# SCHEDULING OLD FOREST INTERIOR SPACE AND TIMBER PRODUCTION: THREE LARGE-SCALE TEST CASES USING THE DPspace MODEL TO INTEGRATE ECONOMIC AND ECOLOGICAL OBJECTIVES

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# Summary

Opportunities exist to better integrate economic and ecological objectives in forest management plans by utilizing new computer models as decision support tools. An overriding objective of this study was to learn more about how one new model called DPspace can help address concerns regarding the amount of older forest in Minnesota's forest landscape and how it can be arranged efficiently in large enough patches (blocks) to be effective for wildlife habitat and natural ecological processes. A related objective was to examine the potential gains from better coordinating forest management of state and federal lands in northern Minnesota to help better achieve ecologically-based spatial management objectives related to patch sizes and shapes of older forest.

In forest management planning, spatial arrangement of the forest is a relatively new concern that is difficult to define precisely and difficult to model directly in forest management scheduling models. Forest management scheduling models have a long history of use in forestry, historically focusing on efficient and effective ways to sustain timber harvest flows over time. Recent applications have added emphasis on also sustaining environmental conditions such as targets related to the desired mix of forest cover types and stand age distributions. Addressing specific spatial arrangement characteristics of the forest is difficult in management scheduling models because spatial arrangement considerations involve interdependencies between specific site-level decisions for the vast majority of the many stands in a typical forest. Decision interdependencies are far less complicated for broader forest-wide goals like those for sustaining overall timber flows or overall forest cover type mixes.

Older forest interior space was the spatial measure used in this study to address spatial objectives. Interior space can be conceptualized as the interior area (or core area) of a homogeneous forest patch. A buffer area surrounds interior space to protect it from outside influences. The specific definition of interior space depends on a number of factors including requirements on the specific conditions necessary for the core area, and the required width and composition of the surrounding protective buffer. For this study emphasis was on older forest interior space that has a core area with stand ages of at least 75 years and a surrounding buffer that is 150 feet wide. The interior area of a patch often involves multiple stands. In fact, larger blocks (patches) are generally more efficient at producing interior space because with large blocks the required area of the buffer, relatively speaking, is smaller compared to the interior space produced. Interior space is a useful measure because it also takes into account the geometric shape of forest patches. Irregular-shaped, (amoeba-shaped) patches tend to have relatively less area producing interior space because of their relatively large amount of edge requiring buffer. For this study it was assumed that the surrounding buffer area for interior space production must be forested areas with stand ages of at least 35 years.

Seven different types of interior space were recognized, one for each of seven ecological land classifications recognized by the USDA Forest Service for the Chippewa National Forest in their current forest planning process. Five of these seven ecological classes are primarily upland areas and two are primarily lowland areas. Each ecological land class has developed under a different rate of natural disturbance with different successional pathways for each of its current forest cover types. Similar to the way that specific timber product flows are valued and tracked explicitly in a forest management scheduling model, interior space flows were valued and tracked for each ecological class in all scenarios modeled for this study. The specific value assumed for interior space was a key difference between scenarios.

Roads can subdivide a forest and impact interior space production. Clearly, large developed roads reduce interior space. For smaller roads, the appropriate assumption is less clear because the forest canopy can remain closed under narrow forest roads. For this study it was assumed that all forest roads impact interior space with 150 feet buffers required between any road and any area considered to be interior space. Roads recognized included all roads open to motorized travel within the Chippewa National Forest proclamation boundary.

The overall study design utilized a series of scenarios with the model applied separately for each scenario. Results were compared across scenarios to learn more about the impact of the assumptions defining the scenarios. Each scenario utilized one of three overlapping study areas: (1) all Chippewa National Forest lands managed by the USDA Forest Service, (2) all forest lands managed by the Minnesota Department of Natural Resources (DNR) that are in Itasca County or Cass County and within the proclamation boundary of the Chippewa National Forest, and (3) the combined area of state and federal forest lands as represented by combining (1) and (2) above. This design was chosen to help develop insight regarding the potential gains from better coordinating management across large public ownerships. The study area is one of the areas in Minnesota with the most intermixed public ownership.

