Bulletin of Mathematics
Vol. 07, No. 02 (2015), pp. 35–46

ISSN Printed: 2087-5126; Online: 2355-8202
http://jurnal.bull-math.org

MODELLING ZONING STRATEGIES IN FOREST SUSTAINABLE MANAGEMENT

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Abstract. *Recently forest companies face the prospect of reduced wood supply and increased costs in order to meet the environmental demand. In this paper, we include the traditional two-zone land allocation framework, which consists of ecological reserves and integrated forest management zones, with the triad (three-zone) scheme that adds a zone dedicated to intensive timber production. Then we model the problem as a mixed integer programming. The problem is solved using a direct search approach.*

1. INTRODUCTION

Forests are increasingly managed for multiple values. Among the multiple benefits of forests we focus on timber production and ecological services that are often in a direct conflict. Nature reserves are critical for protecting ecological values, but in most cases protection of ecological values cannot be achieved merely by reserves. A combination of fully protected reserves and management of the remaining forestland for timber production and the maintenance of ecological values is considered the best approach to biological conservation [10]. It is referred to in literature by such terms as ecosystem management, integrated management and multiple-use forest management [3]. We use the term integrated management in this paper to describe forest

Received 12-03-2015, Accepted 21-07-2015.
2016 Mathematics Subject Classification: 90C11
Key words and Phrases: Integrated forest management, Reserves, Timber production, Zoning, Mixed-integer programming.

management where silvicultural activities, rates and the timing of harvests are chosen to take into account all of the various benefits of the forest simultaneously.

Integrated management has been adopted by many countries to manage both public and private forestlands. The achievement of the goals of integrated management is usually provided by means of regulatory mechanisms. There are many examples of successful implementation of integrated systems but the requirements of integrated forest management, mainly driven by a greater emphasis on environmental objectives, resulted in a shortfall in wood supply and increased production costs in some regions. Increased pressures for protecting the environment expressed as requests for larger areas of reserves and tighter regulations on forestland managed for multiple uses, led some analysts to advocate spatial segregation of forest uses instead of their integration [17]. In this paper, we refer to this segregation of land uses as zoning.

To improve forest management both ecologically and economically, [15] 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. [4] 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 [4]. Bos in [2] studied the allocation of forestland among timber production, nature conservation and recreation, formulating the zoning problem as 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.

2. MODEL FORMULATION

We develop two models for solving classic land allocation and management scheduling problems over large temporal and spatial [4, 18]. The forest is divided into units reflecting administrative, geographic and operational considerations. A large spatial resolution is used to deal with general land allocation issues while leaving other spatial decisions (like adjacency constraints and roads building) for the tactical or operational levels of planning. The problem is modeled from the private operator perspective assuming that lands allocated to ecological reserves do not provide economic benefits. An additional assumption is that land allocated to different uses does not change over time.

The problem of land-use allocation and scheduling of management treatments is modeled as a mixed integer linear program. The model elements are defined as follows. Suppose that the forest is divided into units $u \in U$ and let M be the set of management strata. A management stratum $m \in M$ is defined in terms of species, site quality, ecosystem and age class. If specific forest characteristics are to be emphasized in the model, M can be partitioned accordingly. Here, we express ecological constraints in terms of the required representation of ecosystems $e \in E$, where E is the ecosystems index set. Let $N_e \subseteq M$, $e \in E$ represent a partition of M by the ecosystems $e \in E(N_i \cap N_j = \emptyset, \forall i, j \in E, M = \bigcup_{e \in E} N_e)$. Other partitions of the set M are possible if needed.

Let Z be the set of mutually exclusive zones to which land units can be assigned, namely, timber production(TP), reserves(R) and integrated management(IM), $Z = \{TP, R, IM\}$. $P(z)$ is the set of management regimes appropriate to zone z and $P = \bigcup_{z \in Z} P(z)$ is the set of all regimes. Regimes differ by the intensity of management for timber, and range from no harvest to basic, extensive and intensive management. The no harvest regime consists of planning, protecting and limited access to the areas set aside for ecological purposes. Under the basic regime, we consider natural regeneration of harvested stands, while the extensive regime assumes artificial regeneration. Neither the basic nor extensive regimes include silvicultural activities after regeneration. Intensive management includes different silvicultural practices following artificial regeneration of denuded stands. We assume that once a regime is selected for a stratum, it will be applied thereafter. All the regimes except the no harvest one include harvesting as a management activity. Each regime consists of a set of treatments. We consider a treatment to be the schedule of silvicultural activities and harvest over the planning horizon for a given management stratum. If we denote $P_1 = \{noharvest\}$ and $P_2 = \{basic, extensive, intensive\}$, then $P(R) = P_1$, and $P(IM) = P(TP) = P_1 \cup P_2$.

