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Spatially-constrained harvest scheduling with respect to environmental requirements and silvicultural system

Prostorové plánování mýtních těžeb zahrnující environmentální požadavky a hospodářské způsoby

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Abstract

There has been an increasing demand for environmental considerations (e.g. unharvested patches) in forest harvest scheduling in the last decades. In Slovakia and the Czech Republic, allowable cut indicators are not based on the spatial structure; thus, they are unable to incorporate these additional conditions. Many harvest scheduling models based on integer and mixed integer programming have been developed throughout the world, but their use in forest management in Slovakia and the Czech Republic is rare. These approaches have mostly been developed for clear-cut management systems and do not exist for shelterwood systems. Harvest scheduling approaches for a two-phase, small-scale shelterwood system and a clear-cut system are presented. The models also include environmental requirements that restrict area of forest stands that are not to be harvested over the planning horizon. A mathematical formulation of that requirement was integrated into the forestry decision support system Optimal to solve all analysed harvest scheduling alternatives for small-scale shelterwood and clear-cut systems. Our results indicated that the total harvest volume amounts could be higher when a two-phase, small--scale shelterwood system is applied. While there are legal adjacency constraints regulating clear-cut harvests, the influence of additional environmental requirements on the total harvested amount is more restrictive for the shelterwood system because of greater area available for harvest. Both scenarios of maximization of harvested volume and net present value provided comparable results.

Key words: environmental limits; shelterwood silvicultural system; mathematical programming; adjacency constrains

Abstrakt

V současné době stále narůstají požadavky společnosti na plnění environmentálních aspektů při procesu plánování těžeb. Těžební ukazatelé, které jsou stále ještě používány na Slovensku a v České republice, nemohou takovýto typ omezení zahrnovat, protože nejsou založeny na prostorové struktuře. Mnoho alternativních modelů plánování těžeb, které jsou založeny na celočíselném a smíšeném celočíselném programování, již bylo vyvinuto. Tyto modely jsou ale bohužel ve většině případů určeny pouze pro holosečný hospodářský způsob a modely pro podrostní hospodářský způsob stále chybí. V této práci je prezentován model plánování určený pro dvoufázovou maloplošnou clonnou seč jako jedné z alternativ podrostního hospodářského způsobu. Model zahrnuje také environmentální aspekty, které jsou reprezentovány ponecháním dané plochy mýtních porostů bez zásahu. Uvedený matematický model byl implementován do systému podpory rozhodování Optimal, pomocí kterého byly také analyzovány všechny uvedené alternativy. Naše výsledky ukazují, že celková těžba může být vyšší v případě podrostního hospodářského způsobu. Protože jsou zahrnuty prostorové zákonné podmínky přiřazování sečí, je vliv environmentálních podmínek větší v případě holosečného hospodářského způsobu než u podrostního hospodářského způsobu. Maximalizace těžby i čisté současné hodnoty vykazují srovnatelné výsledky.

Klíčová slova: environmentální limity; podrostní hospodářský způsob; matematické programování; prostorová omezení

1. Introduction

In the former Czechoslovakia after 1989, harvest scheduling methods were influenced by socioeconomic and political changes. The main changes that influenced forest management were the restitution of ownership rights to the original forest owners, a decrease of forest management units (FMU), and a preference of near-natural silvicultural systems. In most Central European countries, particularly in the Czech Republic and Slovakia, harvest scheduling was conducted for large FMU with an area of 5,000 hectares and greater. Presently these large units are divided into many small FMUs with an area of a few tens or hundreds of hectares under the process of forest denationalization. The last known information about the average area of FMU in Slovakia was estimated at 881 ha in 2005 (Green Report 2006); in the Czech Republic average FMU size is not published, but it is estimated to be less than in Slovakia. The age structure of newly-formed FMUs is mostly unbalanced with a striking lack or surplus of mature forest stands.

For these FMUs, near-nature systems, such as shelterwood silvicultural systems, are recommended to increase natural regeneration. Shelterwood regeneration is a common contemporary method for the natural regeneration of forest stands. The ratio of natural regeneration in the Czech Republic and Slovakia is almost 25% and 37%, respectively (Green

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Report 2013 – CR; Green Report 2013 – Slovakia). Unfortunately, analyses on harvest scheduling are largely focused on the clear-cutting system and allowable cut indicators (ACI) in both countries. Greguš (1976, 1983), Žíhlavník (2000), Majoroš (2001), and Marušák (2001) discussed advantages and disadvantages of the individual ACI and their use in forest management. The utilisation of ACI for shelterwood systems has not been analysed, and there are only a few published analyses aimed at ACI in a small-scale forests managed in Slovakia (Šuška & Majoroš 1997; Majoroš 1999). Marušák (2001, 2003) and Žíhlavník (2000, 2005) evaluated empirical cutting percentages and theoretical areas as ACIs for shelterwood systems.