The study area contains 747,000 acres of forestland in approximately 92,000 management units (polygons similar to forest stands or sub-stands) with approximately three-fourths of the area in federal ownership. Land classifications from the current USDA Forest Service planning effort helped define the range of possible management treatment options for each management unit. Specific site-level characteristics considered were the ecological class (as described above), visual quality class, management area class, riparian class, and sensitive species class.

Applications were extremely data intensive utilizing DNR stand level inventory data, associated GIS maps, and much of the management data recently developed as part of the USDA Forest Service planning process in Minnesota. Minnesota Forest Resource Council staff members were instrumental in obtaining data for DNR lands and in developing the detailed GIS database.

Much of the focus in a forest management scheduling model is on how specific management treatment options can be assigned to site-specific management units to best achieve forest-wide economic returns while also achieving broader forest-wide environmental objectives. Management units are assumed to be homogenous at all times. For this study management units were individual stands and substands. Substands were created to recognize riparian areas within stand boundaries, thus allowing those areas to be managed differently than the parent stand. Here, management units will be referred to as stands realizing that some are substands. Treatment options for individual stands differed in terms of type of silvicultural treatment, timings of harvest, type of reforestation activities after harvest, and the type and timing of silvicultural treatments for future rotations. Seventeen different silvicultural treatment types were considered including new types designed to help change aspen stands to other forest cover types through more active management of the understory. The "no treatment" option recognized natural succession with successional rules describing forest cover type and age changes that vary by ecological land classes. Options to convert stands to other forest cover types at the end of the first rotation added substantially to the number of treatment choices for most stands because a host of options for managing the second and subsequent rotations are associated with each forest cover type conversion option.

The modeling process used two forest models, Dualplan and DPspace. Dualplan addresses the aspatial impacts of forest-wide constraints involving even-flow timber objectives and age distribution and forest species mix targets. Dualplan results are key inputs to DPspace, the model where interior space production is modeled explicitly. A strength of Dualplan is its ability to decompose the forest-wide problem into parts to address each stand separately while still taking into account the forest-wide constraints.

A major step in the modeling process was to reduce the number of management options for each stand to a workable number for DPspace, the spatial model. In Dualplan, most polygons had hundreds of potential management options. Defining a workable number for DPspace is somewhat subjective and did not become a major issue because it was found that by using a detailed analysis prior to applying DPspace, numerous options could be trimmed from the DPspace formulation without sacrificing anything in terms of mathematical optimality conditions. Emphasis was placed on preventing the elimination of any option for a given stand that could potentially be optimal in DPspace. Trimming rules used detailed spatial characteristics of each stand in terms of its potential impacts on the decision outcomes for nearby stands. It was found that no stand had more than 32 potentially optimal alternatives, and on average, treatment options could be reduced to approximately 4 per stand. This average actually varied very little over a wide range of potential values assumed for interior space.

A key step in the analysis process involved the development of a new GIS map layer that identifies how management decisions at the stand level are interdependent when providing older forest interior space is a goal. This layer maps all areas of the forest capable of producing interior space, and for each area, identifies which stands influence that area in terms of its potential to produce interior space. For any point on the map, that point is influenced by all stands within the assumed buffer distance for interior space. This new map layer is a map of influence zones where each zone is unique because it represents a unique combination of stands that influence it. Influence zones that involve only one stand are in the center area (core area) of that stand. For the study area involving both federal and state ownerships, there were over 239,000 unique influence zones.

For each of the three study areas, multiple scenarios were used to examine the impact of a range of values for interior space on timber production levels. For all scenarios, older-forest interior space values were assumed to be constant over time. Six scenarios were analyzed for the study area involving both federal and state lands and four scenarios were examined for each of the study areas involving single public ownership. Study results suggest that:

1) The DPspace model, a tool for better integrating spatial objectives into forest management plans, can be applied successfully to problems involving 100,000 or more stands. Initial screenings of stand-level treatment options by the system make it possible to consider substantial detail involving a wide range and number of silvicultural treatment options. The system decomposes large problems into linked smaller problems of manageable size. This characteristic makes it likely that model enhancements can be developed to address additional spatial facets of the management situation.

