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Spatially Constrained Harvest Scheduling for Strip Allocation and Biodiversity Management

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Keywords: Adjacency, heuristics, integer programming, strip cutting, strip shelterwood management

Abstract: We investigate the effect of strip cutting under a strip shelterwood management scheme with adjacency requirements among strips. We compare results from an ordinary spatially constrained solution to a solution with strip windows in the management units. The comparison of management schemes is considered as a spatially constrained harvest scheduling problem, which is solved using the SSMART (Scheduling System of Management Alternatives foR Timberharvest) hybrid heuristic. SSMART uses a partitioning heuristic to solve spatially constrained harvest scheduling problems. Our experimental analysis shows that using strip windows to embed additional spatial buffers into the management scheme reduces profit by almost 30%. In our Slovakian Forest Enterprise case study, it reduces the harvest flow level and harvested area by approximately 30%, while the calculated flow fluctuation over time is 10 times smaller than that from the ordinary adjacency problem without strip windows. However, strip windows could play an indirect role in preserving some resources for future harvest, possibly meeting sustainable management objectives.

1. Introduction

Forest management conditions have changed markedly in Slovakia

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since 1989. Harvest scheduling in Slovakia has traditionally been conducted for large scale units with an area of 5,000 hectares or more. Over the last decade, however, many of these units have been converted into smaller parcels tens or hundreds of hectares as forest land ownership has been denationalized. Slovak Forestry Act No. 326/2005 recommends these units be managed under a strip shelterwood silvicultural system that supports natural stand regeneration. Under the strip shelterwood system, management units are first divided into a strip window, where the unit is harvested over the regeneration period in a series of like-sized, uniformly staggered linear strips that advance progressively through the unit in one direction, most often into the prevailing wind. Strip width is generally set at four times the average dominant height of the target forest stand. Partial or clearcutting (e.g, preparatory cut, establishment cut, and removal cut) takes place in each strip, with adjacency requirements among strips.

The harvest regime detailed above (strip cutting with adjacency requirements) can be described as a spatially constrained harvest scheduling problem. Although the strip shelterwood system requires preparatory and establishment cuttings commonly over a regeneration period of 30 years or three periods before final or removal cutting, we assume one harvesting activity includes a series of these preparatory, establishment and removal cuttings for each strip over the regeneration period. Subject to the adjacency requirement, we assume two adjacent strips cannot be treated during the same harvesting period. In other words, preparatory cutting cannot be completed on adjacent strips during the same period.

Spatially constrained harvest scheduling problems have been intensively analyzed over the past few decades. During the early stages of spatially explicit management problems, harvest constraints are necessary in order to prevent excessively large harvest openings. Examples include Sessions and Sessions (1988), O'Hara *et al.* (1989), Nelson and Brodie (1990), Clements *et al.* (1990), Nelson *et al.* (1991), Daurst and Nelson (1993), Jamnick and Walters (1993), Yoshimoto *et al.* (1994), Haight and Travis (1997), Lockwood and Moore (1993), Murray and Church (1995), and Hoganson and Borges (1998). Most of these consider a simple case where adjacency constraints prohibit harvesting any two adjacent units. There is a variant of this type of problem where adjacent units can be treated in the same way, so long as the total contiguous area of treated units meets a certain size requirement (Lockwood and Moore 1993, Carroll *et al.*, 1995).

Spatially constrained problems are often extended to address specific planning requirements and needs. For example, Snyder and ReVelle (1996) incorporated interval exclusion periods for multiple harvests in the same unit. Yoshimoto (2001) and Boston and Bettinger (2001, 2006) considered exclusion periods for harvesting among adjacent units. These studies offer solutions based on many heuristics with different algorithms. The nature of a heuristic is such that it produces a feasible, or near-feasible, and hopefully very good, but not necessarily optimal, solution within a reasonable computation period.

The objective of this paper is to compare the effect of creating a strip window within a management unit (assuming adjacency requirements among strips) to the same spatially constrained problem without a strip window in order to estimate costs of implementing a strip shelterwood management system. In the next section, we present the target spatially constrained harvest scheduling problem within an integer programming framework and describe the SSMART heuristic, which is used in our analysis. In the third section, we present our case study, and then provide concluding remarks in the final section.