Mathematical programming is a group of traditional methods for harvest scheduling problems. Linear programming has been used to solve harvest scheduling problems since the 1970s (Johnson & Scheurman 1977; Field et al. 1980). The concept of spatial planning was developed alongside the advancement of geographic information system (GIS), which allowed for analysis of harvesting spatial configurations (see for example Baskent & Jordan 1991 or Jamnick & Walters 1993). These advancements in harvest scheduling allowed for more complex analyses, such as maximum clear-cut size (Kurttila 2001; Boston & Bettinger 2001; Murray & Weintraub 2002), spatial restrictions on clear-cut opening size (Nelson & Brodie 1990; Roise 1990; Dahlin & Sallnas 1993; Richards & Gunn 2003), and the effects of different clear-cut restrictions on economic outputs (Barrett et al. 1998). Spatial requirements were also considered in ecological and environmental research (Pukkala et al. 1995; Hof & Bevers 2000; Kurttila 2001), optimization of wildlife habitat and timber in the managed forest ecosystems (Hof & Joyce 1993; Kašpar et al. 2015), land classification strategies (Borges & Hoganson 2000), harvest clustering and reducing fragmentation (Öhman & Lamas 2003, Öhman &d Wikström 2008), and wind damage risk assessment (Lohmander & Helles 1997; Konôpka & Konôpka 2008).

In central Europe, there is a need for analyses of harvest scheduling approaches for alternative types of management, i.e. non clear-cut systems. Marušák (2007) first suggested a scheduling model for shelterwood management systems and its comparison with ACI in the Slovak Republic, later followed by an alternative approach presented by Konoshima et al. (2011b). Kašpar et al. (2013, 2014) compared the use of alternative spatially-restricted scheduling approaches only for clear-cut management systems with ACI used in the Czech Republic.

The objective of this paper is to investigate spatially-constrained harvest scheduling for two-phase small-scale shelterwood and clear-cut systems, including unharvested patches as environmental requirement for a private FMU. Small-scale shelterwood system is defined as a shelterwood harvest in adjacent strips; when a strip is regenerated after a final cut, a seeding cut on an adjacent strip can be performed, but no simultaneous cut in adjacent strips is allowed (Bavlšík et al. 2008).

We considered the following constraints: (i) silviculture was limited to shelterwood and clear-cut systems represented by maximal area and width of harvest units; (ii) owner's requirements for harvest flow; and (iii) environmental requirements to leave a certain portion of forest stands without harvest. We analysed alternative scenarios using integer programming. Because maximization of harvest volume is the main target of harvest scheduling in the Czech Republic and Slovakia, the objective of the proposed problem is to maximize the total cut volume or net present value (NPV) over the planning horizon. We compared both the small-scale shelterwood and clear-cut systemsfor each scenario.

2. Material and methods

2.1. General formulation

The two-phase, small scale shelterwood and clear-cut management systems were designated as a 0–1 integer programming problem. The objective was to maximize the total harvest volume or NPV from all harvest units over *P* planning periods or phases (within whole planning horizon); one period is equal to 10 years in the case of clear-cut system, and a phase is equal to 5 years in the case of shelterwood system.

$$max Z = \sum_{i=1}^{I} \sum_{p=1}^{P} v_{ip} \,.\, x_{ip} \qquad [1]$$

where *I* is the total number of harvest units, *P* is the total number of planning periods or phases, v_{ip} is the harvest volume or NPV of the *i*th unit in the period or phase, *p,* and x_{ip} is a control variable (0 or 1) to specify the harvest of the *i*th unit which belongs to period or phase, *p,* as defined by:

$$x_{ip} = \begin{cases} 1 & \text{if the unit } i \text{ in period or phase } p \text{ is harvested} \\ 0 & \text{otherwise} \end{cases} \qquad [2]$$

Each unit can be harvested only once over the planning horizon or it may remain without harvest, i.e.

$$\sum_{p=1}^{P} Px_{ip} + \sum_{p=1}^{P} x_{ip0} \leq P \quad \forall i \in I \qquad [3]$$

where x_{ip0} is a control variable (0 or 1) to specify no harvest defined by:

$$x_{ip0} = \begin{cases} & \text{if the unit } i \text{ in period or phase } p \text{ is not harvested} \\ & \text{otherwise} \end{cases} \qquad [4]$$

2.2. Spatial and area requirements

The main legal requirement of the clear-cut system is spatial constraints for harvest units (strict area and width). Adjacency constraints in our problem were defined using the formulation of Yoshimoto & Brodie (1994). The greenup time is one planning period for clear-cut or one phase for shelterwood system.

