

Possibilities to Aggregate Raster Cells through Spatial Optimization in Forest Planning

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This study divided the forest into raster cells and used these cells as calculation units in optimisation instead of predefined stand compartments. It was hypothesized that raster cells would result in feasible treatment units and more efficient utilization of the production potential of the forest when spatial optimisation is used to compile the plan. The optimization problems of this study included both ecological and economic objectives. The raster cells were hexagons (721 m^2) and their data were derived from traditionally defined forest compartments. Three forest plans were developed by using the rasterized forest, and they were compared to the corresponding forest plans developed by using compartments. Cutting areas were aggregated in all plans, by maximizing the proportion of the boundaries between two adjacent calculation units that were both cut during the same management period, and by minimizing the proportion of cut-uncut boundaries. In the first plan, only cutting areas were aggregated. In the second and third plan, also old forests were aggregated by using two different spatial objectives. The first maximized the proportion of the boundary between adjacent calculation units that were both considered as old forest. The second objective maximized the mean of the neighbourhood minima of the calculation units' old forest indices. The neighbourhood included the calculation unit itself and all the adjacent calculation units. The growing stock volume targets at the end of the 60-year planning period and the cutting volume targets of the three 20-year management periods were set to the same levels in all plans. The results showed that the raster approach was able to aggregate old forest patches and cutting areas similar in shape and size as the conventional approach. When the aggregation of old forest was a management objective, the total old forest area was larger in the raster forest but the mean size of the old forest patches was larger with predefined compartments. The trade-off curve between harvested volume and old forest area was further from the origin for the raster forest.

Keywords landscape metrics, old forest, threshold accepting, spatial optimisation

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1 Introduction

The basic unit in forest inventory and planning is usually a forest stand compartment, which is a homogenous forest area; in Finnish private forests it is typically 0.5–2.0 ha in size. The sizes and shapes of these units are defined in the course of forest inventory and before selecting the treatments for the compartments. The main criteria of compartment delineation are stand age, tree species composition and other conditions that make it distinguishable from the adjoining forest (van Laar and Akça 1997). The use of stand compartment is common in the Nordic countries (e.g. Haara 2003), and also in many other European countries (Köhl 1993). Particularly the use of spatial management objectives in forest planning requires that the geographical location of management activities is known in planning calculations (Borges et al. 2002).

Fixed and predefined compartments may limit the utilization of the production possibilities of the planning area (Holmgren and Thuresson 1997), particularly if the spatial layout of treatments and ecologically valuable resources are important concerns. To create more flexibility and to avoid the misuse of scarce production factors, the landscape could be divided into smaller units. It can be hypothesized that the use of smaller calculation units with appropriate spatial optimisation techniques enables the manager to create more efficient forest plans due to a greater alternative space. Increased efficiency of production means that, with a given resource, the production of multiple services is higher, i.e. the production frontier (efficient frontier or tradeoff curve) is further from the origin.

Another reason for using fine-grained forest data in planning is the current development of inventory methods. Remote sensing such as satellite or air-born laser scanning produces pixel-level inventory data (Holmgren and Thuresson 1997, Lind 2000, Lu and Eriksson 2000, Næsset 2002, Næsset et al. 2004). Small and homogeneous units (e.g. mini-segments) can also be obtained using image segmentation algorithms (Hyvönen et al. 2005). It would be a logical step to start using these raster cells or mini-segments directly as calculation units in forest planning without the additional step of semi-automated or subjective

compartment delineation prior to optimization.

The problem with a large number of small treatment units is how to aggregate them into practical treatment units. Holmgren and Thuresson (1997) used a “greedy algorithm” for raster cells (18 m × 18 m) in a planning area of 100 hectares to obtain what may be called dynamic treatment units. They aggregated cuttings by minimizing non-optimality losses, using fixed costs for entering a harvesting site (entry costs). In the beginning of the algorithm, all cells were cut and then they were removed from the cutting area according to the lowest net present value and entry cost, until the target cutting volume was met. Lu and Eriksson (2000) used genetic algorithm to aggregate cutting cells (20 m × 20 m). They were able to treat raster cells similarly to stand compartments despite the great number of cells. The total planning area was 400 ha. They minimized entry costs and maximized the core area of management units to aggregate cutting cells. Lind (2000) also used entry-cost minimization to generate feasible management units from raster cells. He used simulated annealing as the optimisation technique. The size of the raster cells was 30 m × 30 m and the total planning area was 558 hectares. In all these three studies, the raster approach was able to produce as good or better forest management plans in terms of net present value than the traditional approach with predefined compartments.

Öhman (2001) used raster cells (20 m × 20 m) to simplify the neighbourhood relationship of the planning problem and solved it with Mixed Integer Programming. She aggregated raster cells based on the interior conditions of cutting areas or uncut old-forest patches in the 400 ha planning area. The cost of aggregating the cuttings was modest, but the cost of aggregating old forests was higher. In all of the above studies the planning problems were to some degree simplified. In most studies the only treatment alternative was final felling, and the planning period often included only one period. In the study by Lind (2000), the planning period was 100 years consisting of ten 10-year time periods.

The objective of the present study was to test the use of an approach that generates operative treatment units and aggregates old forest patches from raster cell data without predefined compartment boundaries. The landscape was divided into

4612 hexagon-shaped cells, which were used as independent calculation units in optimisation in the same way as predefined compartments. Different spatial objectives were used to aggregate raster cells so that they formed contiguous cutting areas during three 20-year time periods and contiguous old forest patches at the end of the time periods. It is hypothesized that this approach is able to utilize the planning area's production potential more efficiently than the traditional predefined forest compartment approach. The approach was compared to the traditional compartment-level approach. The performance of two different landscape metrics in aggregating old forest was examined numerically and visually. The total area, number, mean size, and a shape index of old forest patches and cutting areas were used to measure the differences between the two trial forests and the three plans created for the forests.