2) Providing adequate older forest interior space is likely more of a short-term problem than a long-term one. Interior space levels are likely low today simply because spatial arrangement of the forest received little consideration in past forest planning efforts. In the short-term, forest conditions cannot change rapidly so focus may need to be on the more limited interior space production options for the short-term. Short-term actions have potential long-term impacts so both short term and long term impacts need to be considered simultaneously. With good planning and the lead-time associated with long-term planning, spatial conditions can be improved over the long-term.

3) Patches of older forest can be produced in a variety of ways over the long-term. Effective and efficient strategies likely involve a variety of harvest block sizes with analysis likely key for identifying good spatial and temporal strategies that fit well with existing landscape patterns. Simple management guides like "harvest today in larger patches" will increase patches of older forest for the very long term, but such guides are very simplified guide and potentially quite detrimental to short-term objectives. Such a guide would tend to destroy large patches of forest that are potentially very important for producing older forest over the short-term which might be for fifty years or more.

4) The study area has perhaps as much of an intermixed public ownership pattern as anywhere in Minnesota. Yet for the two ownerships considered, most of the area capable of providing interior space involves areas of single ownership. Assuming 150-foot buffers for interior space, over 95 percent of the study area capable of producing interior space is in blocks of single ownership. With larger buffer widths, interactions between the large public landowners increase, but even with 300 foot buffers, over 90 percent of the area capable of producing interior space is in blocks of single ownership. In effect, much can likely be gained from just good planning for each ownership. While coordination doesn't seem critical for increasing interior space as defined in the study, there are caveats to this finding. The study did not consider directly the patch sizes associated with interior space areas. From a biodiversity perspective, some very large patches of older forest interior area (500 acres +) are likely critical with ownership coordination potentially important for their production.

5) Although the model does not address directly the size of patches developed to produce older forest interior space, results showed a strong tendency to schedule interior space production in patches that are substantially larger than what is currently present on the landscape. Smaller patches are generally more inefficient because larger proportions of them only qualify for producing buffer conditions, not interior space. As one would expect, patches of older forest tended to be larger when larger values were assumed for interior space.

Results also show how multiple model runs can be used to gain insight regarding the impact of specific assumptions. A comparison of scenario runs shows that by assuming higher values for older forest interior space, much more of it is produced. However, this comes at a cost to timber production. Caution must be exercised in generalizing too much about these model results. Had constraints also been included in all scenarios to also produce older forest, then trade-offs between older forest interior space values and production and timber harvest levels would not be as dramatic. Had funding and time permitted, more scenarios could have been developed to learn more about the extent to which harvest reductions are caused by valuing older forest itself or by valuing its spatial arrangement. Of importance is to realize that this modeling tool can help in addressing these types of questions.

Clearly the modeling system has enormous potential for better integrating ecological and economic objectives. These objectives are important with potentially much at stake. The modeling system can recognize enormous stand-level detail over very large study areas. Strong ties to optimization modeling helps build confidence in the efficiencies of the coordinated management schedules developed to achieve forest-wide objectives. Once up and running, the model can be applied to numerous scenarios to help learn more about many facets of the management situation ranging from broad forest-wide policies to the potential role of specific new silvicultural treatment options. With its ability to subdivide the problem into small subproblems, the model has the potential to address additional landscape objectives not considered in this study. Management schedules developed for specific scenarios are easily imported into GIS systems that can help in interpreting results or in developing additional spatial statistics.

It is also important to understand some of the potential limitations about the model and its applications:

1) Forest management scheduling models are data intensive with success of applications dependent on providing the model with a set of potentially good management treatment options for the individual stands. Some pre-analysis work is likely needed to reduce the number of treatment options considered in the model for each stand. Although this pre-analysis worked well for this study, it may be more difficult when additional spatial measures are also valued or constrained. Methods for reducing treatment options may then be needed with some concern about potential loss in optimality.

2) By assuming value in producing interior space, many stand-level decisions become quite interdependent. Substantial data prep work is needed to identify interdependencies explicitly. This process is not fully automated at this point.

3) The model itself is fairly technical. It requires a background in forest management, basic operations research techniques, and computer operations.

4) The model currently uses the same buffer distance for all types of interior space. Recognizing multiple distances will require more data pre-processing and will increase model run times. It will also complicate the pre-analysis process done to keep the number of management options at the stand level to a workable number.