The environmental requirement allowed for defined areas of mature forest stands be left without harvest throughout the planning horizon. The area of harvest units that left without harvesting had to be equal to or greater than the required area (*RA*). This was secured by:

$$\sum_{i=1}^{I} a_i x_{ip0} \geq RA \quad \forall p \in P \qquad [5]$$

where ai is the area of the ith harvest units. We used 5% of total mature forest stands area as the RA standard for this study. The neighbouring harvest units are not restricted by this required area.

2.3. Flow constraints

The requirement for the maximum percentage difference (α) between two sequential periods was used to regulate flow. In this formula, means periodic harvested volume or periodic NPV of harvest in period *p*.

$$(1-\alpha)V_{p-1} \leq V_p \leq (1+\alpha)V_{p-1} \quad [6]$$

To ensure balanced harvesting throughout the planning period (*P*), the maximum percentage difference (α) between the first (*p*=1) and the last period (*p*=*P*) was included in the model.

$$(1-\alpha)V_p \leq V_p \leq (1+\alpha)V_p \quad [7]$$

To calculate NPV, we used an average wood price of 47.83 € m^{-3} and average felling costs of 22.83 € m^{-3}.(Green Report 2010), with an interest rate of 2.00%. We conducted our analyses using the updated version of the forestry decision support system (DSS) *Optimal* (Marušák et al. 2015; Vopěnka et al. 2015). The DSS Optimal was extended by environmental constraints [Eq. 3 and Eq. 5] for this study. The user can select to include environmental constraints and set the area without harvest (Fig. 1).

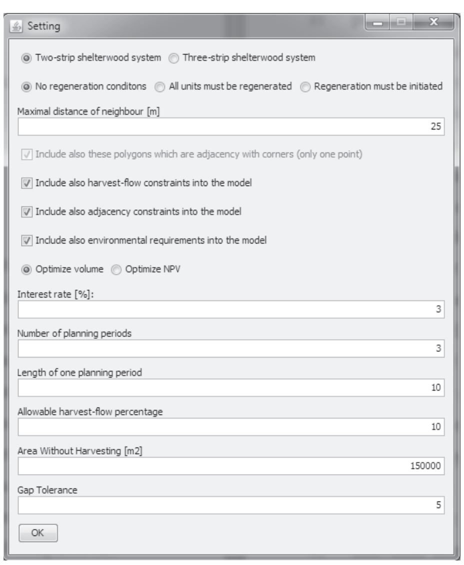

Fig. 1. DSS Optimal User´s interface for constraints setting.

2.4. Case study

For this study, we examined a 513.9 ha FMU (Fig. 2a) with an unblanaced age structure (Fig. 2b). Forest stands were assigned to one of 17 10-year age classes, and there was a surplus of mature forest stands (age class 10 and higher). We assumed a rotation period of 110 years and a regeneration period of 30 years. Growth data for this FMU was obtained in 2013 based on a forest inventory. To simplify the scenarios, species composition of the forest stands was limited to a single species, Norway spruce (*Picea abies* L. Karst), and we assumed a site index of 28 as it is current mean site index of studied FMU.

There were 163 stands available to harvest in the initial three periods with a total area of 300 ha. Each forest stand was divided into harvest units (strips) following the rules of the clear-cut system, i.e. the limited area and width of strips. The total number of harvest units was 1161 with an average area of 0.26 ha. The total area of harvest units without cut had to be at least 5% (15.0 ha) of the total area of mature forest stands.

A planning horizon of 30 years (three periods of 10 years) was used for optimization, which also corresponds to the regeneration period. Both management systems were evaluated separately with a total of eight scenarios to investigate the influence of requirements and limits (Table 1): four alternatives (A, B, C and D) for each of the shelterwood management (Sw) and the clear-cut management systems (Cc). For both management systems, two variants of the model were calculated: (i) harvested volume was maximized (assigned as HV), and (ii) NPV was maximized (assigned as NPV). A maximum 10% fluctuation between two sequential periods was used as a harvest flow constraint in alternatives A and B; this requirement was applied only for periods two and three because no harvest data prior to the planning horizon was available. Alternatives A and C maintained a total area ≥ 15.0 ha in units without harvest as an environmental limit. Alternative D, which evaluated potential harvest and NPV when only adjacency constraints are considered, was used as a comparative scenario.