2 Material and Methods

2.1 Test Forests

The approach was tested in a planning area located in North Karelia, Finland. The total area was 333.7 hectares, which included 10.1 ha of non-forest land. About 83 ha were young stands under 20 years of age and 112 ha carried mature forest over 80 years of age. Scots pine (*Pinus sylvestris* L.) was the most common tree species, followed by Norway spruce (*Picea abies* (L.) Karst.) and birch (*Betula pendula* Roht and *Betula pubescens* Ehrh.). The Forest Centre of North Karelia surveyed the forest applying ocular compartment inventory. The surveyor divided the forest into 242 stand compartments. This traditional compartment-based forest was used as the reference forest (referred to as compartment forest).

The raster forest was constructed by dividing the compartment forest into hexagon shaped cells 721 m² in size (perimeter 100 m). The size of the hexagon is about the same as in raster-based forest inventory (e.g. Lind 2000, Lu and Eriksson 2000, Tuominen and Haakana 2005). The use of hexagons instead of squares is a way to avoid single points of contact between neighbouring cells making the determination of adja-

cent cells unambiguous. The resulting planning data included 4612 hexagons. The forest data for the hexagons were derived from the compartment inventory data by intersecting the compartments and the cell centres in a GIS application. The centre of the hexagon therefore determined the data source of a border cell. This approach resulted in planning data that had no variation in the values of hexagons located within the same compartment. The hexagons were treated in the planning calculations in the same manner as predefined stands.

Both the compartment data and the raster cell data were imported into the Monsu forest planning software (Pukkala 2004). Monsu's automatic simulation tool was used to produce alternative treatment schedules for the calculation units for a 60-year planning period consisting of three 20-year time periods. The simulation model was instructed to schedule a regeneration cut, accompanied by the necessary post-cutting treatments when the stand age reached the minimum regeneration age or the mean diameter reached the minimum diameter required for a regenerative cut. Thinning was simulated when the stand basal area reached the so-called thinning-limit. All cuttings were simulated in the middle of the 20-year time periods. The simulations were based on the silvicultural guidelines of the Forestry Development Centre Tapio (Luonnonläheinen... 1994), but the timing of regeneration cuttings was varied in order to obtain more than one treatment schedule per calculation unit. In addition, one simulated treatment alternative for mature stands was always the "no treatment" option. The total number of schedules was 1054 for the compartment forest and 15 171 for the raster forest. The number of schedules per calculation unit varied from one to eight. Some young stands had only one management option while dense stands approaching to maturity often had eight distinctly different management options.

2.2 Planning Problems

The objective function was an additive utility function. The problem was formulated as follows:

Maximize

$$U = \sum_{i=1}^I a_i u_i(q_i) \quad (1)$$

subject to

$$q_i = Q_i(\mathbf{x}) \quad i = 1, \dots, I \quad (2)$$

$$\sum_{k=1}^{N_n} x_{kn} = 1 \quad n = 1, \dots, N \quad (3)$$

$$x_{kn} = \{0,1\} \quad (4)$$

where U is the total utility, I is the number of management objectives, a_i is the importance of management objective i , u_i is a sub-utility function for objective i , and q_i is the value of objective i . Q_i is an operator that calculates the value of objective i , \mathbf{x} is a vector of binary decision variables (x_{kn}) that indicate whether calculation unit n is treated according to schedule k , N_n is the number of alternative treatment schedules in unit n , and N is the number of calculation units.

The sub-utility functions transform the absolute value of the variable measured in its own units into a relative sub-utility value. These functions were determined through the smallest possible value, the target level, and the largest possible value of the objective variable, and the respective priorities. The relative sub-utility values were weighted by the relative importance of the objective variable (Pukkala and Kangas 1993).

Four spatial objectives, two affecting the patterning of old forest patches and two affecting the relative locations of cutting areas, were applied in the planning calculations. The first spatial objective was the proportion, of the total boundary length, of such a boundary between adjacent calculation units that were old forest in a given year (later referred to as OOB, or old-old border) (Table 1). The goodness of a calculation unit as an old forest patch was measured with an old growth index (OFI), which was a function of tree species, stand age and growing stock volume ($\text{m}^3 \text{ha}^{-1}$). The use of stand volume as a criterion prevented sparse stands of old trees (seed tree stands, retention trees) from having high old forest index values. The index value that bisected stands into old and not-old patches was 0.8. This index value

could be achieved for instance with a growing stock volume of $300 \text{ m}^3 \text{ha}^{-1}$ and stand age of 70 (conifers) or 50 (broadleaved trees) years.

The second spatial objective was the mean of the neighbourhood minima of the calculation units' OFI values (MNM). MNM was calculated so that a calculation unit first got the lowest OFI value in its neighbourhood. The neighbourhood included the calculation unit itself and all adjacent units (i.e., those having common border with it). After this, calculation of the mean of the OFI values produced the MNM metric. Since a poor calculation unit decreases the value of all adjacent units the metric tends to push young stands far from old stands resulting in a smooth landscape in terms of old forest index.

The third spatial objective was the proportion, of the total boundary length, of such a boundary between adjacent calculation units that were both cut during the same 20-year time period (CCB, cut-cut border). The fourth spatial objective was the proportion of the total boundary length between adjacent calculation units of which only one was cut during the 20-year time period (CUCB, cut-uncut border). This objective was minimized while the others were maximized. The sub-utility functions were linear between zero and the maximum possible value for all four spatial objectives. The maxima were found by maximizing one objective at a time.