2. Method

2.1. Formulating the spatially constrained problem

We formulate our spatially constrained problem using a 0-1 integer programming framework. The objective is to maximize the total cut volume from all strips over the planning period. Constraints include harvest flow and land accounting, as well as spatial restrictions to avoid harvesting two adjacent strips during the same period. Let $\boldsymbol{X} = {}^t(\boldsymbol{x}_1, \ldots, \boldsymbol{x}_m) = (\tilde{\boldsymbol{x}}_1, \ldots, \tilde{\boldsymbol{x}}_n)$ be an $(m \times n)$ dichotomous decision matrix with m as the number of strips and n as the number of treatments for one strip, and ^{t} denotes the transpose, where $\boldsymbol{x}_i$ is the i-th row vector of $\boldsymbol{X}$ for the i-th strip and $\tilde{\boldsymbol{x}}_j$ is the j-th column vector for the j-th treatment. An element of $\boldsymbol{X}$ is thus defined by,

$$\text{[1]} \qquad x_{i,j} = \begin{cases} 1 & \text{if the } j\text{-th treatment is implemented for the } i\text{-th strip} \\ 0 & \text{in all other cases} \end{cases}$$

Although Johnson and Stuart (1989) used a decision vector to meet the general formulation requirements of linear programming in their Model I formulation, we introduced a decision matrix to clearly assign the treatment to strips by the row and column of $\boldsymbol{X}$. The objective here is given by,

$$\text{[2]} \qquad Z = \max_{\boldsymbol{X}} \operatorname{tr}\left({}^t\boldsymbol{C}\boldsymbol{X}\right) = \sum_{i=1}^{m}\sum_{j=1}^{n} c_{i,j} x_{i,j}$$

where $\boldsymbol{C}$ is an $(m \times n)$ coefficient matrix and its element, $c_{i,j}$, represents the total volume obtained by implementing the decision $x_{i,j} = 1$. Given a planning period of 10, with 6 periods as a minimum cutting cycle, Table 1 shows an example of 20 treatments for one strip. The treatment regime for one strip can be summarized as, "cut the fifth strip in period three". Note that if the current strip is too young to be cut, the corresponding coefficient of the treatment becomes zero so we

Table 1. Example of treatments

Treatment No.	Decision Variable	Coefficient	Period 1	2	3	4	5	6	7	8	9	10
1	$x_{i,1}$	$c_{i,1}$	x	0	0	0	0	0	0	0	0	0
2	$x_{i,2}$	$c_{i,2}$	x	0	0	0	0	0	x	0	0	0
3	$x_{i,3}$	$c_{i,3}$	x	0	0	0	0	0	0	x	0	0
4	$x_{i,4}$	$c_{i,4}$	x	0	0	0	0	0	0	0	x	0
5	$x_{i,5}$	$c_{i,5}$	x	0	0	0	0	0	0	0	0	x
6	$x_{i,6}$	$c_{i,6}$	0	x	0	0	0	0	0	0	0	0
7	$x_{i,7}$	$c_{i,7}$	0	x	0	0	0	0	0	x	0	0
8	$x_{i,8}$	$c_{i,8}$	0	x	0	0	0	0	0	0	x	0
9	$x_{i,9}$	$c_{i,9}$	0	x	0	0	0	0	0	0	0	x
10	$x_{i,10}$	$c_{i,10}$	0	0	x	0	0	0	0	0	0	0
11	$x_{i,11}$	$c_{i,11}$	0	0	x	0	0	0	0	0	x	0
12	$x_{i,12}$	$c_{i,12}$	0	0	x	0	0	0	0	0	0	x
13	$x_{i,13}$	$c_{i,13}$	0	0	0	x	0	0	0	0	0	0
14	$x_{i,14}$	$c_{i,14}$	0	0	0	x	0	0	0	0	0	x
15	$x_{i,15}$	$c_{i,15}$	0	0	0	0	x	0	0	0	0	0
16	$x_{i,16}$	$c_{i,16}$	0	0	0	0	0	x	0	0	0	0
17	$x_{i,17}$	$c_{i,17}$	0	0	0	0	0	0	x	0	0	0
18	$x_{i,18}$	$c_{i,18}$	0	0	0	0	0	0	0	x	0	0
19	$x_{i,19}$	$c_{i,19}$	0	0	0	0	0	0	0	0	x	0
20	$x_{i,20}$	$c_{i,20}$	0	0	0	0	0	0	0	0	0	x

Note) x denotes harvesting while 0 denotes no harvesting can maintain the same set of treatments, or decision variables, for all strips.