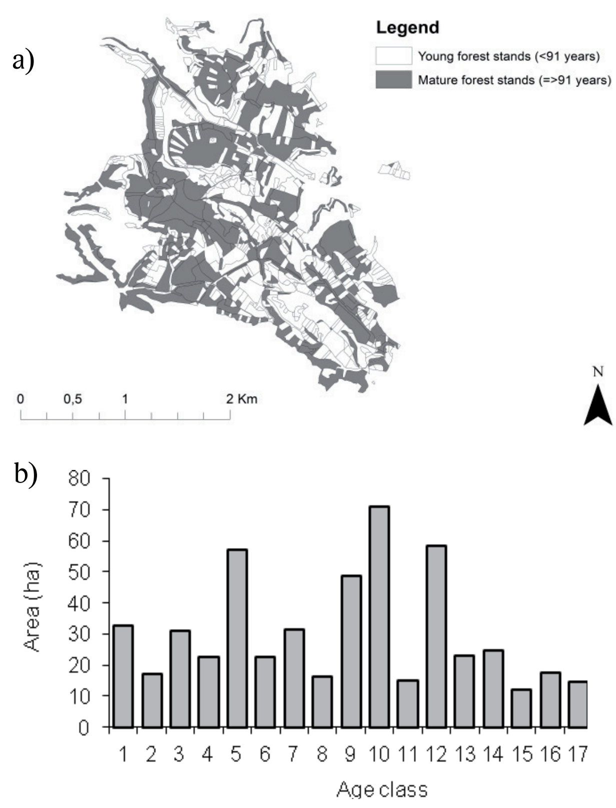

Fig. 2. Forest map of the investigated forest management unit (a) and respective age structure (b).

Table 1. Alternative management scenarios using different combinations of requirements and limits.

Alternative (management system)	Environmental limit	Harvest flow
A (-Cc/-Sw)	Yes	Yes
B (-Cc/-Sw)	No	Yes
C (-Cc/-Sw)	Yes	No
D (-Cc/-Sw)	No	No

Remark: When environmental requirements are modelled, a minimum of 5% (15.0 ha) area must remain unharvested, and when harvest flow limits are included, a maximum 10% fluctuation between two sequential periods is maintained. Cc indicates a clear-cut scenario and Sw indicates a small-scale shelterwood scenario.

3. Results

The influence of environmental limits on harvest volume and NPV is presented by comparing alternatives A and C to alternative D. Similarly, the influence of harvest flow and NPV flow on harvest volume and NPV is presented by comparing alternatives A and B to alternative D.

3.1. Maximising harvest volume

Maximum possible harvest (alternatives D) occurred when no environmental and harvest flow constraints were taken into account (Table 2, Fig. 3a); the total harvest volume was 98,312 m^3 and 117,122 m^3 for clear-cut (D–Cc) and shelterwood systems (D–Sw), respectively, for three planning periods. However, harvest levels were unbalanced in both scenarios; for the clear-cut system (D–Cc), the third period harvest volume was almost twice as much as in period one (41,463 m^3 and 22,132 m^3), and the difference was much higher (60,670 m^3 and 12,010 m^3) under a shelterwood system.

Table 2. Harvest volume (m^3) and net present value (×10^3 €) of alternatives A–D for clear-cut and shelterwood management system when harvested volume was maximized.

Alternative	Objectives	Period 1	Period 2	Period 3	Total
A–Cc	Cut	30,806	33,245	33,886	97,939
	NPV	572	553	495	1,622
B–Cc	Cut	30,713	33,437	33,781	97,931
	NPV	570	556	496	1,622
C–Cc	Cut	22,132	34,717	41,463	98,312
	NPV	411	578	608	1,597
D–Cc	Cut	22,132	34,717	41,463	98,312
	NPV	411	578	608	1,597
A–Sw	Cut	35,401	38,903	38,941	113,245
	NPV	658	647	571	1,876
B–Sw	Cut	36,346	39,791	39,979	116,116
	NPV	675	662	587	1,924
C–Sw	Cut	11,459	43,366	59,413	114,238
	NPV	213	721	872	1,806
D–Sw	Cut	12,010	44,442	60,670	117,122
	NPV	223	739	890	1,852

When environmental constraint of clear-cut system (C–Cc) was introduced to the model, the total harvest volume was the same as that in alternative D–Cc, including unbalanced harvest within planning periods. Spatial requirements of clear-cut systems are so strict that additional environmental requirements did not affect the total harvest level because they dictated that some harvest units were unharvested in the both scenarios. Introducing the harvest flow constraint in alternative B-Cc reduced the total harvest volume to 97,931 m^3, a mere 381 m^3 (0.4%) less than maximum harvest in alternative D–Cc. Similarly, when both environmental and harvest flow constraints were included (A–Cc), the total harvest level was only 373 m^3 (0.4%) less than the maximum cut alternative (D–Cc). Thus, to fulfil environmental and harvest flow requirements using the clear-cut system resulted in no substantial decrease of harvest levels because spatial and adjacency constraints applied with a clear-cut system primarily limit harvest levels.