Three forest plans were developed for both the compartment forest and the raster forest using different combinations of objectives (Table 1). All plans had four common non-spatial objectives: 1) volume of growing stock at the end of planning period, 2) harvested volume during the first time period, 3) harvested volume during the second time period and 4) harvested volume during the third time period. The subjectively defined target level of cuttings (20664 m^3) of each time period was 60 percent of the initial annual growth multiplied by the number of years of the time period. The target level of the growing stock volume after 60 years (57154 m^3) was adopted from a plan that was developed without spatial objectives: the volume of growing stock at the end of the planning period was maximised with cuttings fixed to the aforementioned target levels. The minimum possible value of a non-spatial goal variable produced a sub-utility of 0 while

Table 1. Objectives and their importance in different plans.

	<i>Cut</i>	<i>Plan</i>	
		<i>OOB-Cut</i>	<i>MNM-Cut</i>
Growing stock volume in 2065	0.20	0.20	0.20
Cutting volume, period 1 (2006–2025)	0.20	0.20	0.20
Cutting volume, period 2 (2006–2025)	0.20	0.20	0.20
Cutting volume, period 3 (2006–2025)	0.20	0.20	0.20
OOB in 2025		0.04	
OOB in 2045		0.04	
OOB in 2065		0.04	
MNM in 2025			0.04
MNM in 2045			0.04
MNM in 2065			0.04
CCB	0.10	0.04	0.04
CUCB	0.10	0.04	0.04
Total	1.00	1.00	1.00

OOB = proportion of the total boundary length, of such a boundary between adjacent calculation units that were both old growth forest patches at the end of the time period.

MNM = the mean of neighbourhood minima of the units' old forest index values.

CCB = the proportion of the total boundary length between adjacent calculation units that were both cut during the same time period.

CUCB = the proportion of the total boundary length between adjacent calculation units, where only one is cut during the time period.

values equal to or larger than the target produced a sub-utility of 1.

The differences between the plans originate from the applied data format and spatial objectives (Table 1). In the *Cut* plan only cuttings were aggregated by maximizing CCB (cut-cut border) and minimizing CUCB (cut-uncut border). The *OOB-Cut* plan aimed at aggregating both old forests and cuttings, using OOB (old-old border) together with CCB and CUCB. The *MNM-Cut* plan was otherwise similar, but old forests were aggregated using the MNM goal (mean of neighbourhood minima of the old forest index values).

A production frontier was constructed to demonstrate the effectiveness of the raster approach. Two objectives were employed to generate the solutions that were used to draw the production frontier: total cutting volume during the 60-year planning period, and OOB at the end of the 60-year planning period. The OOB objective was maximized with the total cutting volume fixed to different cutting volume levels.

2.3 Optimisation Method

Threshold accepting (Dueck and Scheuer 1990)

was used as the optimization method. Threshold accepting (TA) is a deterministic version of another local search method, simulated annealing. Threshold accepting has been shown to be able to produce as good, or even better solutions, than simulated annealing (Dueck and Scheuer 1990, Bettinger et al. 2002, Pukkala and Heinonen 2006). In Monsu software, TA uses the best of a set of random combinations of calculation units' treatment schedules as the initial solution. In this study, a move consisted of first selecting a random calculation unit and then a random schedule for the unit that would replace the current schedule of the selected unit. Moves that improved the objective function value were always accepted. Moves not improving the current solution were accepted when they resulted in an objective function value greater than the current value minus the threshold. In the beginning of the search the threshold value was large and thus enabled wider movements in the solution space. The threshold was gradually decreased and finally only improvements were accepted. The search was stopped when the threshold became very small (freezing threshold) or several consecutive thresholds (five in this study) went without any change in the solution.

The parameter values of TA were selected

according to the study of Pukkala and Heinonen (2006). The parameters were first selected for the raster forest and the same parameters were used for the compartment forest. The parameters used were as follows: the number of initial random searches was 100, the initial threshold 0.002, the threshold multiplier (to get the next threshold) 0.94, the freezing threshold 0.000002, the number of iterations with the initial threshold 1000 and the iteration multiplier (to get the number of iterations with the next threshold) 1.05. The entire search process was repeated 5 times for both test forests and different plans, and the best solution is reported. All the computations were conducted with a personal computer that had a Pentium 4 (3.06 GHz) processor and 512 MB of RAM.

2.4 Measuring the Spatial Pattern of Old Forest Patches and Cutting Areas

The differences between the two test forests and three plans were compared in terms of various landscape metrics accounting for the pattern of old forest patches and cutting areas. The measurements concerning the sizes and shapes of the old forest patches and cutting areas were carried out so that neighboring calculation units with similar properties (old forest at the end of a time period or cutting during a time period) were joined so that they formed so-called landscape patches. The sizes and shapes of these landscape patches were then measured after optimization using the Area Weighted Mean Shape Index (AWMSI) (McGarigal and Marks 1995). When using the AWMSI, a circle represents the ideal shape and the AWMSI gets a minimum value of 1. In addition, the number of patches, their total area and mean size were calculated for the landscape patches. The values of these landscape variables were calculated by using GIS routines.

To make the two test forests more comparable with respect to different landscape metrics the stair-step-like boundary of the raster forest patches was smoothed (Fig. 1). The technique used in the GIS software to smooth the boundary lines was Polynomial Approximation with Exponential Kernel (PAEK), which calculates smoothed lines using a parametric continuous averaging technique. The smoothing tolerance



Fig. 1. The effect of smoothing on the boundary of a landscape patch based on hexagons (thin step-wise line = original boundary in the raster forest, thick line = smoothed boundary). The smooth thin lines are original compartment boundaries.

was set to 60. More details about the technique can be found in Bodansky et al. (2002).

