Spatial and temporal allocation of stratum-based harvest schedules

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Stratum-based timber harvest schedules must be disaggregated into operational plans prior to implementation. In most cases this is an expensive and time-consuming manual task that does not ensure consistency between the long-term harvest schedule and short-term operational activities. This paper presents the results of applying the CRYSTAL algorithm, which automates the disaggregation and allocation of a stratum-based harvest schedule into harvest blocks, to a small forest in New Brunswick. The results indicate that it is possible to use a set of allocation guidelines to quickly delineate harvest blocks in a consistent, reproducible manner. We also discuss how the algorithm is used in conjunction with a Monte Carlo integer programming model to estimate the potential losses in timber harvest volumes attributable to deviations from the stratum-based schedule and the addition of adjacency constraints.

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Pour leur mise en oeuvre, les programmes de récolte de bois établis en fonction des peuplements, doivent étre redivisés en plans d'intervention opéradonnels. Dans la plupart des cas, il s'agit d'une tâche manuelle longue et coûteuse, qui ne garantit pas la cohérence des programmes de récolte à long terme et des activités opérationnelles à court terme. Cet article présente les résultats de la mise en application de 1'algorithme CRYSTAL pour planifier la récolte d'une petite forêt au Nouveau-Brunswick. L'algorithme CRYSTAL automatise la délimitation des secteurs de coupe à partir d'un programme de récolte établi en fonction des peuplements. Les résultats indiquent qu'il est possible d'utiliser un ensemble de lignes directrices pour la répartition, afin de rapidement délimiter les secteurs de coupe d'une manière cohérente et reproductible. Nous discutons également comment 1'algorithme est utilisé en conjunction avec un modèle de programmation en nombres entiers Monte Carlo pour estimer les pertes potentielles de volumes de bois attribuables à la modification du programme de récolte établi en fonction des peuplements et à 1'addition de contraintes de contigüité.

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Introduction

Most long-term forest planning is accomplished through the use of stratum-based models. These models are often used to determine timber and other forest output levels in the presence of forest-wide constraints. Because stratum-based models use aggregated land units and averaged cost and growth and yield information, they cannot explicitly recognize the site-specific and operational considerations that actually guide on the ground forest activities. It is widely recognized, therefore, that the solutions to stratum-based models are only estimates of the actual forest outputs that can be obtained from the forest.

In the disaggregation of a stratum-based harvest schedule, a harvest block is a contiguous parcel of forest land that is to be harvested within a specific time frame under the same (or similar) harvesting and regeneration system(s). Because silvicultural interventions are fixed in time and space by the location of harvest blocks, the harvest block is the basic unit of forest management intervention. Harvesting affects forest structure and thus has an impact on all forest outputs, timber and nontimber. The choice and timing of which stands to cut also directly affects the organization and costs of harvesting and transportation systems (Arvanitis 1968). These choices are explicitly stated in a forest management plan in the form of delineated harvest blocks and an explicit schedule for harvesting them. How well the layout and harvest schedule of these blocks fits the management objectives for the forest in terms of providing the desired mix of benefits at the desired times directly determines how successfully the analyst has captured the essence of the forest management problem.

If a stratum-based schedule is used to guide forest management, it is important that there is close correlation between the harvest blocks delineated in the forest management plan and the strata scheduled for harvest in the solution to the long-term model. The greater the deviations from the long- term plan, the more likely it is that the forest output levels calculated in the long-term plan will be unobtainable

This paper presents the results of applying an algorithm (CRYSTAL), which automates the disaggregation and allocation of a stratum-based harvest schedule into harvest blocks, to a small forest in New Brunswick. The results indicate that it is possible to use a set of allocation guidelines to delineate harvest blocks in a consistent, reproducible manner. We also discuss how the algorithm is used in conjunction with a Monte Carlo integer programming model (BLOCK) (Clements et al. 1990) to estimate the potential losses in timber harvest attributable to deviations from the stratum-based schedule and the addition of adjacency constraints.

We begin with a brief description of the CRYSTAL algorithm. Then we describe the forest and its stratum-based timber harvest schedule. By systematically varying the user- controlled parameters in the CRYSTAL algorithm this schedule is allocated to harvest blocks in 31 different patterns. These patterns are evaluated with respect to the proportion of the stratum-based harvest schedule that was allocated to harvest blocks. We conclude with a discussion of the general applicability of the results and recommendations for further research.

The CRYSTAL algorithm

Although the CRYSTAL algorithm is fully described in Walters (1991), a brief description is included here so that the reader may have a better understanding of the results presented in this paper. CRYSTAL was designed to spatially and temporally allocate a stratum-based harvest schedule.

CRYSTAL is a conceptually simple algorithm in which a stand eligible for harvest is initially chosen as a "seed." Then the neighbors of the seed are examined to determine if any of them are also eligible for harvest at this time. If so, the seed and the neighboring stands are aggregated into a potential harvest block. As each eligible neighbor is added to the potential harvest block, other stands that become neighbors are examined for harvest eligibility and are added if appropriate. This process continues until no additional eligible neighbors are found or until the user-defined maximum block size is reached. After exhausting all possibilities, if the potential block exceeds the minimum block size it is assigned a block number and a harvest period that coincides with the harvest period of the seed stand, and its component stands are with drawn from further consideration by the algorithm. If the harvest block is smaller than the minimum block size, then the stands are released and considered for later inclusion in other blocks. Finally, a new seed stand is chosen and the process of aggregation and allocation begins again. The algorithm continues until the entire stratum-based solution, which can be allocated within the constraint of the minimum block size, has been allocated.

Although conceptually simple, CRYSTAL is a relatively complex algorithm that provides numerous options to guide the harvest blocking process. CRYSTAL allows the user to develop alternative harvest blocking patterns by specifying (i) minimum and maximum harvest block sizes, (ii) criteria for choosing seed stands, (iii) the allowable deviation from the timing choices determined in the stratum-based schedule, and (iv) the pattern of the search for stands adjacent to the seed. Because there are numerous combinations of these user-defined parameters, each of which results in a unique harvest blocking pattern, only a small subset of the many possible harvest blocking patterns that can be developed was examined in this study.

CRYSTAL provides seven criteria for choosing seed stands: area (ascending or descending), perimeter (ascending or descending), polygon identification number, stand type number, and allocation potential (defined below).