Similar relationships were observed for the alternatives A–Sw, B–Sw, and C–Sw using a shelterwood system. Harvest flow restrictions (B–Sw) reduced total harvest levels by only 1,006 m^3 (0.9%) relative to D–Sw, and the environmental constraint (C–Sw) reduced total harvest levels by 2,884 m^3 (2.5%). When both environmental and harvest flow requirements were included in the model, the reduction of total harvest volume was higher than that in the clear-cut system; alternative A–Sw harvest levels were reduced by 3,877 m^3 (3.3%) compared to D–Sw. The influence of silvicultural system on the maximum possible cut in the mentioned alternatives A–C was evident; total harvest levels in the shelterwood system were higher compared to the clear-cut system. Environmental and harvest flow constraints reduced total harvest levels in a shelterwood system, however, they had little influence on the harvest levels of the clear-cut system.

3.2. Maximising NPV

Alternatives D–Cc and D–Sw (Table 3, Fig. 3b) yielded maximum possible NPV without environmental and NPV flow constraints. For the clear-cut system, NPV was 1.646 mil €, approximately 3.1% higher than the same alternative (D–Cc) when harvest volume was maximised (Table 2). It was expected that adding environmental constraints into the model (C–Cc, C–Sw) would decrease the total NPV, however, only in the case of the shelterwood system did NPV decrease, while there was no NPV decrease relative to the D–Cc alternative. It means that adjacency constraints in our case affected total NPV more than environmental constraints (unharvested patches) in the case of clear-cut system. In contrast, NPV flow constraints on the clear-cut system (alternative B–Cc) reduced NPV by 1.52% relative to the maximum NPV (D–Cc), while in the case of the shelterwood system (B–Sw) total NPV was lower while total harvest volume was higher.

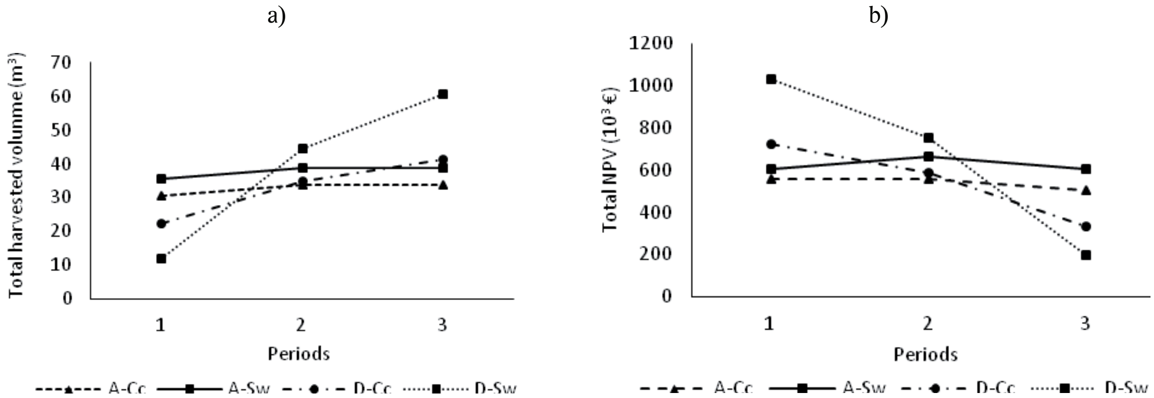

Fig. 3. Total harvested volume when harvest is maximised (a) and total NPV when NPV is maximised (b) by planning period for alternatives A and D for clear-cut and shelterwood systems.

Table 3. Net present value (×10³ €) and cut volume (m³) of alternatives A–D for clear-cut and shelterwood management system when NPV is maximized.

