Spatially constrained harvest scheduling for strip allocation under Moore and Neumann neighbourhood adjacency

M. Konoshima[1], R. Marušák[2], A. Yoshimoto[3]

[1]*Graduate School of Life Sciences, Tohoku University, Aoba, Sendai, Japan*
[2]*Faculty of Forestry and Wood Sciences, Czech University of Life Sciences Prague, Prague, Czech Republic*
[3]*Department of Mathematical Analysis and Statistical Inference, The Institute of Statistical Mathematics, Tachikawa, Tokyo, Japan*

ABSTRACT: Adjacency constraints can be represented by Moore or Neumann neighbourhood adjacency, depending upon how candidate neighbours are assigned at corners adjacent to the target cell. Considering Moore and Neumann neighbourhood adjacency, we investigate the effect of strip cutting under a shelterwood management scheme with adjacency requirements among strips. We compare the effect of creating a strip window within a management unit with the same spatially constrained problem without a strip window. The management scheme comparison is considered as a spatially constrained harvest scheduling problem, which is solved with CPLEX software using an exact solution method. Our experimental analysis shows that the inclusion of additional spatial consideration by strip window creation in the management scheme results in a reduction of the total harvest volume by almost 13% under Moore neighbourhood adjacency, while it has a small effect under Neumann neighbourhood adjacency.

Keywords: integer programming; Moore and Neumann neighbourhood adjacency; Shelterwood management strip cutting

Consideration of adjacency constraints has been a key issue in harvest scheduling over the last several decades because of environmental, ecological, and aesthetic requirements. These constraints are often expressed by Moore neighbourhood adjacency in ecological fields, where all neighbours sharing adjacent lines and corners with the target cell are considered adjacent. In forest management, on the other hand, Neumann neighbourhood adjacency is often used in harvest scheduling, which only designates those sharing adjacent lines as neighbours.

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

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The extension of a spatially constrained problem can be found for example in Snyder and ReVelle (1996), who incorporated interval exclusion periods for multiple harvests in the same unit. Exclusion periods for harvesting among adjacent units were considered by Yoshimoto (2001) and Boston and Bettinger (2001, 2006). These studies developed 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 computational period. As a consequence, such heuristics can result in inaccurate estimates for economic analysis within an optimization framework.

In many European countries, a shelterwood silvicultural system that supports natural stand regeneration has traditionally been the recommended management regime. Under the shelterwood system, management units are often first divided by a strip window, where the unit is harvested in a series of like-sized, uniformly staggered linear strips that advance progressively through the unit in one direction, most often perpendicularly to the prevailing wind. Partial or clear-cutting takes place in each strip with adjacency requirements among strips. Because of these adjacency requirements, this shelterwood silvicultural system with strip cutting can be treated as a spatially constrained harvest scheduling problem.

The objective of this paper is to compare the effect of creating a strip window within a management unit – assuming adjacency requirements among strips imposed by both Moore and Neumann neighbourhood adjacency – with the same spatially constrained problem without a strip window. In the context of a spatial harvest scheduling problem, the choice of adjacent structures – either Moore or Neumann neighbourhood adjacency – in defining adjacency relationships can substantially affect management goals. Increased restrictions in units harvested under Moore neighbourhood adjacency could result in lost harvested timber volume, which in turn reduces profit generated from shelterwood forest management. Therefore, it is important to quantify and examine differences in harvested timber volume under the two different adjacency structures. Furthermore, comparing these two types of strip-based management with a conventional (i.e. without strip, management-unit-based) management scheme will provide useful information for developing and implementing an efficient strip-based shelterwood management regime.

In the next section, we present the target spatially constrained harvest scheduling problem within an integer programming framework. In the third section, we present our case study, and then concluding remarks are provided in the final section. Although the shelterwood system requires several preparatory cuttings – commonly over 30 years or three periods – before final cutting, we assume one harvesting activity includes a series of these preparatory cuttings and the final cut for each strip at each period. In other words, we focus on the starting period that begins the silvicultural treatment for each strip. Subject to the adjacency requirement, we assume that two adjacent strips cannot be treated during the same harvesting period.