CRYSTAL was designed to allocate the stratum-based solution as closely as possible. Because of the spatial distribution of stands, however, it may be impossible to completely allocate a harvest schedule without violating harvest block size constraints. Therefore, deviations from the exact timing of harvest specified in the harvest schedule may be allowed to permit allocation of more of the harvest schedule by selecting tolerance limits that govern how much deviation in timing choices are acceptable.

A user-specified tolerance value of ±1 would allow consideration of any stands adjacent to the seed stand that are within one period of the timing choice for the seed stand. Since the intent of the program is to follow the harvest schedule as closely as possible, the program will deviate from the harvest schedule only if it is not possible to adhere to scheduled periods. This is accomplished by forcing the program to first select any adjacent stand eligible for harvest in the same period as the seed stand. There is also an option whereby the user may wish to make the selection of adjacent stands more restrictive by allowing the use of timing deviations only up to the point where the potential block reaches minimum size; thereafter, only true contemporaries may be included in the harvest block. Once all of the eligible stands have been determined, the program must select which ones will be included in the harvest block. Each stand has three attributes associated with it, one of which may be used as a selection criteria: allocation potential, stand proximity, and stand area.

The allocation potential (AP) is calculated as

$$\mathbf{AP} = \sum_{i=1} X_i$$

where

X_i is the the number of eligible stands contiguous to seed stand in period i

i is the period of allocation

n is the number of periods to be allocated

Selecting stands on the basis of increasing allocation potential will bias the solution to first allocate those stands that have few eligible neighbors.

Stand proximity is calculated as the linear distance between the centroids of a particular stand and the seed stand. By selecting nearest stands first, harvest blocks delineated by CRYSTAL will tend to be circular. This may be advantageous because it will tend to reduce the ratio of perimeter to area within a harvest block. Although other factors such as terrain affect the operability of a harvest block, large perimeter to area ratios generally increase extraction costs and windthrow damage of residual trees (Smith 1962, pp. 413-414).

If stand area is chosen as the selection criteria, CRYSTAL will select the stand with the smallest area first. By building harvest blocks with the smallest stands first, the number of small stands allocated will be maximized. Since small stands tend to have low allocation potentials, the overall allocation of the harvest schedule may be increased using this criterion. CRYSTAL selects the eligible stand with the lowest value for the chosen attribute. If a tie exists between two or more eligible stands, the program selects the stand belonging to the stand type with the largest area remaining to be allocated. Biasing the solution toward unallocated area helps to distribute the allocation across stand types and harvest periods

A final optional allocation procedure, CLEANUP, is available to minimize the number of stands that were not previously allocated. Usually such stands are scheduled for harvest in a period quite different from that of their surrounding neighbors. If the user opts for this procedure, CRYSTAL will search all harvest blocks for unallocated adjacent stands. If the stand is scheduled for harvest within the planning horizon, and if the addition of the stand will not cause the block to exceed the maximum block size, the stand is allocated to the block, regardless of when it was originally scheduled for harvest. The effect of this procedure is to "clean-up" leftover stands, but significant deviations from the original harvest schedule may result. Depending on the number of leftover stands and their expected yield trajectories, use of the CLEANUP procedure may result in reduced harvest volumes. However, the alternative of leaving islands that are not operationally feasible to harvest would likely reduce harvest volumes much more than would occur using the CLEANUP procedure.

Data and methods

The basic input to the CRYSTAL algorithm is a stratum-based timber harvest schedule. Thus, to evaluate CRYSTAL'S usefulness a

TABLE 1. Forest outputs and activities by planning period

	Period				
	1	2	3	4	
Output (m^3 per period)					
Softwood gross volume	123 231	123 231	123 231	123 231	123 231
Softwood pulp volume	87 119	86 462	85 302	84 366	84 138
Softwood sawlogs	36 112	36 769	37 929	38 865	39 093
Hardwood gross volume	21 556	21 967	33 115	70 060	24 593
Activity (ha per period)					
Precommercial thinning	338	459	55	494	512
Planting jack pine	46	10	49	0	0
Planting black spruce	262	55	278	0	0
Light scarification	308	65	172	0	0
Heavy scarification	0	0	155	0	0
Herbicide application	0	802	885	956	974
Clear-cutting	1599	1508	1649	1760	1374

small forest management problem was created. A description of the study forest and the linear program calculated harvest schedule follows.

Study area

The study forest was defined to be four contiguous New Brunswick Forest Development Survey map sheets. Inventory and geographic information were obtained from the New Brunswick Department of Natural Resources and Energy. The forest is composed of 3241 stands, which total 17 458 ha of forested and nonforested land. Following standard wood supply analysis procedures used in New Brunswick, the forest was divided into components that were primarily softwood and primarily hardwood. The harvest schedule was developed only for the 12 393-h softwood component

Strata were defined based on attributes in the provincial geographic information system data base and were described by seven levels of identifiers: cover type, condition class, age, management unit, soil group, silviculture code, and management emphasis. The forest was divided into 57 strata that ranged in size from 2 to 1921 ha. Silvicultural prescriptions for each of the 57 strata included clear-cutting followed by natural regeneration or planting of either black spruce (*Picea mariana* (Mill.) B.S.P.) or jack pine (*Pinus banksiana* Lamb.). If the regenerated stratum was naturally regenerated, then it was eligible to be sprayed with herbicides at age 5 and to have a pre- commercial thinning at age 15. In the case of planting, options for either light or heavy scarification were considered. Costs for all silvicultural activities (except harvesting) were considered in the problem. Yield information for each of the strata and alternative silvicultural prescriptions required 167 yield tables for existing strata and 42 yield tables for regenerated strata.

Stratum-based timber harvest schedule

A 70-year timber harvest schedule, consisting of 14 five-year planning periods, was developed for the forest using PC FORPLAN version 2 (Johnson et al. 1986). This harvest schedule maximized first period softwood timber harvest volume subject to nondeclining yield, FORPLAN'S "perpetual timber harvest" ending inventory constraint, an annual silvicultural budget of $75 000, and a constraint that limited jack pine plantations to 15% of the area planted. Softwood fiber was the objective of management, and hardwood volume merely a by-product of softwood harvests. No constraints were placed on hardwood volumes, but hardwoods were assumed to remain unharvested in any stand that contained less then 50 m^3. $ha^{-}1$ of hardwood volume.

The solution to this model indicated a 5 year allowable softwood harvest of 123 231 m3. The annual silviculture budget was completely utilized in each planning period except the twelfth period. A summary of the first five planning periods of the linear program solution is presented in Table 1.