Alternative	Objectives	Period 1	Period 2	Period 3	Total
A–Cc	NPV	559	559	503	1,621
	Cut	30,087	33,603	34,291	97,981
B–Cc	NPV	562	553	506	1,621
	Cut	30,242	33,273	34,466	97,981
C–Cc	NPV	728	582	336	1,646
	Cut	39,168	35,016	22,876	97,060
D–Cc	NPV	724	586	336	1,646
	Cut	38,998	35,251	22,834	97,083
A–Sw	NPV	603	663	603	1,869
	Cut	32,464	39,859	41,108	113,431
B–Sw	NPV	618	680	618	1,916
	Cut	33,288	40,859	42,151	116,298
C–Sw	NPV	1,019	735	182	1,936
	Cut	54,827	44,182	12,413	111,422
D–Sw	NPV	1,030	754	199	1,983
	Cut	55,427	45,345	13,549	114,321

When both environmental and flow constraints were included in the model of the clear-cut system (A–Cc), total NPV was the same as that for only flow constraints (B–Cc). This confirms that adjacency constraints were stricter than environmental constraints, and it is possible to fulfill environmental requirements without any significant loss of harvest volume in clear-cut systems under current forest management conditions. For the shelterwood system, total NPV was the lowest with both environmental and flow constraints in the model; NPV decreased by 5.75% (A–Sw) relative to the maximum (D–Sw), while it was 2.37% less with only environmental limits (C–Sw). Thus, NPV flow constraints limited total NPV more significantly for the shelterwood system than for the clear-cut system.

3.3. Harvest vs. NPV maximising

It was expected that maximising harvest volumes would result in higher total harvest and lower total NPV, and a higher total NPV and lower total harvest when the NPV objective was maximised. However, within all alternatives under each maximisation scenario, the differences between total harvest level and total NPV were are not significant.

Maximal total harvest in the case of clear-cut system was 98,312 m³ when harvest was maximised and 97,083 m³ when NPV was maximised. It was a small difference of only 1.25% in total harvest volume, but a mere difference of 0.06% in terms of NPV. When both additional constraints were introduced (alternatives A), the total harvest levels and NPV changed very little when either objective was maximised. In contrast, maximising total harvest or NPV using a shelterwood system yielded much greater differences in total harvest volumes and NPV. Maximising total harvest (D–Sw) produced a total harvest volume of 117,122 m³, but, when NPV was maximised, total harvest volume was 2.39% lower (114,321 m³). Maximising total NPV (D–Sw) produced a total NPV of 1.983 mil €, but, when total harvest volume was maximised, total NPV was 6.61% lower (1.852 mil €). When both environmental and flow constraints were added (alternatives A), total harvest was higher when NPV was maximised.

An interesting result was the relationship between total harvest and total NPV in the alternatives which included environmental and flow constraints when harvest volume or NPV are maximised. The total harvested volume was higher when NPV was maximised and NPV was higher when harvest was maximised (alternative A) for both clear-cut and shelterwood system scenarios; this was caused by the limiting effect of used constraints.

4. Disccusion

The spatial structure of mature forest stands or individual harvest units can strongly influence harvesting alternatives in many cases (Konoshima et al. 2011a; Kašpar et al. 2014). It is not possible to precisely schedule harvesting without spatial information. There is no information on where each harvest should take place because the volume under ACI is derived only by the utilization of the summarized volume data of mature age classes. The utilisation of ACI would fail to secure the area and meet the strip width limits of the shelterwood system. The shelterwood system addresses the silvicultural requirements for forest stands, regarding age and natural conditions. The shelterwood system meets the near-nature forest management targets, while more intensive harvest systems would reduce canopy cover too drastically.

Three alternatives (A–C) were considered to investigate the influence of management requirements and limits relative to alternative D that considered only adjacency constraints. For the shelterwood system, the smallest difference in total harvest volume was obtained by alternative B, when only the harvest flow requirement was considered. On the other hand, the smallest difference in total NPV was obtained by alternative A when the constraints of environmental area and harvest flow were included, and it also provided more balanced harvest levels over the planning horizon. Alternative A provided less total harvested volume than alternatives B and C, but the total NPV was equal to or higher in both cases.

Environmental requirements similar to alternative A were analysed in paper by Kašpar et al. (2015). The authors confirmed their assumption that the total harvested volume would be higher when no environmental requirements were considered, even when the model was applied to a clear-cut management system; however, they do not calculate NPV. Öhman & Wikström (2008) tested a harvest scheduling model for a clear-cut management system with similar environmental requirements and they maximized NPV. They determined that the total NPV was also higher when no environmental requirements were considered. However, a previous study by the same authors (Öhman & Lamas 2005) demonstrated that the total harvested volume was almost the same for all variants, i.e. with or without environmental requirements. However, the models presented in the above three studies included the goal of reducing forest fragmentation. The differences between results presented in this paper and the above studies could be caused by different scheduling approaches on the one hand, by differing initial spatial configurations and age structures, or by different management systems as previously mentioned.

Our results demonstrate that is important to test and develop harvest scheduling models for shelterwood management systems. They are needed to apply similar models to different initial conditions of FMUs to obtain comparable results because the role of initial age or spatial structure is likely critical to the results of harvest scheduling under shelterwood management systems.