Formulating the spatially constrained shelterwood management problem

We formulate our shelterwood management problem over the regeneration period (or three periods) using a 0–1 integer programming framework. We assume a forester manages several contiguous stands that are divided into several strips. The objective is to maximize the total cut volume from all strips over the regeneration period. Constraints include harvest flow and land accounting, as well as spatial restrictions to avoid harvesting two adjacent strips during the same period. Harvest constraints, which are often required in forest operations, stipulate a non-declining, even flow of timber. Such constraints reflect one interpretation of "sustainable timber supply" and ensure a continuous supply of wood. Land accounting constraints limit harvest to – at most – one cut during the planning horizon. As a result, we can only consider a single treatment and must assume that replanted stands will not reach a profitable age within the planning horizon. Adjacency is defined by either Moore neighbourhood adjacency or Neumann neighbourhood adjacency.

Let $\mathbf{X} = (x_1, ..., x_m)' = (\tilde{x}_1, ..., \tilde{x}_n)$ be an $(m \times n)$ dichotomous decision matrix with m as the number of strips and n as the number of treatments (or periods in this paper to specify that only one treatment can be started for each strip over the planning period), and ' denotes the transpose, where x_i is the i^{th} row vector of X for the ith strip and $\tilde{x}_j$ is the j^{th} column vector for treatment starting at the j^{th} period. An element of $\mathbf{X}$ is thus defined by

$$x_{i,j} = \begin{cases} 1 & \text{if the treatment is implemented at the } j^{\text{th}} \text{ period for } i^{\text{th}} \text{ strip} \\ 0 & \text{otherwise} \end{cases}$$

where only three periods are explicitly considered (i.e. j = 1, 2, 3 with n = 3), with strip harvesting beginning during the first, second or third period, respectively.

Because we focus on the initial period that begins shelterwood treatment for each strip (in an attempt to examine the effect of strip cutting on management efficiency), we do not consider the cutting order, which is assigned sequentially over space.

The objective here is given by

$$Z = \max_{x} \operatorname{tr}(\mathbf{C}'\mathbf{X}) = \sum_{i=1}^{m} \sum_{j=1}^{3} c_{i,j} \times x_{i,j} \quad (1)$$

where $\mathbf{C}$ is an ($m \times 3$) coefficient matrix and its element, $c_{i,j}$ represents the total volume obtained by the treatment or decision $x_{i,j}$.

Note that if the current strip is too young to be cut, the corresponding coefficient of the treatment becomes zero, so we can maintain the same set of treatments, or decision variables, for all strips.

The harvest flow constraint is formulated as follows: Let $v_{i,j}^{(p)}$ be a harvest volume at the p-th period from the decision variable $x_{i,j}$, and the corresponding $m \times 3$ matrix $\mathbf{V}_p$ as the harvest volume matrix. Harvest flow constraints are then specified by

$$\operatorname{tr}(\mathbf{V}_p'\mathbf{X}) = \sum_{i=1}^{m} \sum_{j=1}^{3} v_{i,j}^{(p)} \times x_{i,j} = v_0, \qquad p = 1, 2, 3 \quad (2)$$

or

$$(1-\alpha)\operatorname{tr}(\mathbf{V}_{p-1}'\mathbf{X}) \leq \operatorname{tr}(\mathbf{V}_p'\mathbf{X}) \leq (1+\alpha)\operatorname{tr}(\mathbf{V}_{p-1}'\mathbf{X}), \qquad p = 2, 3 \quad (3)$$

The latter is to allow ± a fluctuation of harvest flow, and is used here to ensure the problem remains valid in an integer programming framework. In other words, harvest flow constraints prevent the volume of timber extracted during each period from being higher or lower than ± a fluctuation.

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

$$\mathbf{1}_3' x_i \leq 1, \quad i = 1, 2, ..., m \quad (4)$$

where $\mathbf{1}_3 = (1,1,1)'$ is a (3×1) vector with a value of 1.