Let $vl_{m,p}$ be the volume (m3/ha) and $v_{m,p}$ the present value (dollar/ha) of timber from stratum m managed by treatment p. The cost of a treatment depends on the management stratum and on the specific use for which the stratum is managed. Let $c_{z,m,p}$ be the discounted cost (dollar/ha) of managing stratum m by treatment p in zone z, where z is either the integrated management(IM) or timber production zone(TP). We assume that the management cost (dollar/ha) of the reserve zone is constant and denote its present (discounted) value by c_R. Let $A_{u,m}$ be the area (ha) of management stratum m in unit $u; \rho$ the minimum area (ha) to be allocated to reserves and ϵ_e the minimum non-harvested area (ha) of ecosystem $e \in \epsilon$.

Decision variable $x_{z,u,m,p}$ represents the area(ha) of unit u of stratum m managed by treatment p for use z, and $Y_{z,u} = 1$ if unit u is assigned to use z, with $Y_{z,u} = 0$ otherwise.

3. THE TWO-ZONE MODEL

he first problem is to determine the allocation of units to either the reserves or integrated management zone, and to schedule management treatments to maximize the net present value of timber benefits while meeting ecological requirements. The ecological requirements include the minimum area of reserves and minimum non-harvested area of ecosystems. We refer to this as the two-zone problem and model it as:

$$\max N(x) = \sum_{u \in U} \sum_{m \in M} \sum_{p \in P} (v_{m,p} - c_{IM,m,p}) x_{IM,u,m,p} - c_R \sum_{u \in U} \sum_{m \in M} A_{u,m} Y_{R,u} \tag{1}$$

By using LINGO 14 Software, the model becomes:

```
MAX N(X) = @SUM(UNIT(U)@SUM(SPESIES(M)@SUM(REZIM(P):
(V(M,P)-C(IM,M,P))*X(IM,U,M,P)-C(R)@SUM(UNIT(U)@SUM(SPESIES(M):
A(U,M)*Y(R,U))))));
END
```

subject to: Land availability by units and strata

$$\sum_{p \in P} x_{z,u,m,p} = A_{u,m} Y_{z,c} \forall u \in U, m \in M, z \in \{IM, R\} \tag{2}$$

By using LINGO 14 Software, the model becomes:

```
@FOR(UNIT(U),@FOR(SPESIES(M),@FOR(HIMPUNAN(Z):
@SUM(REZIM(P):X(Z,U,M,P))=A(U,M)*Y(Z,C))));
END
```

Minimum area of reserves

$$\sum_{u\in U}\sum_{m\in M}A_{u,m}Y_{R,u}\geq\rho \tag{3}$$

By using LINGO 14 Software, the model becomes:

```
@SUM(UNIT(U)@SUM(SPESIES(M):A(U,M)Y(R,U)))>=rho;
END
```

Minimum non-harvested area of ecosystems

$$\sum_{z\in\{IM,R\}}\sum_{u\in U}\sum_{m\in M}\sum_{p\in P}x_{z,u,m,p}\geq\varepsilon_e\forall e\in E \tag{4}$$

By using LINGO 14 Software, the model becomes:

```
@FOR(EKOSISTEM(E):
@SUM(HIMPUNAN(Z)@SUM(UNIT(U)@SUM(SPESIES(M)@SUM(REZIM(P):
X(Z,U,M,P))))))>="(E));
END
```

Allocation of each unit to only one use

$$\sum_{z\in\{IM,R\}}Y_{z,u}=1\forall u\in U \tag{5}$$

By using LINGO 14 Software, the model becomes:

```
@FOR(UNIT(U):
@SUM(HIMPUNAN(Z):Y(Z,U))=1);
END
```

Non-negativity and integrality

$$x_{z,u,m,p}\geq 0, Y_{z,u}\in\{o,1\}, z\in\{IM,R\}, u\in U, m\in M, p\in P(z) \tag{6}$$