5. Conclusions

This paper discussed spatially constrained harvest scheduling for small-scale shelterwood and clear-cut systems used in the Czech Republic and the Slovak Republic. Our results indicate that harvest scheduling for shelterwood systems should not be conducted using ACI as still applied in forest management in both Republics. Spatial requirements are the most important constraints, which are not typically accounted for in harvest scheduling. Optimization using silvicultural requirements and additional constraints, such as environmental area and/or flow constraints, provided solutions suitable for the application of small-scale shelterwood systems. The proposed spatially constrained harvest scheduling for the shelterwood system can be used as an alternative solution to ACI approaches used in forest management practice. In addition, this paper presented an approach to solve harvest scheduling problems using the forestry decision support system Optimal, which can be a distinct advantage for usage in forest management. One of the most important result which can be generalised for Czech and Slovak conditions is an understanding of the influence of environmental and harvest flow constraints on harvest; these constraints had a greater negative impact on total harvest volume of shelterwood systems than in clear-cut systems.

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References

Barrett, T. M., Gilless, J. K., Davis, L. S., 1998: Economic and fragmentation effects of clearcut restrictions. Forest Science, 44:569–577.

Baskent, E. Z., Jordan, G. A., 1991: Spatial wood supply simulation modelling. Forestry Chronicle, 67:610–621.

Bavlšík, J., Antal, P., Kočik, L., Kominka, V., Kučera, J., Machanský, M. et al., 2008: Pracovné postupy hospodárskej úpravy lesov. Zvolen, NLC, 147 p.

Borges, J. G., Hoganson, H. M., 2000: Structuring a landscape by forestland classification and harvest scheduling spatial constraints. Forest Ecology and Management, 130:269–275.

Boston, K., Bettinger, P., 2001: The economic impact of greenup constraints in the southeastern United States. Forest Ecology and Management, 145:191–202.

Dahlin, B., Sallnas, O., 1993: Harvest scheduling under adjacency constraints: a case study from the Swedish sub-alpine region. Scandinavian Journal of Forest Research, 8:281–290.

Field, R. C., Dress, P. E., Fortson, J. C., 1980: Complementary linear and goal programming procedures for timber harvest scheduling. Forest Science, 26:121–133.

Green Report, 2006: Správa o lesnom hospodárstve v Slovenskej republike 2006. Bratislava, Ministry of Agriculture of the Slovak Republic, 148 p.

Green Report, 2010: Zpráva o stavu lesa a lesního hospodářství České republiky 2010. Praha, Ministry of Agriculture of the Czech Republic, 136 p.

Green Report, 2013: Správa o lesnom hospodárstve v Slovenskej republike 2013. Bratislava, Ministry of Agriculture and Rural Development of the Slovak Republic, 83 p.

Green Report, 2013: Zpráva o stavu lesa a lesního hospodářství České republiky 2013. Praha, Ministry of Agriculture of the Czech Republic, 210 p.

Greguš, C., 1976: Forest Management of Small Area Silviculture System. Bratislava, Príroda, 304 p.

Greguš, C., 1983: Allowable cut calculation by empiric exploitation percentage. Lesnícky časopis, 29:251–267.

Hof, J., Joyce, L. A., 1993: A mixed integer linear programming approach for spatially optimizing wildlife and timber in managed forest ecosystem. Forest Science, 39:816–834.

Hof, J., Bevers, M., 2000: Optimal timber harvest scheduling with spatially defined sediment objectives. Canadian Journal of Forest Research, 30:1494–1500.

Jamnick, M. S., Walters, K. R., 1993: Spatial and temporal allocation of stratum-based harvest schedules. Canadian Journal of Forest Research, 23:402–413.

Johnson, K. N., Scheurman, H. L., 1977: Techniques for prescribing optimal timber harvest and investment under different objectives-discussion and synthesis. Forest Science Monography, 18:31 p.

Kašpar, J., Marušák, R., Vopěnka, P., 2013: Comparison of two alternative optimization techniques for spatial harvest planning. Scientia Agriculturae Bohemica, 44:90–96.

Kašpar, J., Marušák, R., Sedmák, R., 2014: Spatial and non-spatial harvest scheduling versus conventional timber indicator in over –mature forests. Lesnícky časopis - Forestry Journal, 60:81–87.

Kašpar, J., Marušák, R., Hlavatý, R., 2015: A Forest Planning Approach with respect to the Creation of Overmature Reserved Areas in Managed Forests. Forests, 6:328–343.