The volume constraint is formulated as follows: Let $v_{i,j}^{(p)}$ be the harvest volume at the p-th period from the decision variable $x_{i,j}$, with the corresponding $m \times n$ matrix $\boldsymbol{V}_p$ as the harvest volume matrix. Harvest flow constraints are then specified by,

[3] $$\begin{aligned}(1-\alpha)\mathrm{tr}\left({}^t\boldsymbol{V}_1\boldsymbol{X}\right) \leq & \mathrm{tr}\left({}^t\boldsymbol{V}_p\boldsymbol{X}\right) \\ \leq & (1+\alpha)\mathrm{tr}\left({}^t\boldsymbol{V}_1\boldsymbol{X}\right), \quad p = 2, \ldots, T\end{aligned}$$

This allows $\pm\alpha$ fluctuation of harvest flow in the first period. T is the number of periods for planning. If harvest flow is even, then α becomes zero.

To formulate land accounting constraints, which require at most one treatment for each strip, we have the following,

[4] $$^t\boldsymbol{1}\boldsymbol{x}_i = 1, \qquad i = 1, \ldots, m$$

where $\boldsymbol{1}_n$ is an $(n \times 1)$ vector with a value of 1.

Adjacency constraints prevent two adjacent strips from being harvested during the same period. The simplest way to formulate them is to use a pair wise constraint given by,

[5] $$x_{i,j} + x_{k,j} \leq 1, \ {}^\forall k \in NB_i, \quad j = 1, \ldots, n$$

where NB_i is a set of strips adjacent to the i-th strip. Using matrix notation that follows Yoshimoto and Brodie (1994), another simple approach is to use an adjacent matrix $\boldsymbol{A}$, as in network theory:

[6] $$\boldsymbol{M}\tilde{\boldsymbol{x}}_j \leq m_0, \quad j = 1, \ldots, n$$

where,

[7] $$m_0 = \boldsymbol{A}\boldsymbol{1}_m$$

[8] $$\boldsymbol{M} = \boldsymbol{A} + \mathrm{diag}(m_0)$$

and an element of the above adjacent matrix, $\boldsymbol{A}$, is defined by,

[9] $$a_{i,j} = \begin{cases} 1 & \text{if } j \in NB_i \\ 0 & \text{if } j \notin NB_i \end{cases}$$

There are additional methods for determining adjacency constraints (see Murray 1999) that require further calculation and explanation. To keep the model simple, we use the equations described above to build our harvest scheduling problem following integer programming formulation (to be solved using exact solution techniques):

[10] $$Z = \max_{\boldsymbol{X}} \operatorname{tr}\left({}^t\boldsymbol{C}\boldsymbol{X}\right) = \sum_{i=1}^{m}\sum_{j=1}^{n} c_{i,j}x_{i,j}$$

subject to

[11] $$\begin{aligned}(1-\alpha)\operatorname{tr}\left({}^t\boldsymbol{V}_1\boldsymbol{X}\right) \le & \operatorname{tr}\left({}^t\boldsymbol{V}_p\boldsymbol{X}\right) \\ \le & (1+\alpha)\operatorname{tr}\left({}^t\boldsymbol{V}_1\boldsymbol{X}\right),\ p = 2, \ldots, T\end{aligned}$$

[12] $${}^t\boldsymbol{1}\boldsymbol{x}_i \le 1, \qquad i = 1, \ldots, m$$

[13] $$\boldsymbol{M}\tilde{\boldsymbol{x}}_j \le m_0, \qquad j = 1, \ldots, n$$

2.2. Finding a solution using the SSMART heuristic

To solve the problem outlined above, we use a heuristic developed by Yoshimoto *et al.* (1994). They developed a spatially constrained harvest scheduling model called SSMART (Scheduling System of Management Alternatives foR Timber-harvest), which employs a hybrid of heuristics to solve spatially constrained harvest scheduling problems over a long time horizon with multiple harvests in each unit. SSMART combines random ordering selection of control variables with search of feasible solutions over two sequential periods only. The algorithm partitions the problem into sub-problems that are solved over two sequential periods from the first period to the last in order, then merges solutions from the sub-problems into a single result for the overall problem. Because of this partitioning, the computational time required for large problems can be significantly reduced. Another distinguishing feature of SSMART is that it can search not only for a "near-optimal" solution, but also for the "best" harvest flow level. That is, the harvest flow level need not be exogenously specified.