3 Results

3.1 Non-spatial Goals

The non-spatial goals were met in both forests almost equally well (Table 2). The target level of growing stock volume ($57\,154\text{ m}^3$) was achieved in all the plans. The harvest volume target level ($20\,664\text{ m}^3$) was achieved exactly or exceeded in all plans and for both the raster and the compartment-based forests.

Table 2. Growing stock volume at the end of the 60-year planning period and cuttings during three 20-year time periods (tp) in three plans for the compartment forest (Comp.) and raster forest. The volumes are expressed as percent of the target value, which were 57 154 m³ for the remaining growing stock volume and 20 664 m³ for the periodical cutting volumes.

	<i>Cut</i>		<i>OOB-Cut</i>		<i>MNM-Cut</i>	
	Comp.	Raster	Comp.	Raster	Comp.	Raster
Growing stock volume, m ³	100	100	101	100	101	100
Cuttings, tp 1, m ³	100	103	100	100	100	100
Cuttings, tp 2, m ³	103	100	100	100	100	100
Cuttings, tp 3, m ³	100	100	100	100	100	102

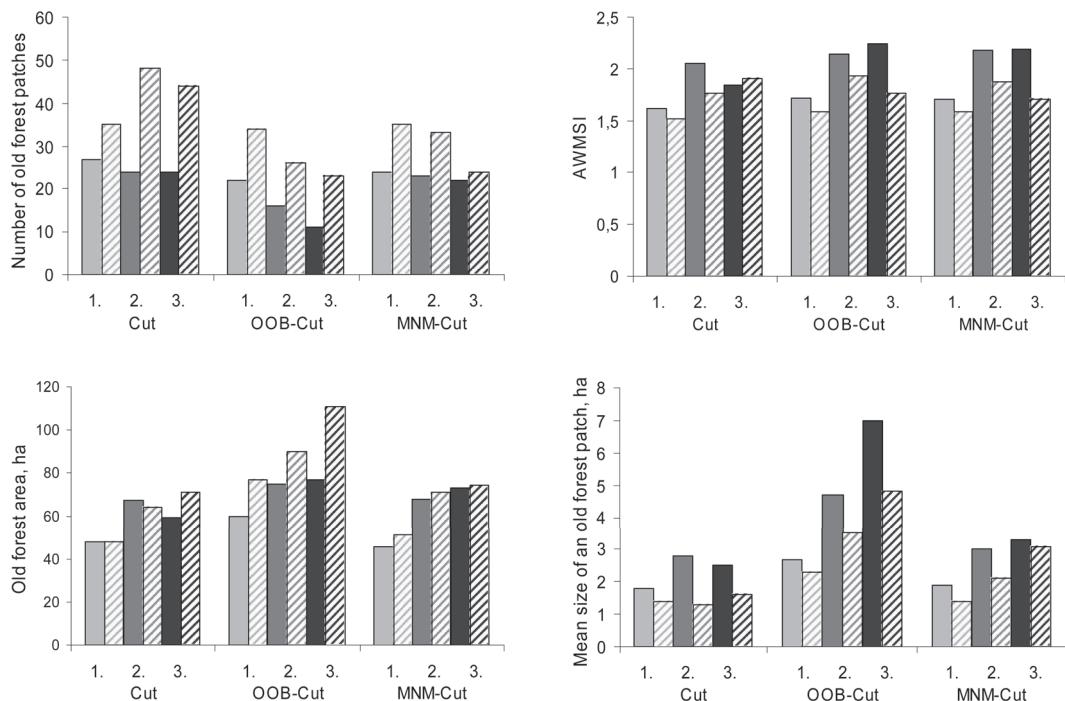


Fig. 2. Variables describing old forest patches in different plans. Solid shadings represent compartment forest and line patterns represent raster forest. Numbers below the x-axis indicate the time period.

3.2 Old Forest

The area of old forest was larger in the raster forest than in the compartment forest in all the plans except the *Cut* plan for the first and second time period (Fig. 2). The mean size of old forest patches was larger in the compartment forest in

all the plans because there were some very small patches in the raster forest. Taking into account that the existence of additional small patches is not a deficiency, it is noteworthy to mention that e.g. in the *OOB-Cut* plan for the raster forest the total area of 11 (number of patches in the *OOB-Cut* plan for the compartment forest) largest old