5) The model does not address explicitly objectives related to very large patches or specific distributions of patch sizes. Large patch objectives are addressed only by using larger buffer distances for interior space, larger interior space values, or pre-allocating some areas for large patch production by planning period.

6) Although the spatial model is linked explicitly with Dualplan to consider a broad range of potential forest-wide constraints and objectives, the linkage with Dualplan is not developed to the point where it is easy to address the impact that the spatial objectives have on the aspatial (DualPlan)

forest-wide constraints. More work is needed on developing a fully integrated system with fully automated linkages.

7) The model is deterministic. It does not recognize natural disturbances. Clearly, losses from natural disturbances would have some impact on the forest-wide output levels if schedules were implemented exactly as modeled. It is erroneous to assume that the management schedules developed will be implemented precisely over the long term. It is assumed that the planning process is dynamic with schedules updated on a fairly regular basis to adjust to uncontrollable events, changing market conditions and changing values. It is assumed that schedules in the short term would need to be adjusted to integrate responses to natural disturbance events.

Methods have been outlined to help overcome these limitations in practice. The USDA Forest Service is currently using the model system to help support their forest planning process in Minnesota. Undoubtedly, more will be learned about the system as more experience is gained.

# Introduction

Most would agree that sustaining healthy forest conditions is an important management objective for most any forest. As more has been learned about the forest, more has been realized about the importance of spatial characteristics of the forest. Forests provide critical habitat for many wildlife species with the quality of that habitat very much dependent on how the forest is arranged spatially. Spatial characteristics involve various scales ranging from site-specific to landscape-level. A key question facing managers is how to best integrate spatial management considerations into good forest management plans. These important considerations certainly complicate the management situation, posing a real challenge to forest managers today.

The multiple facets of the forest management situation make it difficult to offer simple guidelines to managers for making site-specific management decisions. Former guidelines like "cut oldest stands first" are generally no longer acceptable because they ignore not only spatial management objectives but also other broader forest-wide objectives related to overall economic returns under forest-wide policies to sustain timber harvest flows or to change the forest to create more desirable conditions. At least for most forests under public ownership, some old forest is desired. Management policies to simply reserve areas as large patches of old forest have some values, but they are not likely the key to sustaining a diverse set of desirable environmental conditions. Historically, the location of old forest patches changed over time. Today, such shifts in old forest locations rather than relying on long-term reserve areas may be more compatible with timber production objectives. Timber harvesting objectives and objectives to sustain some old forest are potentially not as conflicting if one also recognizes that some partial harvest treatments can be applied to patches of old forest while still maintaining important characteristics of old forest patches. Management science optimization techniques coupled with new computer technologies can potentially help examine a wide range of spatial configurations in substantial detail to help integrate management objectives. Models can help identify long-term and short–term trade-offs between timber production levels, alternative investment levels and alternative targets for the types and amounts of old forest. Model results can also be site-specific, making it easy to map estimates of future conditions and link results to biological models designed to examine wildlife habitat conditions for specific species.

The USDA Forest Service has invested heavily in analysis to support forest planning. Currently the USDA Forest Service is using the University of Minnesota's Dualplan model to help assess the trade-offs associated with a range of forest management strategies for the two National Forests in Minnesota. They are also planning to use the University of Minnesota's DPspace model to help better address the spatial interdependencies of site-specific management decisions as related to the size of forest patches produced. One complicating factor in this process is the fact that public land ownership patterns in the state are very much intermixed. When one looks at an ownership map of Itasca county, one sees intermixed public ownership (Figure 1) involving state county and federal government. An obvious question is: could overall management results be improved substantially in terms of spatial objectives if detailed forest planning were better coordinated across public ownerships?

The overall objective of this research is to explore how detailed site-specific forest management scheduling models for spatial management objectives might be used to help better integrate environmental and economic objectives across public ownerships. The intent is to build off of the detailed baseline modeling work done by the USDA Forest Service and explore the potential gains from coordinated management planning across ownerships to better address spatial considerations. Emphasis is on large-scale case studies focusing on objectives to produce larger blocks of older forest over time while still sustaining relatively high timber harvest levels. Of special interest is to better understand trade-offs between timber production and spatial objectives. Insights regarding specific site-level management strategies are also important as case studies are detailed enough to map and compare site-specific management schedules over time.