Our harvest scheduling problem is reformulated for SSMART by modifying the integer programming framework described above. The resultant problem becomes a quasi-multicriteria problem that maximizes the present net value of returns from all harvesting activities and minimizes harvest flow fluctuations to approximate even-flow constraints over time within the 0-1 integer programming framework. Because even-flow constraints of the integer programming problem are most likely to be violated, these constraints were approximated as minimization of infeasibility on the even-flow constraints in SSMART. Thus, we considered a solution with "minimum" infeasibility or fluctuation on the even-flow constraint a better solution.

The algorithm seeks a final solution by first assigning a random number to each decision variable of the sub-problem, then minimizing harvest flow fluctuation from a given initial even-flow level at each period. Based on the assigned random numbers, an ordered sequence is generated to select decision variables for implementation over two sequential periods. When a decision variable is selected for implementation, the associated conflicting decision variables are removed from the pool of possible solutions. Selection continues based on the ordered sequence until harvest flow constraints over two sequential periods are satisfied for each sub-problem. After a solution is developed for one sub-problem, the iterative process continues for each subsequent sub-problem until one solution is derived for the entire problem. The initial even-flow level is then changed to generate a set of solutions. The final

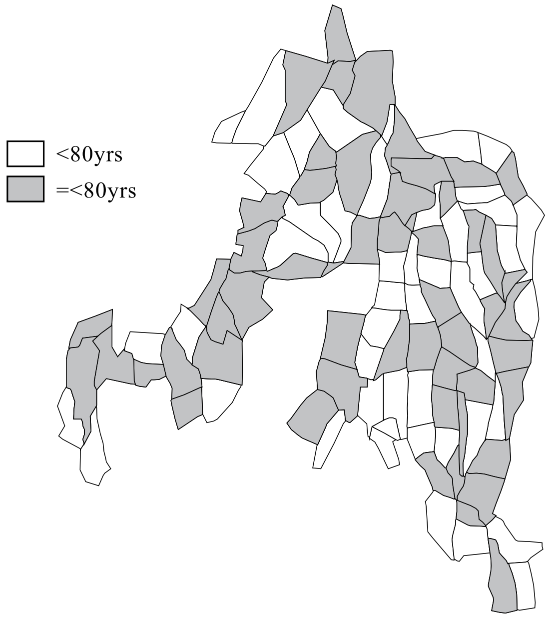

Figure 1. Map of the forest management unit in Zvolen, Slovakia

solution is selected based on the maximum present net value criterion, and deemed "best" when no other solutions outperform it.

3. Analysis

3.1. Date

Our case study considers a forest managed by the School Forest Enterprise at the Technical University in Zvolen, Central Slovakia, which manages forests for many different landowners. We selected a single spatially complete Forest Management Unit (FMU) that is owned by a single individual. The FMU has an area of 950 ha, with 104 units very close to the average FMU area in Slovakia. The rotation period in this forest is approximately 110 years with a regeneration period

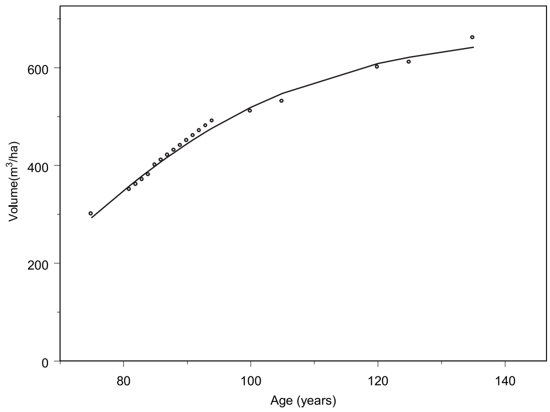

Figure 2. Growth Projection

of 30 years, regeneration cutting starts at age 80 and is completed at 110 years. There are 13 age classes (10 year range) in the forest, the age structure is unbalanced with young and mature groups of stands. Species composition is approximately 86% broadleaf and 14% coniferous, with beech accounting for 69% of forest cover and spruce 13%. The forest landscape is presented in Figure 1. Dark colored areas are mature stands 80 years or older, accounting for a total area of 529 ha.