A total of 31 runs of the CRYSTAL algorithm were made to allocate the FORPLAN harvest schedule. Each run represents a single change in the allocation parameters that direct allocation in CRYSTAL. Although these runs represent only a sample of the possible combinations of allocation parameters, the results are grouped to illustrate the effects that a particular parameter may have on allocation success. In all cases the CLEANUP procedure was applied.

Block harvest scheduling

CRYSTAL does not explicitly consider adjacency as it creates harvest blocks, but does keep track of adjacent blocks. Although it would be possible to incorporate an adjacency routine in CRYSTAL, this is undesirable for at least two reasons. First, reductions in harvest volumes, as compared with the stratum-based schedule, occur in a blocked schedule (i) because some stands are included in blocks even though (according to the stratum-based schedule) they should not and (ii) because of adjacency constraints. If adjacency is considered simultaneously with the blocking process, then is it not possible to separate and measure the reductions in harvest volumes that occur because of each effect. Second, there is a relatively large number of block harvest scheduling models already available (Nelson *et al.* 1988; O'Hara *et al.* 1989; Clements *et al.* 1990). Thus to make CRYSTAL as adaptable as possible we chose not to include an adjacency routine directly in the algorithm.

Given the above considerations, CRYSTAL was designed to provide input to a block harvest scheduling model. After testing the various allocation options in CRYSTAL, two of the harvest block layouts generated by CRYSTAL were used as input to the BLOCK model to generate block harvest schedules. The first block layout (A) was generated using the following criteria: minimum 15 ha, maximum 55 ha, seed stand selection based on area (descending order), and adjacent stand selection based on nearest neighbor (restricted search) with initial tolerance set to contemporaries only. The second layout (B) used the same parameters except that allocation potential with free searching was used to select adjacent stands.

Guidelines for block harvest scheduling were based on the forest management manual (New Brunswick Department of Natural Resources and Energy 1988): the maximum size for any opening was 125 ha and a delay of one period was required before harvesting adjacent blocks. Two runs of BLOCK were done for both the A and B block layouts. In the first run, block availability constraints were applied to all blocks, which prevented them from being harvested earlier than originally designated by CRYSTAL. In the second run, no block availability constraints were applied.

TABLE 2. Percentage of harvest schedule allocated with different number of periods to allocate

No. of periods to allocate	Harvest period						4-period average
	1	2	3	4	5	6	
4	86.08	91.25	85.54	86.25	na	na	87.19
5	88.64	93.77	90.67	82.43	88.74	na	88.66
6	89.96	95.60	94.58	89.33	92.92	93.04	93.61

NOTE: Block size: 15 ha minimum, 55 ha maximum. Seed stand criterion: area (descending). Adjacent stand criterion: allocation potential. Tolerance limits: 0 starting, 5 ending.

To estimate harvest flow constraints, 100 feasible harvest schedules were developed for each block layout using BLOCK without any harvest flow constraints. In subsequent runs, the highest average harvest level found without flow constraints was used as the target annual allowable cut (AAC) for the block harvest schedule. Harvest levels were allowed to range from ±2.5% of the target AAC value in each run. In each case, 1000 feasible harvest schedules were found using BLOCK, and the schedule with the highest average harvest was selected as the final harvest schedule for each block layout.

Results

Number of allocation periods

The first set of runs varied only in the number of periods from the harvest schedule to allocate (Table 2). Dallain (1989) suggested that the inclusion of additional blocks from beyond the first five harvest periods might offset the volume loss due to harvest delays. It was similarly hypothesized in this study that by including additional harvest periods more of the overall harvest schedule might be allocated by delaying the harvest of some of the five-period stands while harvesting some of the post-planning horizon stands earlier.

Since deviations from the timing choices of the original harvest schedule are inevitable, it would appear that additional periods of allocation do increase flexibility and improve the overall allocation. Except for the fourth period in the five-period runs, adding additional periods to the planning horizon increased the proportion of the harvest schedule allocated. Planning horizons beyond six periods were not investigated for two reasons: (i) as the number of periods is increased the solution time for the algorithm also increases and (ii) CRYSTAL was not designed to examine and allocate harvest blocks for regenerated strata. Thus, as the number of allocation periods increases and regenerated stands become part of the harvest schedule, CRYSTAL is unable to keep track of regenerated activities. Since the six-period planning horizon performed best, it was used in all subsequent runs.

Seed selection criteria

The second set of runs examined the effect of different seed selection criteria (Table 3). Because stands with few neighbors offer the least flexibility to the allocation process, it was hypothesized that choosing these stands first as seeds would result in more of the harvest schedule being allocated. Because the number of neighbors a stand has is *ceteris paribus* proportional to its perimeter and area, it was assumed that area (ascending order), perimeter (ascending order), and allocation potential would offer the best selection criteria. This was not the case.

The three best results were obtained using polygon identification number, perimeter (descending order), and area (descending order). Polygon identification number consistently performed third best, but perimeter and area were either first or second best, depending on whether the five or six- period average was used. Although there were fairly large differences among the runs within individual periods, the overall results indicate very little difference among the seven criteria listed in Table 3. Using the six-period averages, the best allocation left 717 ha unallocated, whereas the worst left 869 of the 9543 ha unallocated.

A possible explanation for the counter-intuitive results is that the largest stands are easily allocated first, and as more of the schedule is allocated, the smaller stands can be used to "fill in the gaps" of a potential block between its current size and the maximum block size permitted. However, it is important to note that seed stands represent only a small portion of the total area allocated in any run. Therefore, the selection of adjacent stands for inclusion in any one block is likely more important than the seed stands in determining the proportion of the harvest schedule that is ultimately allocated. In any case, area in descending order was used as the seed selection criterion in all subsequent runs.

Block size

The next two sets of runs examine the effects of block size on the ability of CRYSTAL to allocate a particular harvest schedule. First, the minimum block size was varied from 10 to 30 ha (Table 4). The hypothesis for minimum block size is that smaller minimum block sizes will yield better results. Common sense indicates that without limits on block size any harvest schedule can be completely allocated; even the smaller, isolated stand would be harvestable in such a case. What is interesting to determine is how much more of a harvest schedule is not allocated because of a small increase in minimum block size.