Konôpka, J., Konôpka, B., 2008: Prognóza náhodných ťažieb v smrečinách v dôsledku mechanicky pôsobiacich abiotických škodlivých činiteľov v oblasti Kysuce a Orava, Tatry, Spiš, Slovenské rudohorie. Lesnícky časopis - Forestry Journal, 54:325–346.

Konoshima, M., Marušák, R., Yoshimoto, A., 2011a: Spatially constrained harvest scheduling for strip allocation under Moore and Neumann neighbourhood adjacency. Journal of Forest Science, 57:70–77.

Konoshima, M., Marušák, R., Yoshimoto, A., 2011b: Harvest scheduling with spatial aggregation for two and three strip cut system under shelterwood management. Journal of Forest Science, 57:271–277.

Kurttila, M., 2001: The spatial structure of forests in the optimization calculations of forest planning: a landscape ecological perspective. Forest Ecology and Managament, 142:129–142.

Lohmander, P., Helles, F., 1987: Windthrow probability as a function of stand characteristics and shelter. Scandinavian Journal of Forest Research, 2:227–238.

Majoroš, Š., 1999: Overenie možnosti adaptívnej regulácie obnovných ťažieb súboru podrastovo obhospodarovaných porastov. Acta Facultatis Forestalis Zvolen, XLI:211–224.

Majoroš, Š., 2001: Alternatívne možnosti ťažbovej úpravy adaptívnymi ukazovateľmi. Acta Facultatis Forestalis Zvolen, XLIII:209–218.

Marušák, R., 2001: Possibilities of using of allowable cut indicators in shelterwood system. In: Gadow, K. V., Nagel, J., Saborovski, J. (ed.): Continuous Cover Forestry – Assessment, Analysis, Scenarios. International IUFRO Conference, 19. – 21. 9. 2001, Göttingen, Germany, p. 195–202.

Marušák, R., 2003: Harvest scheduling and close to nature forestry. In: Novotný, J. (ed.): Close to nature forestry. Zvolen, Forest Research Institute Zvolen, p. 28–37.

Marušák, R., 2007: Alternative harvest scheduling for final cut with respect to silvicultural requirements. Lesnícky časopis - Forestry Journal, 53:117–127.

Marušák, R., Kašpar, J., Vopěnka, P., 2015: Decision Support System (DSS) Optimal – A case study from the Czech Republic. Forests, 6:163–182.

Murray, A. T., Weintraub, A., 2002: Scale and unit specification influences in harvest scheduling with maximum area restrictions. Forest Science, 48:779–789.

Nelson, J., Brodie, J. D., 1990: Comparison of a random search algorithm and mixed integer programming for solving area-based forest plans. Canadian Journal of Forest Research, 20:934–942.

Öhman, K., Lamas, T., 2003: Clustering of harvest activities in multiobjective long-term forest planning. Forest Ecology and Management, 176:161–171.

Öhman, K., Lamas, T., 2005: Reducing forest fragmentation in long-term forest planning using mixed integer programming. Forest Ecology and Management, 212:346–357.

Öhman, K., Wikström, P., 2008: Incorporating aspects of habitat fragmentation into ling-term forest planning using mixed integer programming. Forest Ecology and Management, 255:440–446.

Pukkala, T., Nuutinen, T., Kangas, J., 1995: Integrating scenic and recreational amenities into numerical forest planning. Landscape Urban and Planning, 32:185–195.

Richards, E. W., Gunn, E. A., 2003: Tabu search design for difficult forest management optimization problems. Canadian Journal of Forest Research, 33:1126–1133.

Roise, J. P., 1990: Multicriteria nonlinear programming for optimal spatial allocation of stands. Forest Science, 36:487–501.

Šuška, M., Majoroš, Š., 1997: Teoretické princípy a využitie adaptívnej regulácie a kontroly rubných ťažieb. Vedecké štúdie 10/1997/A, TU Zvolen, 57 p.

Vopěnka, P., Kašpar, J., Marušák, R., 2015: GIS tool for optimization of harvest-scheduling. Computers and Electronics in Agriculture, 113:254–259.

Yoshimoto, A., Brodie, J. D., 1994: Comparative analysis of algorithm to generate adjacency constraints. Canadian Journal of Forest Research, 24:1277–1288.

Žíhlavník, A., 2000: Ťažbová regulácia v lesných užívateľských celkoch s podrastovým hospodárskym spôsobom. Acta Facultatis Forestalis Zvolen, XLII:213–225.

Žíhlavník, A., 2005: Vplyv vlastníckych vzťahov k lesu na metódy ťažbovej úpravy lesa. Vedecké štúdie 10/2004/A, TU Zvolen, 62 p.