Growth data for this FMU was obtained from a regular forest inventory conducted in 2003, and is depicted in Fig. 2 (Marušák, 2003). The following Richards growth function (Richards, 1958) was used to project growth over the time horizon:

[14] $$w(t) = 677.6862\left(1 - e^{-0.04510663t}\right)^{24.22714}$$

where $w(t)$ represents volume per hectare at age t.

Each forest stand was divided into strips following strip shelterwood system guidelines. Figure 3 shows an example of strip window creation and a cutting pattern that meets adjacency requiements for three units.

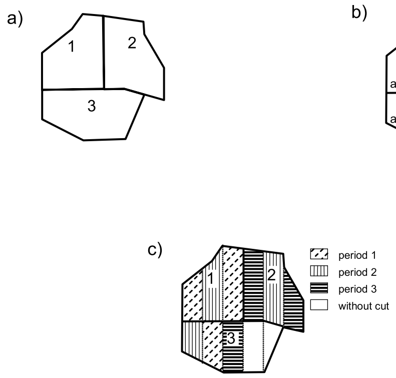

Figure 3. Strip window example

Table 2. Number of cutting units and strips

Period	Ordinary		Strip Cutting	
	# of Units	Remaining Area with age $\geq$ 80 yrs	# of Strip	Remaining Area with age 80 yrs
1	21	381.0730	239	413.0220
2	19	215.1404	216	288.6818
3	18	86.8760	183	211.1221
Sum	58		638	

Strips were created one-by-one in a uniform direction, considering adjacency requirements. Post-treatment, there were 1,364 strips-more than 10 times the original number of units in the FMU-with an average area of 0.69 ha (Fig. 4).

The map of this study area with and without strips was created using ArcView (ESRI, 2006), and adjacency information was derived by SpatialRel in Spatial Filter, provided by ArcObjects Class.

3.2. Management effects of strip cutting

A planning horizon of 30 years (3 periods, 10 years each) a typical forest management practice in Slovakia was selected for our study (Note

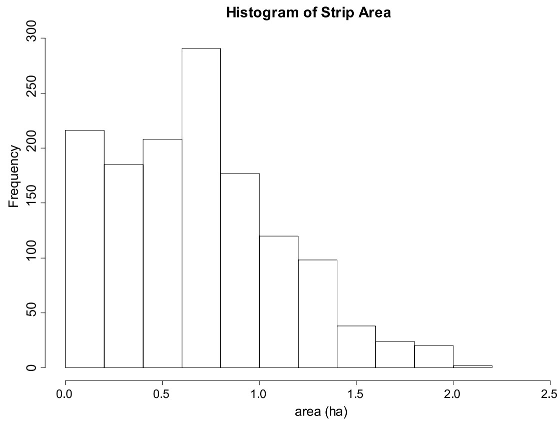

Figure 4. Histogram of Strip Size

that 30 years corresponds to the regeneration period). The analysis was conducted with and without strip windows over three periods. We first solved a spatially constrained problem without considering a strip window. Figure 5 shows the final solution over three periods. Only adjacency constraints among forest stand units were applied. Among 55 units eligible for harvest in the first period, 22 were selected, 19 were selected in the second period, and 18 in the last (Tab. 2). Only four of the original units remained uncut at the end of the third period. In other words, about 92% of forest units eligible for harvest were cut. Harvest flow changed from 101,000.11 m^3 to 102,526.92 m^3, with a total harvest volume of 304,583.81 m^3 under a 1.51% fluctuation of the harvest flow (Tab. 3). Figure 6 shows the changes in age distribution. Because the planning horizon only included three periods, most mature units were harvested for regeneration, leaving less for future harvest. Note that if we were to assume three periods are required for regeneration, all harvested areas would require a three period delay for reestablishment, as shown in Figure 6.