The proportion of the harvest schedule allocated drops much more when the minimum block size is increased from 15 to 20 ha than it does when the minimum increases from 10 to 15 ha. With a 10-ha minimum, 185 stands are not allocated to harvest blocks. When the minimum block size is increased to 15 ha, an additional 44 stands cannot be allocated. A further 5-ha increase in minimum block size results in an additional 81 stands that cannot be allocated. Compounding the problem was that not only were more stands impossible to allocate, but also the average size of the unallocated stands increased. For instance, 30-ha minimum block size resulted in only 80% allocation of the harvest schedule. Starting at 10 ha, every additional 10-ha increase in the minimum block size roughly doubled the area unallocated. Although the trend is logically common to any forest, the magnitude of the changes is probably case specific.

The allocation process appears to be much less sensitive to maximum block size over the tested range of sizes than it is to minimum block size (Table 5). Increasing maximum block size did not always yield a higher degree of allocation, and there was very little difference over the range of 40-100 ha. Although there was little difference in the proportion of the harvest schedule allocated at the various block size limits, it would likely be more difficult to develop a feasible block harvest schedule for the block layouts using large blocks. Dallain (1989) suggested that larger blocks would have fewer harvesting possibilities for a given maximum opening size and that blocks with a larger number of adjacent blocks would have fewer harvesting possibilities for a given set of adjacency constraints.

TABLE 3. Percentage of harvest schedule allocated using different seed stand selection criteria

Criterion	Harvest period 1	2	3	4	5	6	5-period average after CLEANUP	6-period average prior to CLEANUP	6-period average after CLEANUP
Area									
Ascending	90.60	93.84	91.42	94.28	83.02	92.82	90.89	81.24	91.22
Descending	89.96	95.60	94.58	89.33	92.92	93.04	92.38	81.24	92.49
Perimeter									
Ascending	91.67	92.25	91.68	94.65	83.12	92.36	90.96	81.91	91.20
Descending	90.16	94.10	93.81	88.13	93.20	91.94	91.75	80.83	91.78
No. of polygons	92.86	95.46	93.69	95.22	84.17	91.26	92.54	82.00	92.32
Stand type	90.93	92.13	92.51	95.14	84.43	90.42	91.30	81.62	91.15
Allocation potential	89.43	95.08	92.34	95.28	84.68	91.73	91.59	81.84	91.62

NOTE: Block size: 15 ha minimum, 55 ha maximum. Adjacent stand criterion: allocation potential. Tolerance limits: 0 starting, 5 ending.

TABLE 4. Percentage of harvest schedule allocated using different minimum block sizes

Minimum block size (ha)	Harvest period 1	2	3	4	5	6	5-period average after CLEANUP	6-period average prior to CLEANUP	6-period average after CLEANUP
10	94.04	96.58	95.31	92.86	95.24	95.43	94.74	86.29	94.86
15	89.96	95.60	94.58	89.33	92.92	93.04	92.38	81.24	92.49
20	86.70	94.53	88.73	88.42	84.85	87.71	88.68	78.43	88.51
30	80.88	91.04	75.55	83.47	72.84	71.60	80.88	71.02	79.28

NOTE: Block size: 55 ha maximum. Seed stand criterion: area (descending). Adjacent stand criterion: allocation potential. Tolerance limits: 0 starting, 5 ending.

Since the number of neighbors for a block is proportional to its size, large blocks can be expected to yield a large number of adjacency conflicts and a lower allowable cut in the block harvest schedule.

Selection criteria for adjacent stands

Table 6 presents the results of different selection criteria for adjacent stands. In the first three runs, CRYSTAL was allowed to deviate from the timing choices in the original harvest schedule when generating harvest blocks (unrestricted search). In the last three runs, CRYSTAL was restricted to stands eligible for harvest in the same period as the seed stand once the size of the block exceeded the minimum block size (restricted search).

Overall, there was little difference among the three selection criteria for adjacent stands whether the search was restricted or not. Selecting the nearest neighbor resulted in the highest success rate when the average of six periods was calculated. When the average of five periods was used, the nearest-neighbor criterion performed better in the restricted search and allocation potential performed better in the free search.

The difference in results using restricted and unrestricted searches was extremely small. However, the results for this forest are likely case specific. In a less homogeneous forest than the one used in this study, more temporal conflicts would be expected, which would force CRYSTAL to deviate from the harvest schedule more often. Therefore, allocation success would be expected to be lower when using restricted searches.

Initial tolerance values

Although it was expected that higher initial tolerance values would allocate a greater proportion of the stratum-based harvest schedule, this was not the case (Table 7). The CLEANUP procedure negated any advantages of initially allowing more flexibility in the allocation procedure. Despite yielding the poorest results prior to applying the CLEANUP procedure, initially restricting adjacent stand selection to true contemporaries produced the highest overall allocation after CLEANUP was complete, even though more noncontemporary stands are included in harvest blocks than would otherwise be the case. Obviously, extending the eligibility window earlier in the allocation process reduces the need for CLEANUP later on, since it appears that tight restrictions on allocation prevent inferior allocations overall. Loose restrictions allow the program to allocate the solution much faster, although at a cost of reduced allocation success overall.

Special operating zones

Special operating zones, as would be encountered in a wildlife management area, may require that harvest blocks in some regions of the forest be restricted in size. In Table 8, a standard run is compared with a run where harvest blocks in the lower right quadrant of the forest are restricted to 50% of normal size. As expected, the requirement for smaller blocks resulted in a lower overall allocation of the harvest schedule. However, the drop in allocation success is due primarily to CRYSTAL'S inability to aggregate leftover stands in the CLEANUP procedure. Prior to invoking CLEANUP, CRYSTAL was able to allocate more of the harvest schedule with special zones than without them.

Block harvest scheduling

The harvest levels calculated in the block harvest schedules developed with CRYSTAL and BLOCK are presented in Table 9.

TABLE 5. Percentage of harvest schedule allocated using different maximum block sizes

Maximum block size (ha)	Harvest period 1	2	3	4	5	6	5-period average after CLEANUP	6-period average prior to CLEANUP	6-period average after CLEANUP
25	79.71	88.56	82.30	77.96	86.07	81.52	82.66	77.91	82.46
40	88.27	93.35	93.54	86.34	90.58	93.22	90.31	80.33	90.82
55	89.96	95.60	94.58	89.33	92.92	93.04	92.38	81.24	92.49
70	90.39	95.61	94.83	88.06	92.09	92.72	92.09	80.40	92.20
100	90.69	95.71	96.01	89.69	93.22	90.90	92.98	80.75	92.61

NOTE: Block size: 15 ha minimum. Seed stand criterion: area (descending). Adjacent stand criterion: allocation potential. Tolerance limits: 0 starting, 5 ending.