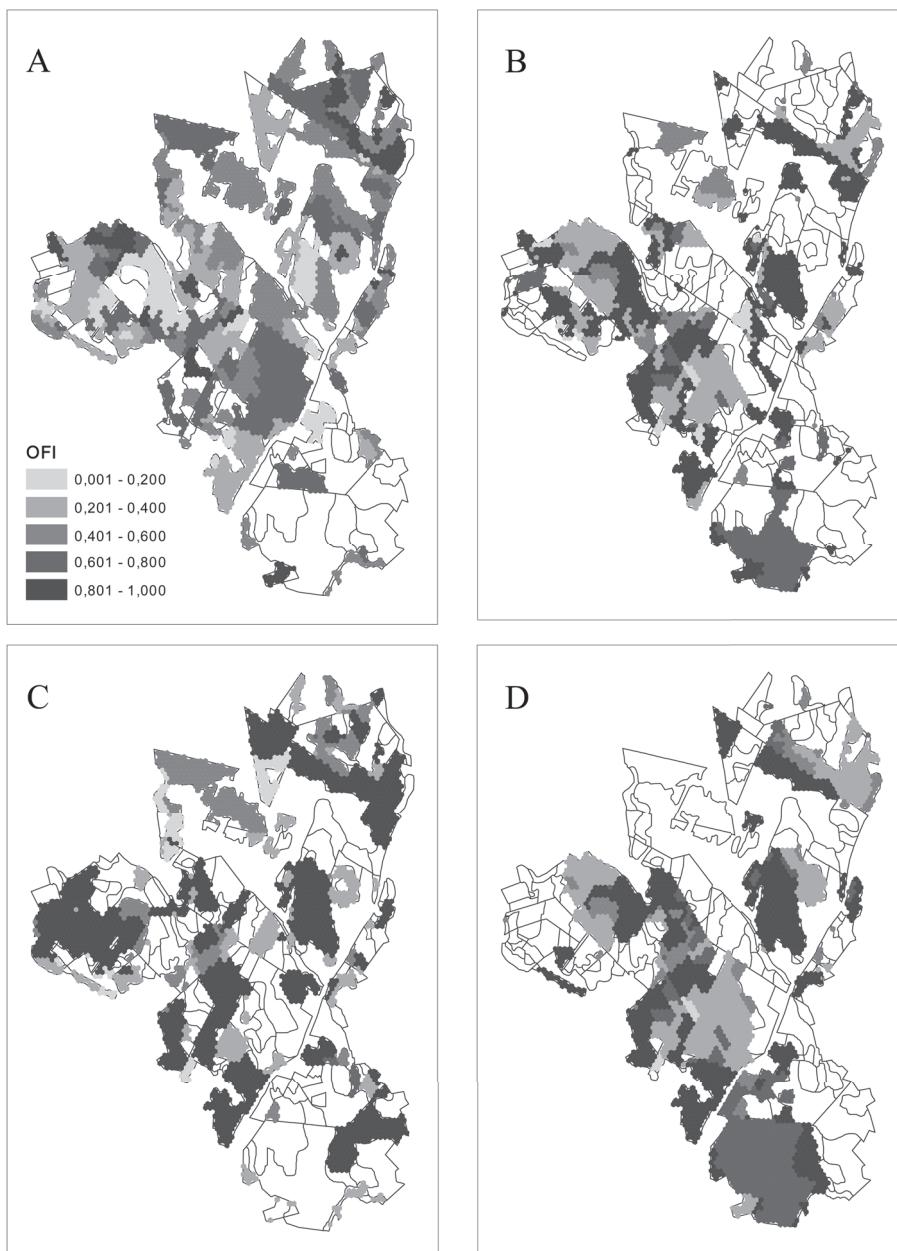


Fig. 3. Old forest index (OFI) values in the raster forest in 2005 and in different plans at the end of the 60-year planning period. (A = initial state in 2005, B = Cut plan in 2065, C = OOB-Cut plan in 2065, and D = MNM-Cut plan in 2065).

forest patches was 33% larger and their mean size 34% higher than in the compartment forest. Therefore, the existence of some very small old forest patches affects much the mean patch size statistic for the raster forest. The AWMSI values were lower (better) for the raster forest in all the plans except the *Cut* plan at the end of the third time period.

In both forests the total area and the mean size of old forest patches were at their highest when the OOB (old-old boundary) was used as the spatial objective (*OOB-Cut* plan). The use of the OOB as an objective resulted in clearly larger areas of old forest than the use of MNM (mean of neighbourhood minima of the old forest index). On the other hand, the use of the MNM led to slightly lower shape index values (AWMSI) in the raster forest and thus in old forest patches that were more compact in shape.

The old forest index in the raster forest revealed clear differences in the functioning of the OOB and MNM metrics (Fig. 3). In all plans the area

of old forest ($OFI > 0.8$) increased from the initial situation, and the aggregation of cuttings in the *Cut* plan forced also old forests to aggregate (Fig. 3B). The difference between the OOB and MNM objectives was that while the OOB produced more old forest ($OFI > 0.8$) the MNM resulted in less abrupt edges: old forests patches were often surrounded by areas with only slightly lower OFI values when MNM was used (Figs. 3C and 3D). This means that the MNM produced a smoother landscape.

3.3 Cutting Areas

The total number of cutting areas and their mean size did not depend systematically on the use of compartment vs. raster data (Fig. 4). The AWMSI was lower for the compartment forest in the *Cut* and *OOB-Cut* plans during the first time period. Otherwise the AWMSI was slightly lower for the raster forest.