# Background

Historically, forest managers have used timber harvesting and forest regeneration activities to influence the composition, quantity and age of vegetation on a landscape. The spatial changes occurring to the landscape were often recognized but not directly addressed in forest management planning. The situation is changing with the ever-growing knowledge of natural systems and advancements in computing technology for planning.

## Habitat Fragmentation

In general terms, habitat fragmentation refers to subdividing or separating habitat such that the overall quality of the habitat is reduced. Although simple conceptually, specific impacts are very much species dependent. Researchers have demonstrated the potential of current forest policies to fragment habitat on the landscape (Gustafson and Crow 1994, Barrett et al. 1998). The concern over the impacts of habitat fragmentation on plants and animals is evident by the volume of literature being published on the topic. When reviewing the literature on habitat fragmentation, two terms often mentioned are “edge effects” and “‘patch size effects.” A brief overview of these concepts is provided below.

### Edge effects

Edge effects refer to the gradients in abiotic and biotic factors that exist when two different types of ecosystems or habitats abut one another. There is general consensus in the literature regarding the types of gradients that exist between edges for several abiotic factors. The extent of an abiotic gradient from an edge depends on the edge environment and the abiotic factor itself; however, abiotic factors typically have farther reaching gradients along south and west facing edges in the northern hemisphere than north and east facing edges (Matlack 1994, Fraver 1994).

Biotic factors respond to edge environments because gradients exist in abiotic factors. Among the biotic factors, vegetation responds most closely to abiotic gradients, but the relationship between the two is not always a simple one (Gehlhausen et al. 2000). The ability to relate responses to abiotic gradients becomes more challenging as one considers other biotic factors besides vegetation. Furthermore, the challenge becomes even greater as a species’ habitat needs become larger and more complex because the species is no longer responding to a single edge but a collection of edges on the landscape. The responses of mammalian, avian, and arthropodan species to edge environments are usually researched via patch size effect or similar concepts.

### Patch size effects

The term patch size effect refers to the situation where a species' response to an amount of habitat is affected by the spatial arrangement of that habitat. A similar concept to patch size effect is landscape connectivity. A high level of connectivity on a landscape will have many of the larger areas of habitat connected, either physically or functionally. Whether the term patch size effect or landscape connectivity is used, the issue being addressed is a species' response to both the composition and arrangement of habitat on a landscape.

In the literature on patch size effect, species are usually divided into different classes that represent typical responses to edge. Bevers and Hof (1999) refer to Hunter's (1990, p. 102-108) classification of wildlife species into one of three different Groups: A, B, and C. Group A species are present in edge environments because they require resources from all of the adjoining habitats that comprise an edge. Group B species require transitional habitats known as ecotones, and Group C species are associated with only one of the adjoining habitats that comprise an edge. More commonly in the landscape ecology and conservation biology literature, a species' habitat association is simply categorized as edge, interior, or generalist (Bender et al. 1998).

It has been suggested that early studies did not properly differentiate habitat loss from habitat fragmentation (Bender et al. 1998, Trzcinski et al. 1999), which leads to the possibility of the patch size effect being accounted for mostly through habitat loss and not fragmentation (Trzcinski et al. 1999). Response classes to edge have been shown to explain most of the variation when considering only the habitat fragmentation component of patch size effect. Bender et al. (1998) explain this result as the 'geometric' effect because measuring suitable habitat on the landscape, i.e., accounting for edge effects, instead of total habitat lessens the effect.

## Forest management scheduling Models

Models for forest management planning are broadly classified as either optimization or simulation models. Optimization models are derived from mathematical programming techniques and attempt to find an optimal solution to a problem given a range of management choices. Simulation models are provided a specific set of management activities and rules and then simulate the outcome of following such actions. Heuristic search techniques are used with simulation models to explore a range of management choices and attempt to find the best available solution.

Historically, the strength of optimization techniques was their ability to provide an optimal solution, but the limited amount of information that could be handled by them was considered a weakness. Conversely, the uncertainty in the optimality of the solution given by simulation techniques was a weakness, but their ability to track large amounts of information was considered their strength. Both modeling techniques are evolving as advancements are made in computing technology and the field of operations research. Advances in computers allow optimization models to handle larger amounts of information while improvements in search heuristics are providing better solutions for simulation techniques.