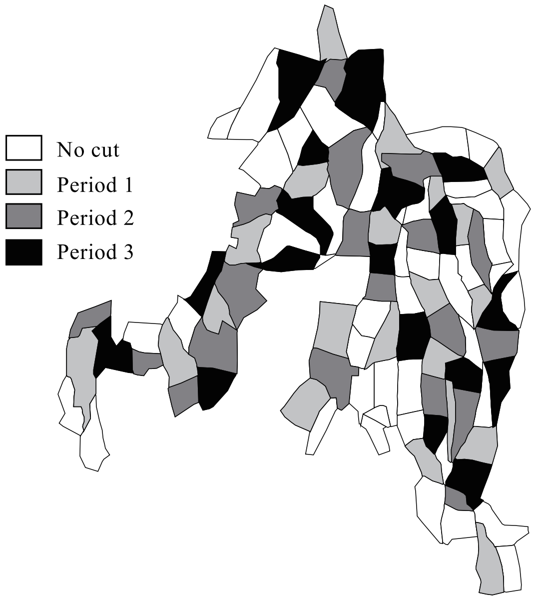

Figure 5. Final solution without strips

Table 3. Comparison of volume and area harvested over the planning period

Period	Volume			Area		
	Ordinary	Strip	Dif%	Ordinary	Strip	Dif%
1	101000.11	79500.04	27.04	196.13	164.78	19.03
2	101056.78	79500.45	27.11	191.18	149.54	27.85
3	102526.92	79610.06	28.79	194.18	143.37	35.44
Sum	304583.81	238610.55	27.65	581.49	457.69	27.05
Fluctuation(%)	1.51	0.14				

With strip windows in the FMU, we derived the final solution depicted in Figure 7. Among strips, both line and corner adjacent cuts were avoided. Because the number of strips increased tenfold, there were 762 eligible for harvest in the first period, 236 were cut, followed by 216 in the second period and 183 in the last (Tab. 2). Among strips

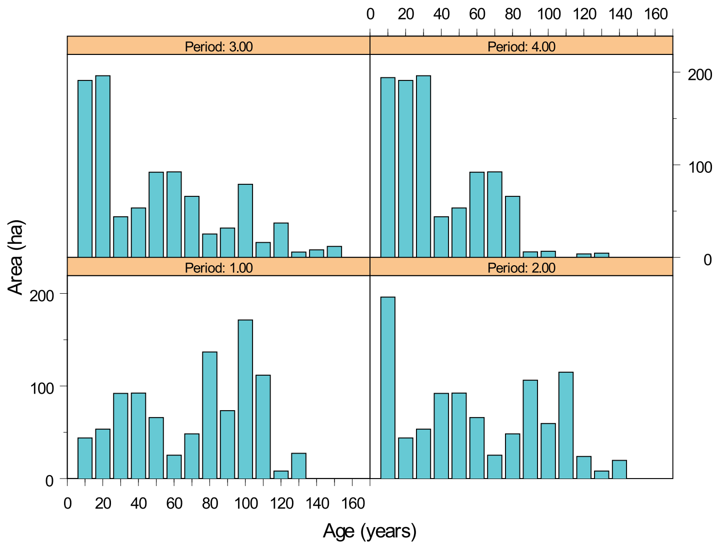

Figure 6. Change in age distribution of the solution without strips

eligible for harvest in the first period, 175 or about 23% were left uncut (Fig. 7). Unlike the solution from the ordinal problem above, strip window creation reserved an area of 211 ha more than twice that of the other scenario for the next harvest. This is an indirect effect of strip adjacency on the management scheme. In other words, creation of strip windows seems to reduce harvest opportunity, but it indirectly reserves resources for future harvest. When compared to Figure 6, the age distribution shown in Figure 8 is characterized by a smooth transition from mature stands to younger stands. The total volume harvested reduced to 238,610.55 m^3. Harvest flow changed from 79,500.04 m^3 to 79,610.06 m^3, with 0.14% fluctuation (Tab. 3). Although the harvest flow fluctuation decreased approximately 10 times less under the strip window scenario, the harvest flow itself decreased by about 27%, along with the total harvested volume (with adjacency requirements

Figure 7. Final solution with strips

for strips).