Adjacency constraints are defined by either Moore neighbourhood adjacency or Neumann neighbourhood adjacency. Fig. 1 shows how each of them is typically structured, using an example of spatial map. The central cell is the target and the surrounding cells its neighbours. As the figure demonstrates, there are eight neighbours adjacent to the target cell under Moore neighbourhood adjacency, but only four under Neumann neighbourhood adjacency. To avoid cutting two adjacent strips in the same period, it is simplest to use a pair-wise constraint:

$$x_{i,j} + x_{k,j} \leq 1, \quad \forall k \in NB_i, \quad j = 1, 2, 3 \quad (5)$$

where: NB_1 is a set of strips adjacent to the i^{th} strip.

In the Fig. 1 example, neighbourhood adjacency to the central target cell can be defined as follows:

1. for Moore neighbourhood adjacency, $NB_0 = \{1,2,3,4,5,6,7,8\}$
2. for Neumann neighbourhood adjacency, $NB_0 = \{1,2,3,4\}$

Using the matrix notation that follows Yoshimoto and Brodie (1994), another simple approach is to use an adjacent matrix $\mathbf{A}$, like in network theory:

$$\mathrm{M} \times \tilde{x}_j \leq m_0, \qquad j = 1, 2, 3 \quad (6)$$

where

$$m_0 = \mathbf{A} \times \mathbf{1}_m \quad (7)$$

$$\mathbf{M} = \mathbf{A} + \operatorname{diag}(m_0) \quad (8)$$

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

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

As a result, our harvest scheduling problem is formulated by the following integer programming formulation (to be solved using exact solution techniques):

$$Z = \max_{x} \operatorname{tr}(\mathbf{C}'\mathbf{X}) = \sum_{i=1}^{m} \sum_{j=1}^{3} c_{i,j} \cdot x_{i,j}$$

subject to

$$(1-\alpha)\operatorname{tr}(\mathbf{V}_{p-1}'\mathbf{X}) \leq \operatorname{tr}(\mathbf{V}_p'\mathbf{X}) \leq (1+\alpha)\operatorname{tr}(\mathbf{V}_{p-1}'\mathbf{X}), \quad p = 2, 3$$

$$\mathbf{1}_n' x_i \leq 1, \quad i = 1, 2, ..., m$$

$$\mathrm{M} \times \tilde{x}_j \leq m_0, \qquad j = 1, 2, 3$$

where an individual decision variable is $x_{i,j} \in \{0,1\}$.

In the case study that follows, we use this analysis to compare the effect of creating a strip window within a management unit with the same spatially constrained problem without a strip window.

Overview of the study site

Our case study considers a forest managed by the School Forest Enterprise at the Technical University in Zvolen, Central Slovakia. Our study encompasses an area of 950 ha with 104 units. The rotation period in this forest is approximately 110 years with a regeneration period of 30 years; regeneration cutting starts at age 80 and is completed by age 110. There are 13 age classes (10-year range) represented in the forest. The age structure is unbalanced with young and mature groups of stands. The species composition is approximately 86% broadleaf and 14% conif-

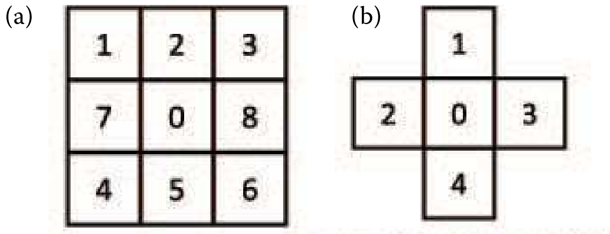

Fig. 1. (a) Moore and (b) Neumann neighborhood adjacency structures

erous species, with beech accounting for 69% of forest cover and spruce for 13%. The forest landscape is presented in Fig. 2. Dark coloured areas are mature stands at the age of 80 years or older, representing the total area of 529 ha.

Growth data for this study was obtained from a regular forest inventory conducted in 2003, and is depicted in Fig. 3 (Marušák 2003). The following Richards growth function (Richards 1958) was used to project growth over the time horizon:

$$w(t) = 677.6862 \times (1 - e^{-0.04510663 \times t})^{24.22714} \quad (10)$$

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

In the case of strip window management, each forest stand was divided into strips following common shelterwood management conventions for strip width and forest stand borders. Strips were created one-by-one in a uniform direction, considering adjacency requirements. Post-treatment, there were 1,274 strips – more than 10 times the original number of units – with an average area of 0.74 ha. Harvestable timber volume in the i^{th} strip in period j represents the volume harvested from shelterwood management – a series of preparatory cuttings and the final cutting – when shelterwood management was assigned to strip i in period j.