TABLE 6. Percentage of harvest schedule allocated using different adjacent stand selection criteria

Criterion	Harvest period 1	2	3	4	5	6	5-period average after CLEANUP	6-period average prior to CLEANUP	6-period average after CLEANUP
Allocation potential (unrestricted search)	89.96	95.60	94.58	89.33	92.92	93.04	92.38	81.24	92.49
Area (unrestricted search)	89.05	94.74	93.17	87.13	91.36	93.00	90.97	79.95	91.32
Nearest neighbor (unrestricted search)	91.48	95.30	94.37	88.56	92.88	92.79	92.41	80.05	92.47
Allocation potential (restricted search)	90.08	95.48	94.39	89.43	93.03	92.44	92.38	80.65	92.39
Area (restricted search)	89.11	94.22	92.22	88.54	92.44	93.28	91.19	79.69	91.55
Nearest neighbor (restricted search)	91.48	95.16	94.50	89.03	93.21	93.78	92.57	79.99	92.78

NOTE: Block size: 15 ha minimum, 55 ha maximum. Seed stand criterion: area (descending). Tolerance limits: 0 starting, 5 ending.

Without block availability constraints (when no restrictions were placed on the periods when blocks were available to be harvested), BLOCK was able to generate solutions that yielded higher harvests. The run A block layout yielded a 3.7% higher harvest volume on average than did the run B block layout with no block availability constraints. Two factors account for much of the difference between the harvest levels: *(i)* the run A layout allocated more of the original harvest schedule than did run B and *(ii)* one block from run B remained unharvested at the end of the six periods because of adjacency conflicts.

The run A block layout allocated 92.5% of the area originally scheduled by FORPLAN, whereas the run B layout allocated only 89.5%. The run A block layout was composed of 277 harvest blocks averaging 45 ha. Only 205 harvest blocks averaging 55 ha composed the run B layout. The larger average block size in run B was responsible for the increase in the number of unharvested blocks when block availability constraints were imposed.

In run A, the cost of imposing block availability constraints was a 0.5% decreased in harvest volume. In run B, the cost of block availability constraints was higher, resulting in a 1% decrease in harvest volume even after relaxing the flow constraints to ±5%. In both cases, blocks remained unharvested after six periods because of adjacency conflicts. Only one block remained unharvested in run A, whereas two blocks remained unharvested in run B.

Schedules based on run A

In the first block harvest schedule for run A where no block availability constraints were applied, all of the harvest blocks could be harvested over six periods. However, most of the harvest blocks were not scheduled for harvest in the period originally determined by CRYSTAL. In fact, there were several blocks originally scheduled for harvest in period 6 that were scheduled for harvest in period 1 in the BLOCK harvest schedule. Whereas in the original block layout harvest blocks scheduled for harvest in a particular period tended to be localized in a particular area, the block harvest schedule more evenly distributed harvests in each period across the forest.

When block availability constraints were applied, blocks scheduled for harvest in later periods could no longer be harvested in earlier periods. Thus, the pattern of harvests under this schedule was not much changed from the original block layout. In a few cases, the harvest of blocks scheduled for harvest in earlier periods was delayed. However, because of the constraints on block availability and maximum opening size, one block scheduled for harvest in period 5 could not be harvested in the six-period planning horizon.

TABLE 7. Percentage of harvest schedule allocated using different initial tolerance values

Initial tolerance value	Harvest period						5-period average after CLEANUP	6-period average prior to CLEANUP	6-period average after CLEANUP
	1	2	3	4	5	6			
Contemporary stands only	89.96	95.60	94.58	89.33	92.92	93.04	92.38	81.24	92.49
Contemporary stands ± 1 period	90.97	96.33	91.72	88.29	92.84	93.20	91.88	85.62	
Contemporary stands ± 2 periods	87.39	94.54	90.57	87.15	91.66	92.76	90.11	86.78	90.57
Anything in periods 1–6	86.49	94.01	91.80	84.07	90.27	91.69	89.16	87.88	89.59

NOTE: Block size: 15 ha minimum, 55 ha maximum. Seed stand criterion: area (descending). Adjacent stand criterion: allocation potential.

Schedules based on run B

As was found with the run A block layout, without block availability constraints, all of the blocks developed for run B could be harvested over the six-period planning horizon. Again, many of the blocks were scheduled for harvest in different periods than was originally determined by CRYSTAL, although it would appear that the shifts in harvest period were less than those in run A. The block harvest schedule developed by BLOCK again improved the spatial distribution of harvests over the forest.

The block layout developed for run B was less flexible than that for run A when block availability constraints were applied. Two blocks, one from period 5 and another from period 6, could not be scheduled for harvest during the planing horizon without violating one or more constraints.

Discussion

This paper has demonstrated a technique that could be used for disaggregation and allocation of stratum-based timber harvest schedules. Although individual harvest blocks may need boundary adjustments on the ground to eliminate spurs and slivers, the basic patterns of blocks across the forest generated by CRYSTAL represent close approximations of the long-term harvest schedule.

It must be remembered, however, that the results found for this forest management problem are valid for a particular situation only. Therefore one must interpret the results in light of the unique characteristics of the problem. The formulation of the problem, the constraints imposed on the problem, and the data structures used to store spatial data may profoundly influence the outcome.

Problem formulation

Difficulties encountered in this study relating to problem formulation fell into one of four major categories: stratification of the forest, incorporation of operational constraints, spatial distribution of stand types, and forest policy constraints.

Stratification of the forest

The forest used in this case study is primarily composed of spruce-fir types, with a mixture of hardwoods. A large portion of the eastern half of the forest has been harvested, whereas the western half is largely untouched. As a result, the age-class distribution of the forest is bimodal with relatively little area in the middle age-classes (Fig. 1). Many of the mature stand types are very similar in composition and have similar yield trajectories. Because of this similarity, and because there is little change in stand yield in the early planning periods, the harvest schedule tends to spread the harvest of these stand types over two or more periods. Because of the splits in the allocation of stand types to prescriptions, it is relatively easy for the algorithm to generate harvest blocks from adjacent stands. If the forest were more fragmented and variable in composition, the generation of harvest blocks would necessarily be more difficult.