By using LINGO 14 Software, the model becomes:

```
@FOR(HIMPUNAN(Z),@FOR(UNIT(U),@FOR(SPESIES(M),@FOR(REZIM(P):
@FOR(0,1(Y(Z,U))
X(Z,U,M,P))))))>=0;
END
```

Denote by $(\overline{x}, \overline{Y})$ the optimal solution of the mixed-integer linear program (1)(6), by $\overline{N} = N(\overline{x})$ the optimal net present value and by $\overline{V} = V(\overline{x}) = \sum_{u\in U}\sum_{m\in M}\sum_{p\in P}$
$vl_{m,p}\overline{x}_{IM,u,m,p}$ the volume generated by the optimal combination of the land allocation and the management schedule.

4. THE TRIAD MODEL

Suppose now that newly introduced environmental legislation tightens the rules regarding both the area of reserves and protected area of specific ecosystems. Denote by α the required increase (ha) relative to ρ of the minimum area to be allocated to reserves, and by βe the required increase (ha), relative to ϵe, the minimum area of ecosystem $e \in E$ not to be harvested. Under tighter environmental regulations that increase the area of nature reserves and/or non-harvested area by ecosystems, the net present value of timber benefits declines if all other conditions remain unchanged. This comes as a reduction of the optimal value of the two-zone model (1)-(6) under tighter constraints.

Introducing an additional zone for intensive timber production increases the number of management options and allows for better performance in terms of the objective value achieved. The new zone permits relaxation of regulatory constraints and the possibility of intensive silviculture. The size and location of timber production zones may vary depending on regulatory constraints and the application of different silvicultural regimes.

Under the triad framework, we determine the minimum size of the timber production zone, its location and the management schedule that will make up for the volume lost and economic opportunities foregone. The performance of the two-zone alternative is used as a benchmark to evaluate the triad option. We use the model to analyze and assess land allocation alternatives for different policy scenarios in the context of a case study. The scenarios include different regulatory requirements, overall environmental constraints, and different assumptions regarding productivity and costs of intensive management prescriptions.

The problem that we formulate now is to allocate each unit to one of the three zones and schedule management treatments to minimize the area of the intensive timber production zone, while meeting tighter ecological constraints in addition to timber supply and economic performance requirements. The timber supply requirement is formulated as a constraint on harvest volume it cannot be less than the harvest volume $\overline{V}$ achieved with the two-zone model (1)-(6) under the original environmental regulations. The economic performance requirement is expressed as a constraint that the net present value of timber benefits be at least as high as the optimal value $\overline{N}$ of the two-zone model under the original environmental regulations. The ecological requirements include minimum areas of reserves and ecological type protected from harvest under the new (tighter) regulations. This is modeled as:

$$\min TA(y) = \sum_{u \in U} \sum_{m \in M} A_{u,m} Y_{T,u} \tag{7}$$

By using LINGO 14 Software, the model becomes:

```
MAX TA(Y)=@SUM(UNIT(U)@SUM(SPESIES(M):
A(U,M)*Y(T,U)));
END
```

subject to: Minimum net present value (requirement of economic performance)

$$\sum_{z \in Z/\{R\}} \sum_{u \in U} \sum_{m \in M} \sum_{p \in P} (v_{m,p} - c_{z,m,p}) x_{z,u,m,p} - c_R \sum_{u \in U} \sum_{m \in M} A_{u,m} Y_{R,u} \geq \overline{N} \tag{8}$$

By using LINGO 14 Software, the model becomes:

```
@SUM(HIMPUNAN(Z)@SUM(UNIT(U)@SUM(SPESIES(M)@SUM(REZIM(P):
(V(M,P)-C(Z,M,P))*X(Z,U,M,P)-C(R)@SUM(UNIT(U)@SUM(SPESIES(M):
A(U,M)*Y(R,U)))))))>=NILAI(N);
END
```

Minimum volume (requirement on timber supply)

$$\sum_{z \in Z/\{R\}} \sum_{u \in U} \sum_{m \in M} \sum_{p \in P} vl_{m,p} x_{z,u,m,p} \geq \overline{V} \tag{9}$$

By using LINGO 14 Software, the model becomes:

```
@SUM(HIMPUNAN(Z)@SUM(UNIT(U)@SUM(SPESIES(M)@SUM(REZIM(P):
(VL(M,P)*X(Z,U,M,P))))))>=VOLUME(V);
END
```