In the case of conventional management without a strip window, each stand represents a management unit and can be harvested in any period (i.e. 1st, 2nd or 3rd) during the planning horizon. Harvestable timber volume in a management unit in period j represents the volume harvested from this unit in period j, which can be computed by multiplying vol/ha generated from the above growth equation by the area of the unit. The objective of this study is to examine how the introduction of strips in a management unit affects management efficiency, assuming the management goal is to supply a sustainable volume of timber (which is the management mandate of the School Forest Enterprise). Therefore, we only consider Neumann neighbourhood adjacency as an adjacent structure for a conventional management-unit-based problem, which generates a higher timber volume because of fewer harvest restrictions when compared to Moore neighbourhood adjacency.

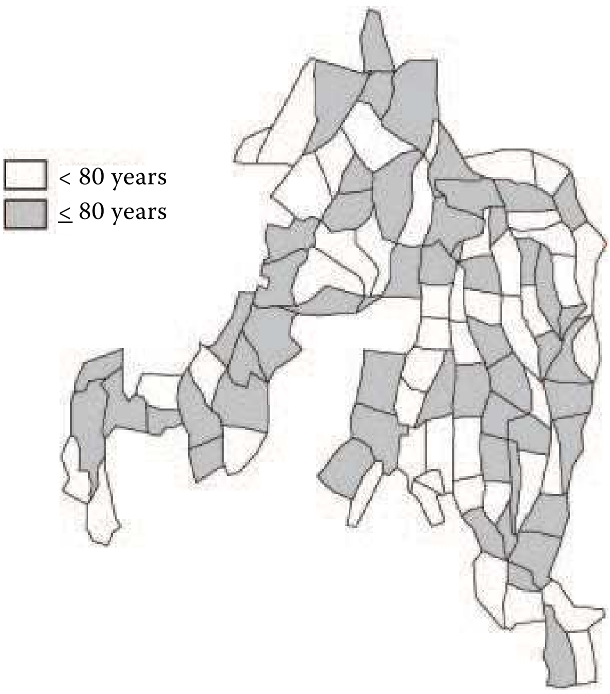

Fig. 2. Map of the forest management unit in Zvolen, Slovakia

Strip cutting effects on management scheme

The analysis was conducted with and without strip windows over three periods. We used five values for flow allowance on harvest flow change over time – 10%, 1%, 0.1%, 0.01% and 0.001% (almost even) – because even-flow constraints are often violated. We first solved a spatially constrained problem without considering a strip window, where adjacency was expressed by Neumann

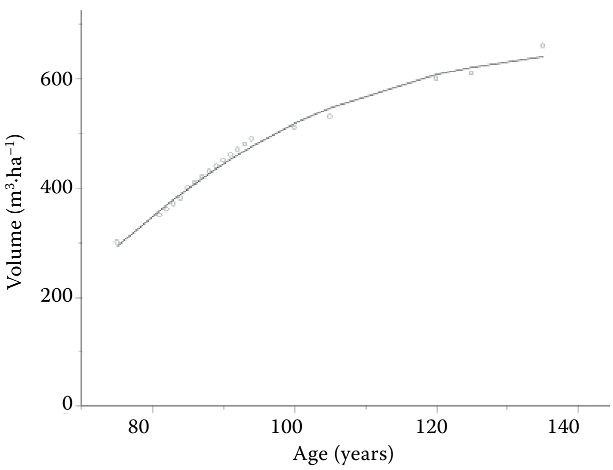

Fig. 3. Growth projection

Table 1. The number of cutting units and remaining uncut area with 10% flow allowance