The harvest schedule was developed for the softwood component of the forest only, and no controls were placed on the hardwood harvest that resulted from harvest operations in mixed-wood stands. Although such a problem formulation is easier to develop, two problems arise from this artificial separation of the hardwood and softwood forest:

(1) Because of a negative allowable cut effect, a reduction in harvest levels (although likely small) is almost guaranteed. When a forest is subdivided, the allowable cut effect works in reverse, and because the feasible region is reduced in size, the objective function is likely to be reduced as well. Although combining forests to generate an allowable cut effect can have drawbacks such as harvest instability within the component forests (Davis and Johnson 1987), combining the softwood and hardwood components of a single forest does not share these drawbacks because they are conceptual divisions only.

(2) By considering the two components separately, the difficulty in generating feasible blocks is increased. When the softwood component is considered separately, stands from the hardwood component act as barriers, preventing stands on either side of the hardwood stand from being aggregated into a single cut block. By combining the two components into a single analysis, stands from both components can be candidates for inclusion into a single harvest block. Such harvest blocks would not be homogeneous, particularly in terms of silvicultural prescriptions, but they would reduce the need for smaller harvest blocks and the concomitant increased cost of moving equipment. Such trade-offs need to be carefully considered before a decision is made either way.

TABLE 8. Percentage of harvest schedule allocated using a special operating zone

Type of run*	Harvest period						5-period average after CLEANUP	6-period average prior to CLEANUP	6-period average after CLEANUP
	1	2	3	4	5	6			
1	89.96	95.60	94.58	89.33	92.92	93.04	92.38	81.24	92.49
2	88.86	93.39	86.90	82.94	89.36	87.45	88.08	83.56	87.97

NOTE: Seed stand criterion: area (descending). Adjacent stand criterion: allocation potential. Tolerance limits: 0 starting, 5 ending.
*1, Standard run without zones (block size limits: 15–55 ha); 2, zone block size limits applied in lower right quadrant: 8–28 ha.

Incorporation of operational constraints into the harvest schedule

Operational constraints found in forest management problems are rules and regulations affecting on the ground practices, and these constraints are usually the most difficult to incorporate into long-term wood-supply analyses because of the spatial relationships they entail. The harvest scheduling model developed for this study is representative of problem formulations used in many jurisdictions.

It is widely recognized that once harvest blocks are developed for a forest, the AAC will be lower than the pure stratum-based harvest schedule initially predicted (Dallain 1989; Jamnick *et al.* 1990; Chong 1991). When spatial constraints were considered, Dallain (1989) found that allowable cut levels were reduced by between 2.45 and 10.92%, depending on block size and adjacency constraints. The drop in the allowable cut is due to the blocking process and the inability to follow the harvest schedule exactly while ensuring spatial feasibility. If the AAC derived from a block harvest schedule is deemed the true AAC for a forest, the difference between this AAC and the AAC from a stratum-based harvest schedule is not so much a "loss" of AAC, but rather an artifact of the stratum-based harvest scheduling model. However, it is possible (to a degree) to reduce the magnitude of such artifacts by controlling harvest block size in a linear-programming-based harvest scheduling model.

Since explicit spatial constraints quickly become unwieldy in a linear program, an alternative method for controlling harvest block size must be used. A common procedure that has been used relates the harvest block area and associated buffers to total area. Consider a scenario where harvest blocks are perfectly square and average 25 ha and where buffer zones of at least 100-m must be maintained between contemporary harvest blocks. If 50-m buffers are maintained on each side of every block, it will always be possible to meet the 100-m buffer requirements. The total area required for each block and buffer is 36 ha, but since only 25 ha is actually harvested, at most 69.44% of the total area can be harvested in any one period. Applying this ratio to the entire forest, an upper bound on harvest area can be incorporated into the linear program.

If such a constraint were incorporated into the harvest scheduling model, the allowable cut would necessarily fall. However, at least part of the reduction in harvest levels due to spatial constraints is due to the need for buffer strips. Because this reduction would already be incorporated into the harvest schedule, the difference between the stratum-based harvest schedule and the harvest block schedule would be smaller. It should be noted that this type of constraint will only work well if the forest is composed of large stand types unlikely to be liquidated in a single harvest period. For example, it would be foolish to globally apply such a constraint to a forest that recognizes stand types smaller than the minimum block size, since the small stand types likely represent only a few stands and the constraint would prevent the model from completely harvesting them within a single period. In reality, these stands would likely be harvested all at once.

Spatial distribution of stand types

The spatial distribution of stand types over the forest can exacerbate adjacency conflicts. If stand types are located close to each other, it may be difficult, if not impossible, to harvest such stand types without exceeding maximum opening sizes and (or) deviating significantly from the harvest schedule. In the case study, some stand types tended to be localized, but because of the nature of the yield curves, there was very little loss in harvest volumes because of harvest delay and adjacency constraints. However, if stand types represent very discrete portions of the forest and constraints are not incorporated into the analysis to ensure that harvests are distributed over the entire forest, considerable difficulty may be encountered in blocking out the resulting harvest schedule. Even if blocks can be developed, significant deviations from the long-term schedule may be required to address adjacency constraints and constraints on maximum opening size.

Depending on the methods used to stratify the forest, stand composition and spatial distribution may have greater or lesser impacts on allowable cut levels. Jamnick *et al.* (1990) and Chong (1991) demonstrated that harvest schedules based on homogeneous stand types yielded higher long-term sustained yields than schedules based on heterogeneous harvest blocks for a particular forest.

Policy constraints

The problem of forest plan implementation is affected by both policy constraints (usually reflected in the harvest schedule) and regulatory constraints (usually reflected in operational guidelines). Interpretation of policy constraints can drastically alter the implementation of a forest plan. Consider the problem of cover-type conservation. In New Brunswick, it is widely perceived that a change in cover type is not allowed. If this policy were interpreted at the stand level, and each stand was required to regenerate as before, implementation of a forest plan may be severely hampered. This can be a problem in a forest that is very fragmented by ownership and stand history. The forest used in this study illustrates this problem well.

Much of the forest is composed of small stands or fragments of stands because of property boundaries with an average stand size of only 5.8 ha. The forest cover is fragmented, comprising largely spruce-fir and mixed-wood stand types with some stands over 50 ha but many less than 1 ha. With a minimum block size of 15 ha, at least three average-sized stands are required to comprise a feasible harvest block. Even though the harvest schedule represents only the predominantly softwood portion of the forest, some treatments will result in type conversions (particularly in the mixed wood stands).