Linear programming (LP) models are the most common optimization models used for forest management scheduling. Initially, linear programming applications for forest management focused almost entirely on timber production with forest-wide constraints often included to limit the forest-wide area or timber volume harvested during each planning period. In the 1980's the USDA Forest Service was using linear programming models as the basis for analysis for developing management plans for each US national forest. Johnson and Scheurman (1977) classified the mathematical structures that represent linear programs in forestry as either Model I or Model II formulations. In Model I formulations, each management activity for each land unit modeled (analysis area) represents a sequence of actions over the entire planning horizon. In contrast, in Model II formulations, each management activity represents a sequence of actions over a single rotation. The mathematical structure that represents a linear program is important because it influences the number of activities (variables) and constraints in the problem formulation. Model II formulations increase the number of constraints in a problem formulation, but they have the possibility of greatly reducing the number of activities for situations where the planning horizon is long compared to the rotation length of typical stands modeled (Johnson and Scheurman 1977). Both Model I and Model II formulations increase substantially in size when management options are included to address options for changing forest cover types for future rotations.

Researchers and forest managers have been using computers to apply operations research techniques for forest management planning for several decades. Only more recently has work begun on addressing spatial concerns at the strategic and landscape level. Spatial detail in management scheduling models adds complexity to the modeling process because of the additional information required to determine and track spatial interdependencies among stands.

To address most spatial aspects of forest management, it is generally important to recognize that the problem is binary in nature -- management activities occur to whole stands and splitting of stands is not allowed. Formulations known as mixed-integer linear programming (MILP) are often used in such situations. Efforts to better address the spatial arrangement of the forest in forest management planning focused initially on the size of harvest blocks. The National Forest Management Act of 1976 (NFMA) calls for "maximum size limits for areas to be cut in one harvest operation" when using clearcutting or other even-aged harvesting systems. Adjacency constraints have been used to address this limitation with varying ways of formulating such constraints in management scheduling models. Murray (1999) classifies mathematical programming formulations of the adjacency constraint problem as either area restriction models (ARM) or unit restriction models (URM). A URM assumes that any two or more adjacent stands cannot be harvested during the same time period, regardless of the size of the stands involved. An ARM allows for harvesting of adjacent stands as long as the maximum harvest block size is not exceeded. An ARM model formulation can become especially large in size if the cutting block size limit is large compared to the size of most stands.

The motivations behind policy makers instituting limits on harvest block size are many and varied. Policies that set maximum harvest block sizes are generally a simplified indirect approach to landscape objectives. Such policies have been criticized because of the the potential to disperse harvests more across the forest with harvests potentially reducing the size of older forest patches present on the landscape. In light of this possibility, it is important to consider alternatives to harvest block limits for managing spatial concerns on landscapes.

LP and MILP are not the only optimization techniques applied to forest management issues. Dynamic programming (DP) has recently been used to address adjacency constraints (Hoganson and Borges

1998, Borges and Hoganson 1999) and interior space production (Bergmann 1999). Dynamic programming is a structure for solving specific kinds of mathematical programming problems. When applicable, dynamic programming is a very efficient means of solving problems. A concern in using DP formulations to solve forest management problems is the 'curse of dimensionality.' Dynamic programming formulations have a tendency to increase exponentially in size with increases in the number of state variables. Hoganson and Borges (1998) and Bergmann (1999) successfully use overlapping subproblems to ensure tractability while maintaining near optimality with large problems.

Ohman and Eriksson (1998) use simulated annealing to address the production core area of older forest. Simulated annealing is a search technique that searches to improve an existing solution by considering marginal changes in the existing solution. It searches all possible changes and randomly selects some changes that show no immediate improvement so as to help prevent the solution from getting trapped at solutions that are only locally optimal. Others use simulated annealing (Lockwood and Moore1993; Boston and Bettinger 1999) to address forestry problems generally considered to large and complex for optimization techniques.

Ohman and Eriksson (1998) modeling of core area and Bergmann's modeling of interior space are similar in that both focus on producing an interior area of older forest surrounded by a protective buffer. Ohman and Eriksson use smaller buffer distances with neighboring raster cells from a GIS map used to represent map distances. Bergmann (1999) focuses more on a fixed buffer distance and is not tied to a marginal analysis for improving management schedules.

