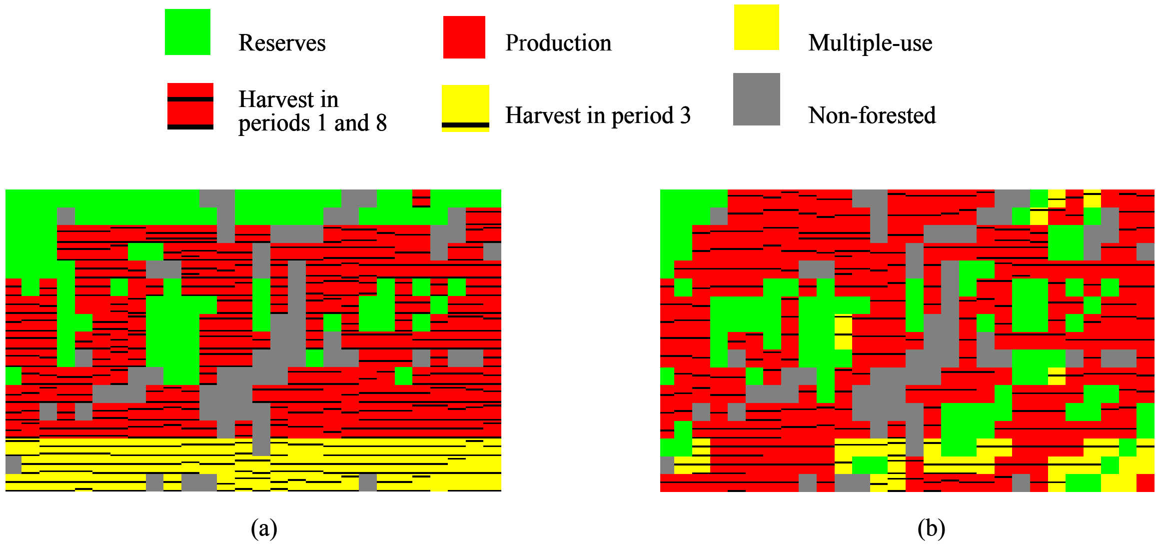

Figure 2. (a) Initial solution and (b) solution to Phase I of tabu search procedure.

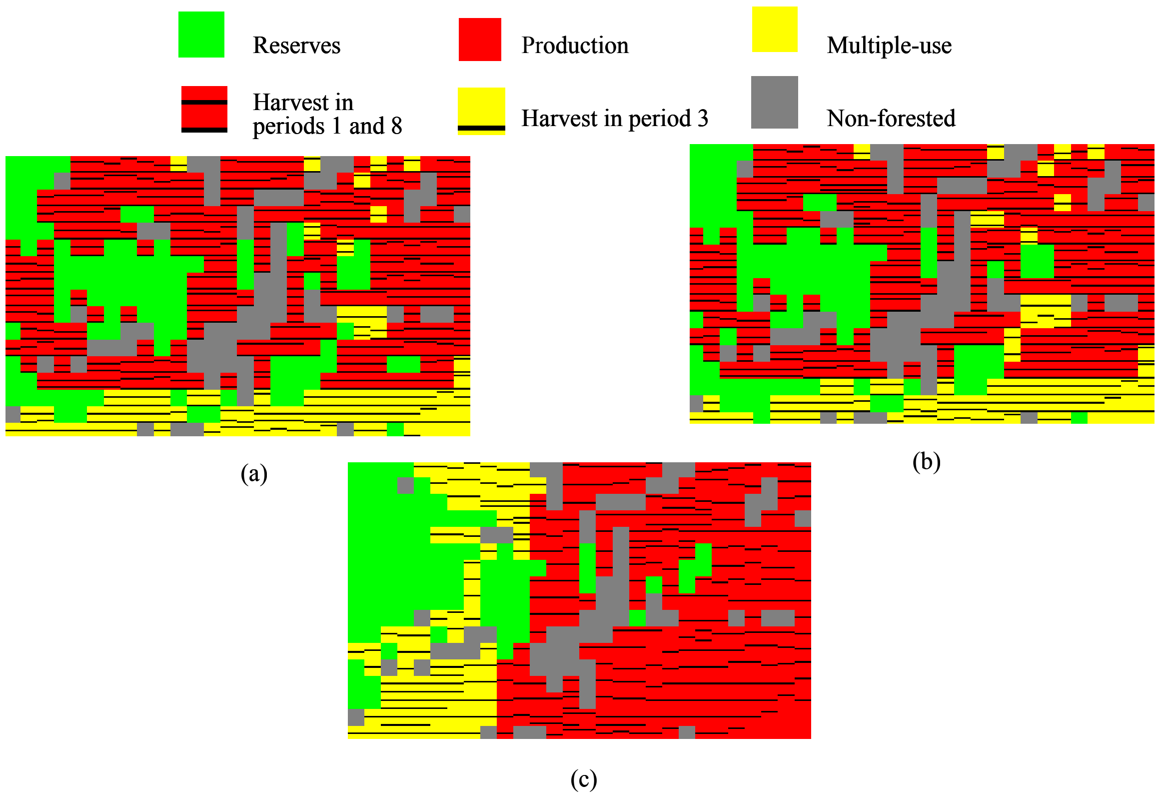

Figure 3. Solutions to Phase II of tabu search procedure when: (a) *PCNT* is 3%, (b) *PCNT* is 5%, and (c) *PCNT* is 10%.

Table 1: Solution algorithm outcomes

Solution	Objective values				
	z[a]	NPV[b] (mil. $)	avgPP[c]	avgRR[d]	avgPR[e]
Initial		4.512	3.41	3.14	3.62
Phase I		5.019	3.63	3.59	3.62
Phase II-3%	-0.05475	4.849	3.49	2.96	3.65
Phase II-5%	-0.01858	4.764	3.45	2.75	3.78
Phase II-10%	0.21008	4.523	2.76	2.19	4.79

[a] Overall objective function value
[b] Net present value in million of Cad $
[c] Average distance between two cells, each belonging to the *P* zone; the objective is *min avgPP*
[d] Average distance between two cells, each belonging to the *R*; the objective is *min avgRR*
[e] Average distance between two cells, one belonging to the *P* zone and the other belonging to the *R* zone; the objective is *max avgPR*