TABLE 9. Softwood harvest levels (m^3/period) from four block harvest schedules

Block layout	Harvest period 1	2	3	4	5	6	Average
Run A							
Block availability constraints not applied	115 574	115 444	111 316	115 966	111 928	111 822	113 675
Block availability constraints applied	110 631	110 332	115 252	113 490	113 712	114 820	113 040
Run B							
Block availability constraints not applied	109 223	108 153	110 941	108 681	108 559	112 155	109 619
Block availability constraints applied*	106 020	108 261	105 099	104 225	113 882	113 571	108 510

NOTE: Block size: 15 ha minimum, 55 ha maximum. Seed stand criterion: area (descending). Adjacent stand criterion: nearest neighbor – restricted search. Tolerance limits: 0 starting, 5 ending (run A), 5 starting, 5 ending (run B). Harvest flow constraints ±2.5%.
*BLOCK generated 100 infeasible solutions in attempting to restrict harvest flows to ±2.5% of target. Constraint was relaxed to ±5% for this run.

If heterogeneous harvest blocks were not allowed under the cover-type conservation policy, a large portion of the harvest schedule could not be allocated.

Alternatively, if the same policy is interpreted at the forest level, and the proportion of each cover type is to be maintained across the forest, stand conversion may be allowed, making it easier to deal with heterogeneous harvest blocks. If one harvest block is composed mainly of hardwood stands while another is composed mainly of softwood stands, logic would suggest that regeneration efforts be aimed at maintaining the predominant species composition over each of the blocks. Although species diversity is sacrificed at the stand level, it is maintained at the forest level (Baskerville 1987).

Operational constraints

The definition of what constitutes a feasible harvest unit has a large influence on the overall harvest block pattern developed for a forest. A layout consisting mainly of large blocks will likely result in more adjacency conflicts over time than a similar layout of smaller harvest blocks. Although the proportion of the harvest schedule that CRYSTAL was able to allocate was higher at the 55-ha maximum than at 40 or 70 ha, problems were encountered in BLOCK when individual blocks approached the maximum opening size. Because there are fewer units to work with, there are necessarily fewer ways to arrange them in different configurations.

The minimum block size is also important. If the minimum block size is too large, allocation of the harvest schedule becomes infeasible because too few candidate stands can be incorporated into harvest blocks. Large-scale deviations from the harvest schedule may occur in offer to produce feasible harvest blocks with the risk that the analysis may become invalid. Therefore, the choice of allowable block sizes (both minimum and maximum) ultimately affects how harvest blocks are distributed over the forest.

Another consideration when generating harvest blocks is the difference between the minimum and maximum block sizes. Although each factor can independently affect the ability of CRYSTAL to generate feasible blocks, a narrow size range can further reduce the program's ability to generate blocks. The effect of size range on allocation success is related to the average stand size in the forest. If the average stand size approaches the difference between minimum and maximum block size, many of the candidate stands will be too large to combine into feasible blocks.

This is particularly evident when special operating procedures are required for wildlife habitat protection. In many cases, operational constraints require very small patch cuts that are rarely composed of entire stands. Because CRYSTAL allocates whole stands to harvest blocks, it cannot adequately address these kinds of problems. Stands would first need to be subdivided in the geographic information system (GIS) file before attempting allocation. However, such prescriptions are usually preplanned anyway, and a better method would be to include such prescriptions as coordinated allocation choices in the FORPLAN model.

Geographic information

The CRYSTAL program basically requires three types of information to allocate a harvest schedule: information on the size and characteristics of stands, a schedule for harvesting particular stand types, and information on how candidate stands are located relative to each other. Most G1Ss can readily provide the stand information, and if stand types are carefully linked to component stands via the GIS, a harvest schedule can be readily linked to stand information. However, information on how stands are located relative to each other is less readily available. The New Brunswick Forest Development Survey (FDS) map sheets encoded in ARC/INFO can provide information on stands that are immediately adjacent to each other, but for the PC version used in this study, this required a fair amount of data massaging to create the required adjacency table. There are three major impediments to using the GIS information to establish adjacency links:

(1) Using information directly accessible from the database manager in ARC/INFO, it is impossible to determine adjacency relationships for stands that cross map boundaries; such relationships must be determined by inspection. One way to minimize this problem is to increase the size of ARC/INFO map coverages. However,

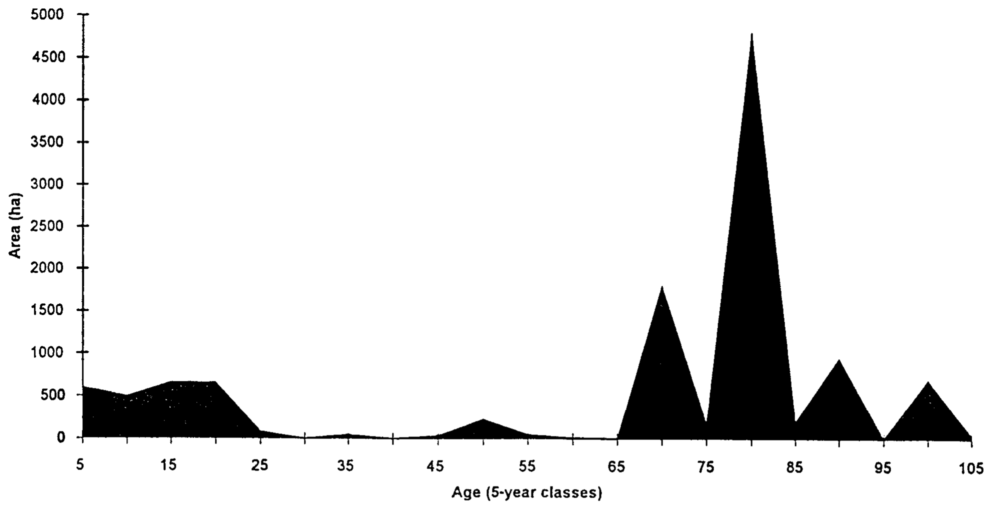

FIG. 1. Age-class distribution of the study forest.

there are system limits on how large a map coverage can be because ARC/INFO allows no more than 5000 polygons per coverage. Depending on the stand resolution (minimum stand size) desired, this limit may or may not be restrictive. The FDS map coverages used in this study have between 600 and 1000 stands, which allows the map information to be printed and reasonably legible at 1 : 12 500 scale on standard size sheets. Unfortunately, the small area covered by each coverage increases not only the number of coverages required for a forest area, but also the number of map boundaries.