Period	Ordinary under Neumann adjacency		Strip cutting under Neumann adjacency		Strip cutting under Moore adjacency	
	# of units cut	remaining area with age ≥ 80 years	# of strips cut	remaining area with age ≥ 80 years	# of strips cut	remaining area with age ≥ 80 years
1	19	352.71	234	351.63	207	368.56
2	21	200.80	271	198.47	221	242.93
3	22	12.65	279	13.10	233	84.51

neighbourhood adjacency. Fig. 4 shows the final solution over three periods with 10% flow allowance. Among 55 units eligible in the first period, 19 were selected for harvesting. As time progressed, the number of units available for harvest increased, so that 21 were harvested in the second period and 22 in the last (Table 1). The area remaining eligible for harvest changed from 352.71 ha in the first period to 200.80 ha in the second and 12.65 ha in the third. Harvest flow changed from 95,176 m^3 to 113,468 m^3, with the total harvest volume of 312,574 m^3. Imposing lower flow allowance, the total harvest volume was reduced to 308,381 m^3 with a very even-flow level of 102,794 m^3 over time (Table 2).

Neumann neighbourhood adjacency was next applied to a strip shelterwood management regime.

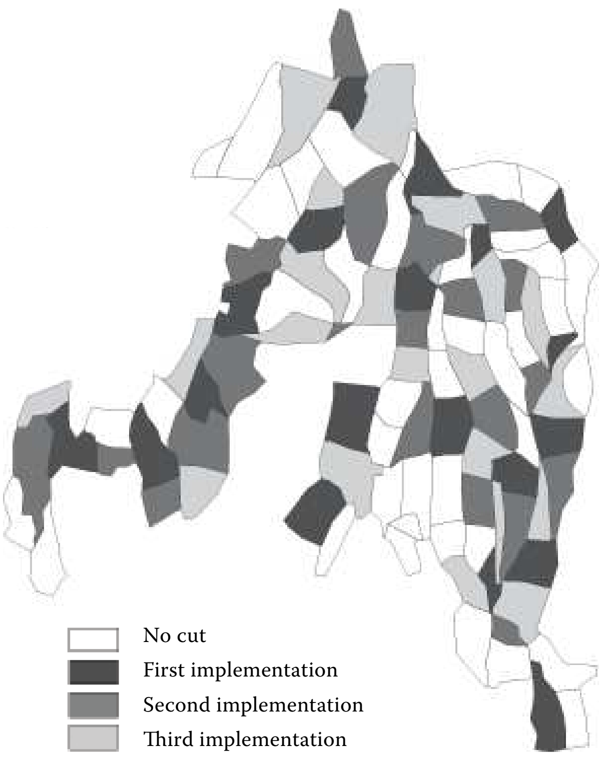

Fig. 4. Final solution without strips under Neumann neighborhood adjacency with 10% flow allowance

With strip windows in the units, we calculated the final solution depicted in Fig. 5 with 10% flow allowance. Among strips, only line-adjacent cuts were avoided. As the number of strips increased approximately ten-fold, 709 strips were eligible for harvest at the beginning of the first period. Of these strips, 234 were cut in the first period, 271 in the second, and 279 in the third (Table 1). The remaining area eligible for harvest in each respective period was 351.63 ha, 198.47 ha, and 13.10 ha. Harvest flow changed from 94,119 m^3 to 113,797 m^3 with the total harvest volume of 311,414 m^3. With lower flow allowance, the total harvest volume was reduced slightly to 309,240 m^3 with an even-flow of 103,080 m^3 over time – slightly more than the previous scenario without strip windows (Table 2). This could be so because, subject to the flow constraints, there are more possible combinations for selecting strips and still meeting the objective. In other words, when compared to the original larger forest stands, smaller strips make it easier to meet the flow constraints.

Moore neighbourhood adjacency restricts harvest opportunities. Under this regime, 207 strips are cut in the first period, 221 in the second, and 233 in the last. Among strips eligible for harvest at the beginning of the first period, 368.56 ha were left uncut in the first period, 242.93 ha in the second, and 84.51 ha in the last (Table 1). Unlike the solutions from the Neumann neighbourhood adjacency scenario, an area of 84.51 ha – almost six times the other cases – was reserved for subsequent harvesting by the Moore neighbourhood adjacency management scheme. In other words, the creation of strip windows under Moore neighbourhood adjacency seems to reduce the current harvest opportunity, but it indirectly reserves resources for future harvesting (Fig. 6). The total volume harvested was reduced by 12.38% with a 10% allowance (Table 2). It was slightly increased to 11.92% as the flow allowance became tight at 0.001%. Harvest flow changed from 82,851 m^3 to 100,051 m^3 with a 10% flow allowance (Table 2).