4. Conclusion

The strip shelterwood forest management system specifies strip windows for harvest and regeneration of forest stands, along with an adjacency requirement among strips. Adjacency requirement is an important aspect of the shelterwood system because it requires that corresponding adjacent strips be left uncut during the regeneration period on one strip. In this paper, we investigated the management effects of strip cutting under the strip shelterwood system with adjacency requirements, examining the effect on the volume and area harvested, as well as harvest flow over the planning horizon. We compared the effect

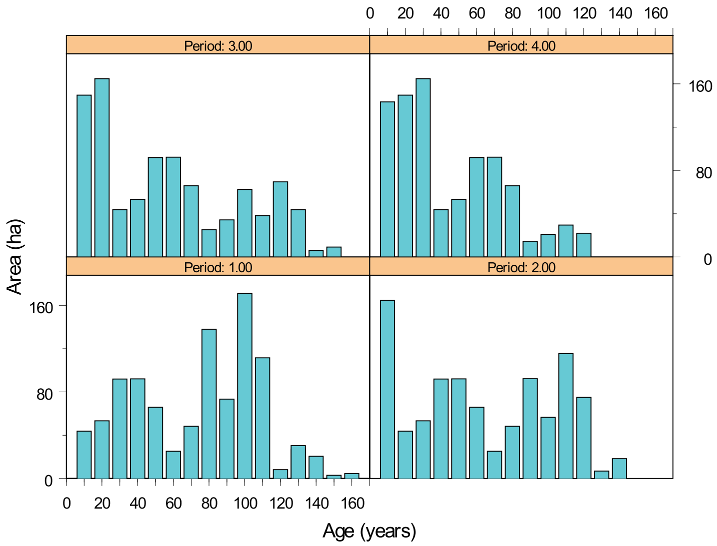

Figure 8. Change in age distribution of the solution with strips

of creating a strip window within a management unit to the same spatially constrained problem without a strip window. For a case study, we selected a forest managed by the School Forest Enterprise at the Technical University in Zvolen, Slovakia.

Our analysis assumed a goal of total harvest volume maximization over a three period planning horizon for a 528 ha FMU with mature forest units. Under the scenario without strip windows, 92% of the FMU was harvested, while only 77% of the FMU was harvested under the scenario with strip windows. Creating strip windows resulted in a 27% reduction of the harvest flow and total harvested volume. From a harvest sustainability perspective, however, the scenario with strip windows reserves 23% of the original mature forest for future harvest. When maturing forests are also considered, 221 ha are reserved under the scenario with strip windows, while only 87 ha are reserved under the scenario without strip windows. This implies that strip window creation in forest stands could play an indirect role in preserving some resources for future harvest, possibly meeting sustainable management objectives. We limited our analysis to a three period horizon because that is a common forest management planning window. Further analysis is needed to investigate the long-term effect of strip window creation under the shelterwood system.

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帯状区画 (Strip) 配置と生物多様性管理のための空間的制約下における伐採計画

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要約: 傘伐管理計画における列状あるいは帯状区画 (strip) 伐採の影響を調べるため, 通常の隣接林分伐採規制による空間的制約下における最適伐採計画と, さらに帯状区画 (strip) 伐採を導入した際の最適傘伐計画を比較し, 帯状区画 (strip) 伐採導入の影響について分析した. まず, それぞれの問題を空間的制約問題として定式化し, ハイブリッドヒューリスティックの一つである SSMART (Scheduling System of Management Alternatives foR Timber-harvest) を用いて解を探索した. なお, SSMART は分割ヒューリスティックを用いて空間的制約問題の解を探索するモデルである. スロバキアの Slovak Forest Enterprise の森林を対象に分析を行った結果, 帯状区画伐採の導入により伐採量および伐採面積が 30% 程度減少するものの, 伐採量フローの変動は 10 分の 1 に減少し安定することが分かった. 帯状区画伐採の導入はこのような伐採量の減少を引き起こすものの, 将来的な資源の確保による持続的管理の実現に間接的に寄与するものと考えられる.

キーワード: 隣接制約, ヒューリスティック, 整数計画法, 帯状区画伐採, 帯状傘伐管理計画