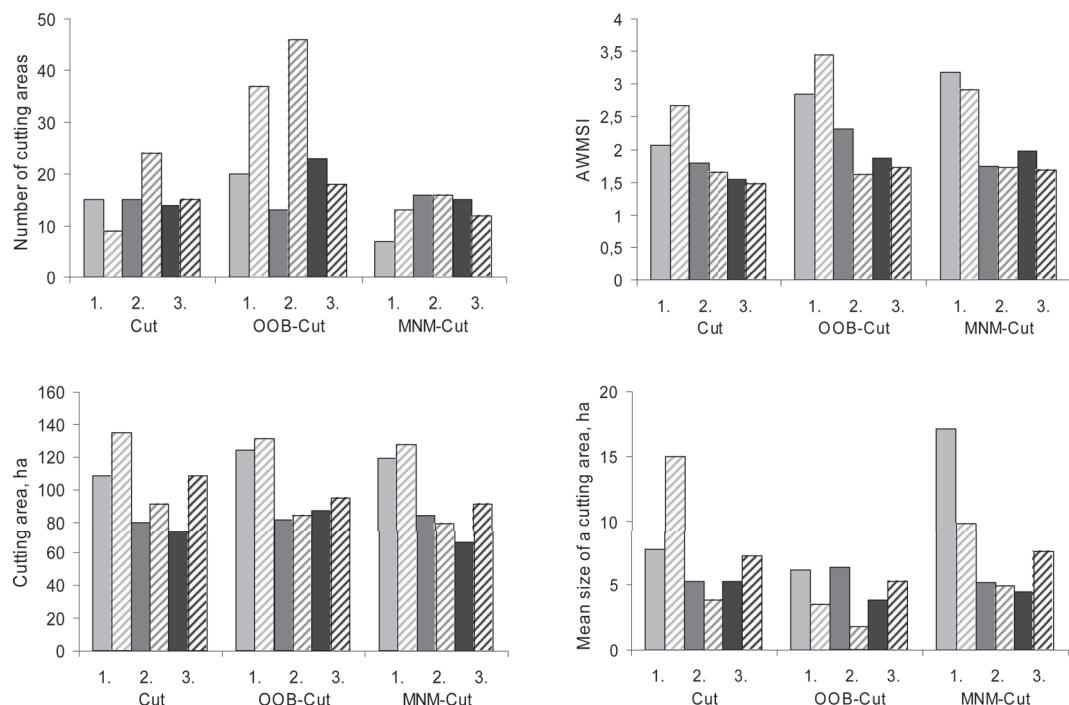


Fig. 4. Variables describing cutting areas in different plans. Solid shadings represent compartment forest and line patterns represent raster forest.

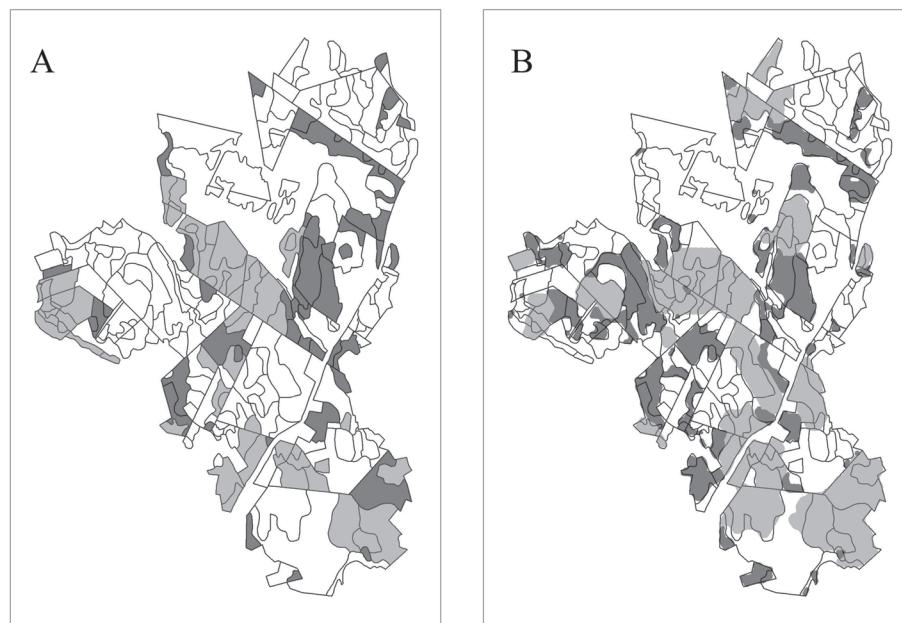


Fig. 5. Old forest patches at the end of the 60-year planning period (dark grey) and cutting patches during the third 20-year time period (light grey) in the Cut plan. (A = compartment forest, B = raster forest).

Maximising CCB (cut-cut border) and minimising CUCB (cut-uncut border) worked better in combination with the MNM objective than with the OOB objective: the total number of cutting areas was smaller and the mean size of the cutting area larger in the *MNM-Cut* plan than in the *OOB-Cut* plan. This can be explained by the nature of the MNM objective, which (in addition to clustering old forest) also attempts to cluster poor stands in terms of old forest index, i.e. cutting areas.

Visual examination of the plans confirmed the numerical results. The neighbouring raster cells formed cutting areas that seem to be feasible for operational forest management (Figs. 5 and 6). The cutting areas did not always follow the compartment boundaries, even though the forest data of raster cells were derived from the compartment forest. The old forest patches formed from raster cells were good in size and shape and frequently in different places than in the compartment forest. The raster approach frequently generated old forest patches that did not follow the compartments boundaries.

3.4 Production Frontier

Total harvest and OOB at the end of the third time period were used to create a trade-off curve (production frontier). As the OOB values of the two forests are not comparable (due to much higher initial amounts of border between similar adjacent units in the raster forest), the OOB metric was only used to aggregate and increase the area of old forests, but the trade-off curve was drawn between the total harvest and the ending area of old forest. The trade-off curve (Fig. 7) together with other results (Fig. 2) confirms that the raster approach was able to generate more old forest than the compartment approach. At all cutting levels the old forest area was larger in the raster forest. This verifies that the raster approach enables a more efficient joint production of old forest and harvested timber. At the end of the 60-year planning period the raster approach produced at most about 25 hectares (14%) more old forest than the compartment forest with the same total harvest. Spatial objectives to aggregate cuttings