Table 2. Results from three spatially constrained management scheme

		Flow allowance (%)				
		10	1	0.1	0.01	0.001
No strips under Neumann adjacency	period 1	95,176	102,880	103,047	102,880	102,794
	period 2	103,929	103,548	103,106	102,871	102,793
	period 3	113,468	104,044	103,080	102,878	102,794
	total harvested volume	312,574	310,471	309,233	308,629	308,381
	base %	100	100	100	100	100
Strips under Neuman adjacency	period 1	94,119	102,187	102,995	103,080	103,079
	period 2	103,498	103,198	103,091	103,071	103,080
	period 3	113,797	104,104	103,171	103,079	103,080
	total harvested volume	311,414	309,488	309,257	309,230	309,240
	relative difference (%)	99.63	99.68	100.01	100.19	100.28
Strips under Moore adjacency	period 1	82,851	89,774	904,96	90,546	90,546
	period 2	90,967	90,635	90,543	90,547	90,545
	period 3	100,051	91,504	90,634	90,546	90,545
	total harvested volume	273,868	271,914	271,673	271,639	271,635
	relative difference (%)	87.62	87.58	87.85	88.01	88.08

DISCUSSION AND CONCLUSION

The strip shelterwood forest management system specifies strip windows for harvest and regeneration of forest stands, along with an adjacency requirement among strips. The adjacency requirement is an important aspect of the shelterwood system because it requires leaving corresponding adjacent strips uncut during the regeneration period on one strip. In this paper, we investigated the management effects

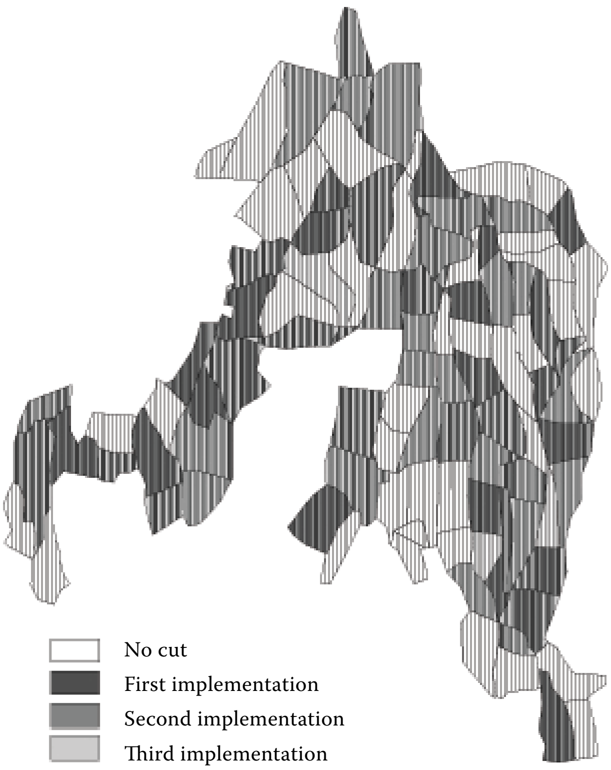

Fig. 5. Final solution with strips under Neumann neighborhood adjacency with 10% flow allowance