Land availability by land units and strata

$$\sum_{p \in P(z)} x_{z,u,m,p} = A_{u,m} Y_{z,c} \forall u \in U, m \in M, z \in Z \tag{10}$$

By using LINGO 14 Software, the model becomes:

```
@FOR(UNIT(U),@FOR(SPESIES(M),@FOR(HIMPUNAN(Z):
@SUM(REZIM(P):X(Z,U,M,P))= A(U,M)*Y(Z,C))));
END
```

Minimum area of reserves

$$\sum_{u\in U}\sum_{m\in M} A_{u,m}Y_{R,u} \geq \rho + \alpha \tag{11}$$

By using LINGO 14 Software, the model becomes:

```
@SUM(UNIT(U)@SUM(SPESIES(M):
A(U,M)Y(R,U)))>= rho + alpha;
END
```

Minimum non-harvested area of ecosystems

$$\sum_{z\in Z/\{T\}}\sum_{u\in U}\sum_{m\in M}\sum_{p\in P} x_{z,u,m,p} \geq \varepsilon_e + \beta_e, \forall e \in E \tag{12}$$

By using LINGO 14 Software, the model becomes:

```
@FOR(EKOSISTEM(E):
@SUM(HIMPUNAN(Z)@SUM(UNIT(U)@SUM(SPESIES(M)@SUM(REZIM(P):
X(Z,U,M,P)))))>="(E)+(E));
END
```

Each unit allocated to only one useno split of units between uses is allowed

$$\sum_{z\in Z} Y_{z,u} = 1 \forall u \in U \tag{13}$$

By using LINGO 14 Software, the model becomes:

```
@FOR(UNIT(U):
@SUM(HIMPUNAN(Z):Y(Z,U))=1);
END
```

Non-negativity and integrality

$$x_{z,u,m,p} \geq 0, Y_{z,u} \in \{o, 1\}, z \in Z, u \in U, m \in M, p \in P(z) \tag{14}$$

By using LINGO 14 Software, the model becomes:

```
@FOR(HIMPUNAN(Z),@FOR(UNIT(U),@FOR(SPESIES(M),@FOR(REZIM(P):
@FOR(0,1(Y(Z,U))
X(Z,U,M,P))))))>=0;
END
```

5. THE ALGORITHM

After solving the relaxed problem, the procedure for searching a sub-optimal but integer-feasible solution from an optimal continuous solution can be described as follows. Let

$$x = [x] + f, 0 \leq f \leq 1$$

be the (continuous) solution of the relaxed problem, $[x]$ is the integer component of non-integer variable x and f is the fractional component.
Stage 1.
Step 1. Get row $i*$ the smallest integer infeasibility, such that

$$\delta_{i*} = min\{f_i, 1 - f_i\}$$

(This choice is motivated by the desire for minimal deterioration in the objective function, and clearly corresponds to the integer basic with smallest integer infeasibility).
Step 2. Do a pricing operation

$$v_{i*}^T = e_{i*}^T B^{-1}$$

Step 3. Calculate $\sigma_{ij} = v_{i*}^T \alpha_j$ With j corresponds to

$$min_j \mid \frac{d_j}{\alpha_{ij}} \mid$$

Calculate the maximum movement of nonbasic j at lower bound and upper bound. Otherwise go to next non-integer nonbasic or superbasic j (if available). Eventually the column $j*$ is to be increased form LB or decreased from UB. If none go to next $i*$.
Step 4. Solve $B\alpha_{j*} = \alpha_{j*} for \alpha_{j*}$
Step 5. Do ratio test for the basic variables in order to stay feasible due to the releasing of nonbasic $j*$ from its bounds.
Step 6.Exchange basis
Step 7. If row $i* = \{\emptyset\}$ go to Stage 2, otherwise Repeat from step 1.

Stage 2.

Pass1 : adjust integer infeasible superbasics by fractional steps to reach complete integer feasibility.

Pass2 : adjust integer feasible superbasics. The objective of this phase is to conduct a highly lovalized neighbourhood search to verify local optimality.

6. CONCLUSIONS

1. 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.

2. This paper presents two models for solving classic land allocation and management scheduling problems over large temporal and spatial scales.

3. These two models are formulated as mixed integer linear program.

4. These two solve the model using a direct search approach.

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