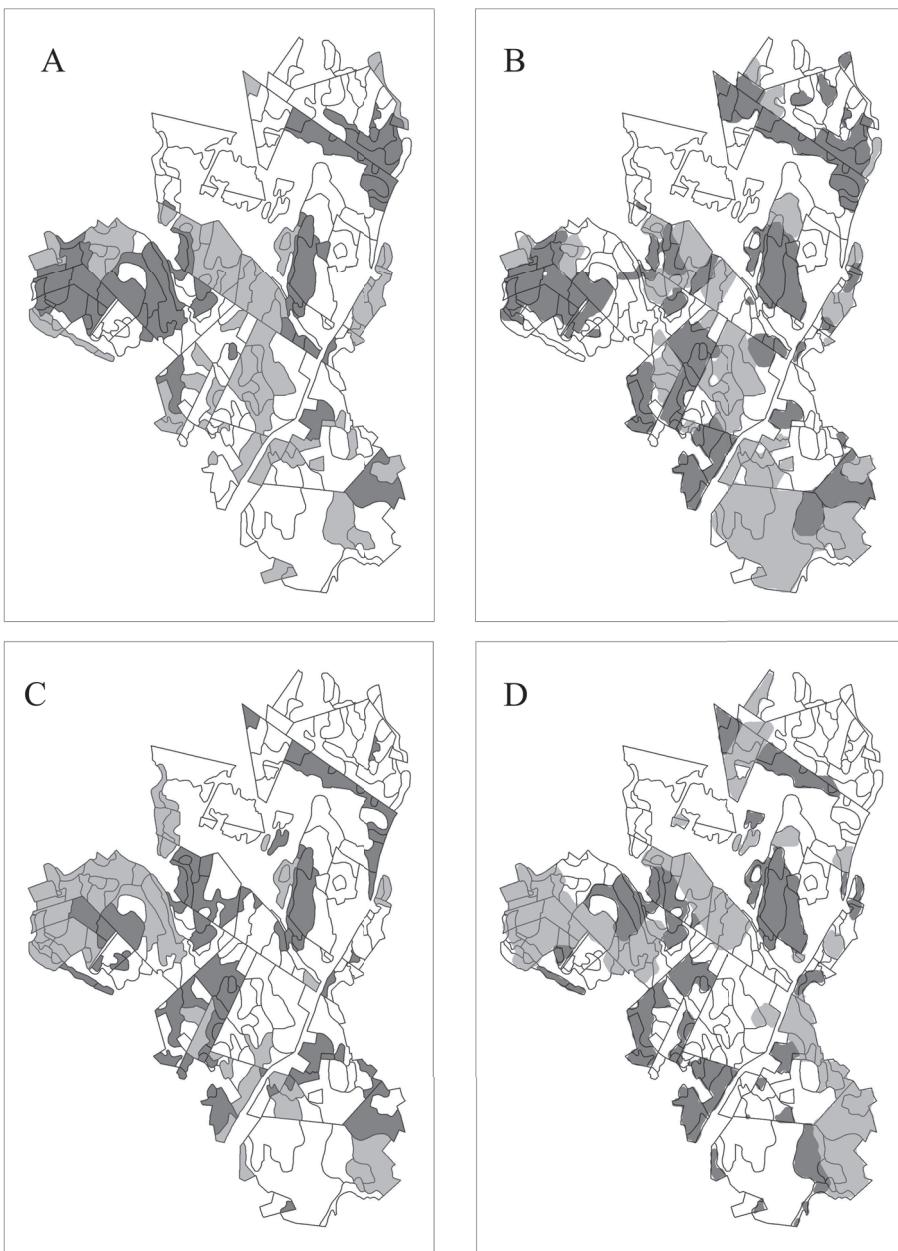


Fig. 6. Old forest patches at the end of the 60-year planning period (dark grey) and cutting patches during the third 20-year time period (light grey). (A = OOB-Cut plan, compartment forest, B = OOB-Cut plan, raster forest, C = MNM-Cut plan, compartment forest and D = MNM-Cut plan, raster forest).

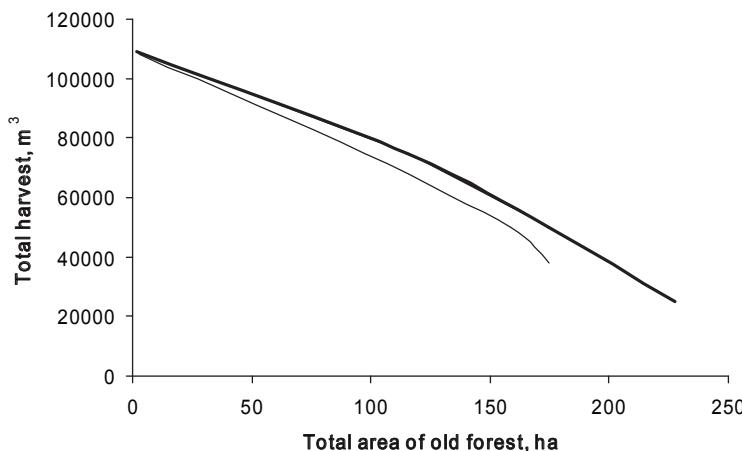


Fig. 7. Production possibility frontier. Thick line = raster forest, thin line = compartment forest.

were not used in the optimisations for the production frontier, and therefore cutting areas in the plans might be impractical. However, the earlier results (Fig. 2) showed that when cuttings were also aggregated the raster approach was still able to produce more old forest area, especially when the OOB objective was used.

4 Discussion

The approach tested in this study utilized fine-grained raster data in planning calculations. Spatial objectives were used to simultaneously influence the locations of cuttings and the patterning of old forest habitats. Compared to the results of some earlier studies (Holmgren and Thuresson 1997, Lind 2000, Lu and Eriksson 2000), this approach should be more feasible both ecologically and from the viewpoint of forestry practice. The results of this study showed that the use of spatial objectives in optimisation enables one to generate feasible cutting areas and old forest patches without predefined compartment borders.