(2) There are artificial boundaries created by digitizing linear features, such as roads or transmission lines, as polygons. The CRYSTAL program relies on a simple adjacency table that tells it what stands are adjacent to a particular stand. Whereas harvest blocks do not usually cross rivers or lakes, it is common to have a single harvest block on both sides of a road. However, when the road is digitized as a polygon it acts as a barrier in the same way that a water body does. To get around this limitation, visual inspection was required to establish the adjacency relationships between stands on either side of the road. There are two ways to circumvent this problem. First, linear features such as roads can be digitized as line coverages rather than as part of the polygon coverage. Although this would simplify the determination of adjacency relationships, it would no longer be possible to calculate such things as the forest area used for right-of-ways, etc. Alternatively, the road stands could be segmented where the road crosses stand boundaries. By including road segments in the stand eligibility table with area counted for allocation purposes equal to zero, and by removing adjacency relationships among road segments in the adjacency table, there would be no need for manually adjusting the adjacency table.

(3) The recognition of ownership boundaries is difficult. When stands are divided by ownership, and particularly if the stand fragments are small, all of the stand may not be allocated to the same block. If a forest composed of Crown land and industrial freehold is to be managed as a single entity, it is preferable not to explicitly recognize these boundaries during the allocation process, in the same way that stand boundaries are not recognized within stand types. By removing the artificial ownership boundaries, the forest becomes less fragmented and the number of adjacency relationships to be maintained is reduced. The chief benefit of this step is faster processing and fewer stands split between harvest blocks.

Yield and cost information

CRYSTAL allocates a harvest schedule based on stand attributes, but assumes that yields and costs associated with treating those stands are the same as those used in the harvest scheduling model. However, these are average yield and cost functions that may be quite different than the actual yields and costs related to a particular harvest block. Therefore, before scheduling the harvest of these blocks using the BLOCK model, it would be preferable to replace the yield and cost functions from the harvest scheduling model with ones that are more site specific, at least for the first period. Not only would this provide a more acceptable operational schedule, but also it would provide an opportunity to evaluate how well the strategic planning model corresponds to the real world.

CRYSTAL is presently limited to allocating clear-cut prescriptions only. It does not explicitly recognize other silvicultural treatments such as planting, thinning, or shelterwood harvests. The primary reason for this is that the allocation algorithm is based on stand attributes that must be explicitly available in the GIS data base. Presently, there is no information given in the FDS data base to indicate whether a particular stand would require planting or thinning. Since it is assumed that such decisions are made in *situ* after harvesting, it serves no real purpose to incorporate these decisions into CRYSTAL. Shelterwood harvests are not common yet in New Brunswick, nor have they been explicitly dealt with in the forest management manual regarding operational restrictions: Do harvest delays apply to the regeneration harvest, to the overstory removal, or to both? Is a shelterwood harvest considered an opening in terms of wildlife requirements?

Harvest block allocations

The results indicate that CRYSTAL is capable of allocating a major portion of a stratum-based harvest schedule. In most cases, the program was able to successfully allocate over 80% of the area scheduled for harvest in the planning horizon. However, three features of this forest management problem are unique and may not be applicable under other circumstances:

(1) The study area is small. To maximize softwood volume, the forest must be cut heavily, with a higher concentration of harvesting than is likely to occur on most New Brunswick Crown licenses. This results in less flexibility in allocating stands for harvest with more of the harvest blocks being adjacent to one another. In this sense, the example management problem was a "worst-case" scenario.

(2) The yield curves for most of the stand types harvested in the first six periods did not exhibit large changes in volume over the 30-year period used in the allocation process. This allowed for significant deviations from the original harvest schedule without large losses in harvest volume. In other forests, mortality losses may be significantly higher than was the case in this example. In this sense, the example management problem was a "best- case" scenario.

(3) The forest used in this study was predominantly softwood. The uniformity of the forest cover and the ability to combine dissimilar stand types within a single block allowed CRYSTAL to allocate over half of the harvest schedule without deviating from schedule timing choices. In a forest with more variability in forest cover, the number of deviations from scheduled timing choices may be necessarily higher.

Conclusions

This study has produced a tool for allocating stratum-based harvest schedules to stands in the form of harvest blocks. Although the harvest schedule used in the study was developed using FORPLAN, a linear-programming-based model, CRYSTAL will work with any stratum-based model. Similarly, although PC ARC/INFO was used in this study, the required geographic information may be obtained from any GIS. Moreover, since CRYSTAL is a dbase IV application that uses its own data base management system, a GIS is not explicitly required.

The allocation algorithm is based on a directed least-cost search for solutions. Using stand-level information, seed stands are selected from a list of eligible stands and harvest blocks are developed by aggregating eligible stands adjacent to the seed stand. The selection of seed and adjacent stands to include in a particular block is controlled by stand attributes used as selection criteria. Beyond any stand attribute directly available from the GIS, CRYSTAL offers two additional selection criteria: allocation potential and stand proximity. In addition, the user determines the size limits for acceptable blocks and how much deviation will be acceptable from the schedule timing of harvest. Overall, the CRYSTAL program is very flexible, allowing a virtually unlimited number of ways of generating harvest blocks.

The results have shown that CRYSTAL is able to allocate over 80% of the area scheduled for harvest in the first 30 years of a 70-year harvest schedule. In addition to following the harvest schedule as closely as possible, additional operating constraints such as local block size limits can be handled by CRYSTAL. Once an allocation has been completed, CRYSTAL can generate the input files required for block harvest scheduling using BLOCK. Results indicate that harvest blocks generated by CRYSTAL yield acceptable spatially feasible harvest schedules. Unlike many manually derived harvest block layouts, the harvest blocks generated using CRYSTAL do not include unscheduled stands.

Beyond demonstrating the usefulness of the CRYSTAL program, the case study has also indicated a need for better stand-level information. There are no built-in decision criteria in CRYSTAL, rather the program depends on information available from the forest data base. The information available from the FDS limits the ability to incorporate more site factors into the blocking strategy.

Future research should focus on two issues: improvements to the rules used by CRYSTAL to allocate stands to blocks and determination of what site factors not presently available in the forest data base are necessary for effective blocking strategies. CRYSTAL in its present form is quite limited: it can only allocate clear-cut harvest prescriptions, only one search method (least cost) is available to the user, and there is limited control over block location (through seed stand selection). Before such problems can be addressed, however, CRYSTAL needs to be applied to other forests and forest management problems to fully evaluate the strengths and weaknesses of the current system.

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