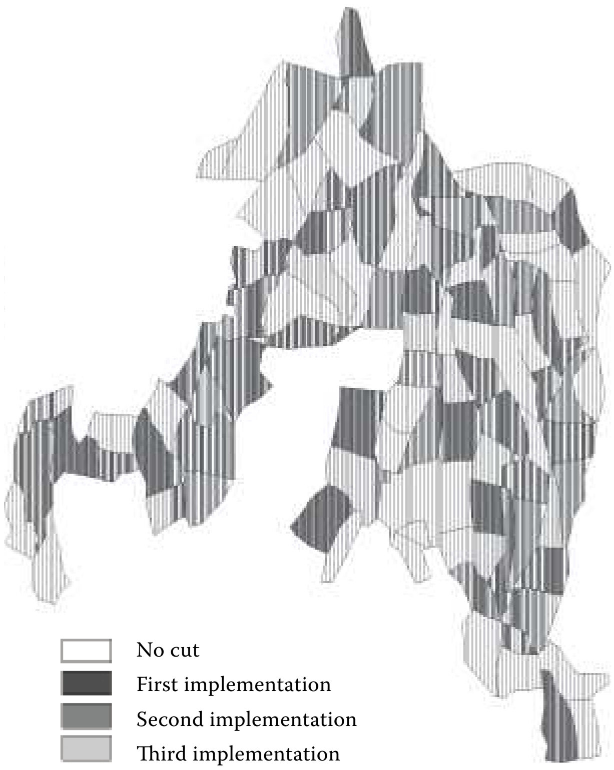

Fig. 6. Final solution with strips under Moore neighborhood adjacency with 10% flow allowance

of strip cutting under the strip shelterwood management system with adjacency requirements imposed by Moore neighbourhood adjacency and Neumann neighbourhood adjacency, examining the effect on the volume and area harvested, as well as harvest flow over the planning horizon. We compared the effect of creating a strip window within a management unit with 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.

With an objective of maximizing the total harvested volume, we showed the following: given 529 ha of mature forest units eligible for harvest, 33% of the area was harvested in the first period in both the scenario without strip windows and the scenario with strip windows subject to Neumann neighbourhood adjacency. 30% was harvested in the scenario with strip windows subject to Moore neighbourhood adjacency. Thus, as a whole, avoiding corner-adjacent strip cutting under Moore neighbourhood adjacency reduced the total harvest volume and harvest flow by approximately 13%.

From a sustainable harvest perspective, however, the scenario with strip windows under Moore neighbourhood adjacency reserved about six times more area for future harvest than the other scenarios, which held almost no area in reserve. This implies that the creation of strip windows in forest stands under Moore neighbourhood adjacency could play an indirect role in preserving some resources for future harvest, possibly meeting sustainable management objectives.

This analysis also demonstrates that more latitude in cut unit selection would contribute to meeting management goals more efficiently. Our comparison of "with" and "without" strips shows that strip-based management, which gives managers greater choice in selecting trees to cut, more closely meets the harvest flow constraint. Management science theory has argued that allowing more latitude in management decisions improves management outcomes. Our results confirm this argument and suggest that creating strip windows not only contributes to a sustainable use of forest resources but also it may improve management efficiency.

We limited our analysis to a three-period horizon because this 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. Nonetheless, by modelling spatial adjacency in shelterwood management and comparing different adjacency structures, we were able to explore a management plan that explicitly addresses the efficient spatial allocation of a forest treatment and examine the effect of strip creation on management efficiency. Although we only consider a strip shelterwood management system in this study, our spatial harvest scheduling model can be extended to another type of shelterwood system called the "group" method, which removes groups of trees at each cut.[1)] In this case, we would first need to develop a rule that determines the size and spatial pattern of a "group" within a management unit. The rule must reflect those forest attributes necessary to grow a stand into a "target" condition. (For example, the percentage of remaining canopy cover required to provide enough protection and space for regeneration should be considered.) Then, we would formulate a spatially explicit forest management plan with adjacency constraints that prevents harvesting two adjacent "groups" simultaneously.

As the ecological and environmental aspects of forest management gain more and more attention, the need for forest management that explicitly addresses these concerns has increased. Additionally, there has been an increasing interest in studies that integrate ecology into management science and economic analyses. As we demonstrated in this study, exploring and examining those ecological concepts within an optimization framework will provide useful information and support for improving the efficiency and effectiveness of forest management that aims to balance ecological and economic objectives.

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[1)]Another implementation of the shelterwood system is often called the "uniform" method, where harvested trees are evenly scattered throughout a management unit. The proposed model cannot address the spatial pattern of a single tree within a management unit. A spatial pattern of individual trees, which involves a decision on which trees should be removed within a management unit, is generally determined on-site. We often treat these types of operational plans differently than a harvesting schedule.

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Corresponding author:
Doc. Ing. Róbert Marušák, Ph.D., Czech University of Life Sciences, Faculty of Forestry and Wood Sciences, Kamýcká 129, 165 21 Prague 6-Suchdol, Czech Republic
e-mail: marusak@fld.czu.cz