The theoretical fact is that the raster forest is at least as efficient as the compartment forest. From the production point of view this results from a less constrained use of resources: the treatments

are not forced to follow compartment boundaries. The degree of superiority of the raster approach depends on the set management objectives, composition and structure of the forest, and the way in which the surveyor delineates the compartments. Therefore, overall conclusions about the magnitude of superiority of the raster approach cannot be drawn on the basis of this study. However, our study demonstrates that the current tools for spatial optimisation are sufficient for creating feasible treatment units from raster cells, implying that prior-planning compartment delineation is not necessary.

When treatment units are formed in optimisation they may be regarded as temporary, i.e. they are no longer used after the treatment has been implemented. Fortunately, modern harvesting technology can cope with this type analytical and transient cutting areas. The boundaries of cutting areas may be transferred from the planning system to the computer of the harvester, which is equipped with a GPS device. Therefore, the position of the harvester in relation to the cutting area is exactly known all the time. It should also be remembered that many of the traditional compartment boundaries are also invisible in the forest; they are subjectively drawn on aerial photographs in places in which the change in forest features is only gradual.

The logging costs were not explicitly analysed in this study. Taking into account that the terrains are flat in Finland and the network of forest roads is dense, cutting aggregation is not as important for cost-effective logging in Finland as in several other countries. Logging is cost-effective when a high enough total volume can be harvested within a reasonable radius. The cut areas need not to be next to each other. Therefore, the main benefit of aggregating cuttings may in fact be ecological as cutting aggregation decreases the overall fragmentation of the forest. For cost effective cutting it is enough to avoid small and distant cutting areas.

Because the values of the non-spatial goals were very similar in all plans, the main differences between the plans were in the patterning of cutting areas and old forest patches. The differences between the spatial objectives were more clearly shown in the raster forest where optimisation had more freedom to generate landscape patches. When compartment boundaries were not predefined, the desired shape and size of landscape patches should be easier to achieve. The OOB objective is only dependent on the boundary between adjacent old stands and therefore tends to maximise only the area of those calculation units that exceed the OFI threshold value. In the MNM, a calculation unit gets the minimum value of the neighbours. This property of the MNM takes into account the whole range of variation in the OFI values and is not dependent on any threshold value, which also explains the rather clear difference in the total old forest area between the MNM and OOB objectives. The MNM objective also tends to move unfavourable calculation units as far as possible from good calculation units. In the *MNM-Cut* plan for the raster forest this phenomenon is clearly shown (Fig. 4; see also González et al. 2006). The OOB objective generates landscapes with more isolated and distinct old forest patches, with a consequence that the landscapes have more edge effect than what results from the use of MNM. It may be concluded that for a good landscape in terms of old forest habitats it is not enough to maximize the area and aggregation of the patches, but a smooth landscape in terms of stand age should also be pursued. This can be achieved, in addition to using the MNM metric, for instance by maximising the spatial autocor-

relation of stand age or old forest index (Kurttila et al. 2002), or minimising the mean difference of the ages of adjacent stands (González et al. 2006).

The AWMSI calculates the edge to area ratios of patches. For some species, e.g. certain saprophytic polypores, the edge zone can be an unsuitable habitat. The AWMSI values were better in the raster forest than in the compartment forest, implying a more compact shape in the raster forest. However, the total number of patches was lower and the mean size of the patches larger in the compartment forest. From this viewpoint, the use of predefined compartment boundaries can lead to more complex landscape patch shapes, although this can in part result from the characteristics of the planning area. Of the two landscape metrics that were used to aggregate old forest, the MNM seems to be slightly more capable of generating landscape patches of good shape.

The use of raster cells created stair-step-like landscape patch boundaries. As a consequence, some landscape metrics where the length of the patch boundary was used (e.g. AWMSI) gave incomparable estimates in the test forests. Patches with very fine-grained boundary are also impractical. Therefore, raster forest boundaries were smoothed. The smooth tolerance, which determines how smoothed the resulting lines are, naturally affects the values of AWMSI. In this study, the smooth tolerance was set in such a way that the resulting landscape patches looked practical, but did not excessively favour the raster forest (Fig. 1).

Replacing the predefined and generally over one hectare forest compartments with small raster cells dramatically increases the number of calculation units that are used in the optimisation. This makes optimisation more difficult and leads to longer running times. As a result, more attention must be paid to further development of heuristic optimisation techniques. New computers with powerful processors and better algorithms for problem solving will hopefully enable the development of new methods to solve these conventionally difficult tasks in a more efficient way. One way to reduce computing time could be the use of decentralized computing methods like cellular automata, which are based on localized computing units and neighbourhood relations,

and they lack the property of time consuming evaluation of solution quality (e.g. Strange et al. 2002). However, it should also be noted that the additional computing cost (a few hours of computer time) is negligible compared to the potential benefits of using raster cells.

In the present study, the forest data for raster forest were derived from conventional and predefined forest compartments that had been already divided into homogeneous compartments and inventoried using a compartment inventory technique (e.g. Haara 2003). There was no variation in the initial forest data between raster cells that were located within the same initial compartment. As a result, the old forest patches and cutting areas often followed the initial compartment boundaries. However, the visualization of the plans also showed that the landscape patches, especially cutting areas, also frequently deviated from the compartment boundaries. The differences would most probably be larger with data lacking any influence of predefined compartments. These kind of data can be obtained through automated interpretation of remote sensing material, which is becoming more common in forestry planning (e.g. Lu and Eriksson 2000, Næsset 2002, Næsset et al. 2004). These data would be more heterogeneous, show gradual changes in forest features, and include stand-level variation and trends in growing stock characteristics.

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