In effect, models that explicitly value the production of interior space (core area) will influence forest patch sizes. Higher values for interior space will tend to produce larger patches as larger patches produce more interior space. A strength of the interior space /core area concept lies in its compromise approach. The modeling of interior space is an improvement over maximum harvest block size because it recognizes explicitly the value of interior space on a landscape. Although interior space modeling does not directly recognize individual species' habitat requirements, the approach has a feasibility advantage over explicitly accounting for wildlife dynamics because information on all or many species on a landscape in not necessary.

Other issues in forest management are inherently spatial. One particular issue deserving of mention is road network development. The ability of road networks to influence timber revenues has been understood since the beginnings of forest management. More recently, road networks have been shown to have a significant impact on habitat fragmentation, in certain cases surpassing the fragmentation effect caused by harvesting (Reed et al. 1996). The future of integrating spatiality into management scheduling models lies in modeling multiple spatial concerns simultaneously. The challenges involved in this process are significant and require more research to overcome.

## Influence Zones: Building Blocks For Spatial Analysis

DPspace, the forest management scheduling model used in this study, uses influence zones to identify all of the spatial interdependencies associated with management decisions that impact the production of interior space (core area). Interior space is assumed to be an area that is surrounded by a protective buffer area that protects the interior space from outside influences. Influence zones are very much dependent on the assumed buffer distance assumed in defining interior space. An influence zone represents an area that is all influenced by the same set of stands in terms of the area's ability to produce interior space. Management decisions for the stands that define an influence zone are thus interdependent in terms of the potential for that influence zone to produce interior space. Influence zones can be thought of as areas of potential interior space. Each is generally smaller than a stand. Stands are assumed to be the smallest management unit with all of a stand managed in the same way. Whether or not an influence zone produces interior space depends on the conditions of the stands that define (influence) it. In this study the concept of influence zones has been expanded from its use by Bergmann(1999) to give more flexibility in defining the requirements for the surrounding buffer for interior space. With this expansion influence zones are subdivided into components based on the stand in which it occurs. Some components of the influence zone can provide interior space while others provide the required buffer conditions for interior space. A key concept is that all of the stands that define an influence zone influence the entire area of that influence zone in terms of the potential for producing any interior space from that area. All of those stands must at least meet the buffer requirements for interior space for the influence zone to produce any interior space.

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Figure 2(a) shows a five-stand example forest. Figure 2(b) displays the influence zones for the example forest given a buffer distance of 150 ft. In this example, the area surrounding the five-stand forest is considered to be other ownership. As such, future conditions of those area are assumed unknown, and all areas of the example forest that are within the buffer distance of the other ownership are not considered as areas that can be managed to produce interior space. The labels in Figure 2(b) indicate which stands have influence over a given area. A single letter implies an area that is influenced by only one stand. These areas are referred to as one-way interactions. The ability of one-way interactions to produce interior space depends only on the condition of one stand. Multiple letters imply an area influenced by multiple stands, and the potential for interior space production in those influence zones relies on the conditions of all the stands defining the influence zone.

Table 1 lists each influence zone for the five-stand example, the area of each influence zone and shows, in the total for each column, the total area each stand influences in terms of areas that are potentially capable of producing interior space. This total area for a stand is the maximum area, for a given buffer distance, a stand can potentially influence for producing interior space. Both the stand condition and the interior space definition determine the actual area influenced by a given stand. Over 95 percent of the area that can produce interior space for the 5-stand example is in one-way or two-way interactions (Table 1). The number, and to a lesser extent the area, of influence zones depends upon the spatial layout of stands and the buffer distance relative to the average stand size. Larger buffer distances will increase the relative importance of interactions involving more stands.

All stands defining an influence zone influence that zone; however, influence zones do not reside equally within each constituent stand. Some influence zones do not reside within one or more of the constituent stands of the zone. Figure 3 displays the *ABCD* influence zone overlaid on the four stands that create the zone. Although stands A,B,C, and D all influence *ABCD*, the influence zone resides only in stands A and C. The total area of influence zone *ABCD* is 0.37 acres with 0.21 acres within stand C and 0.16 acres within stand A.

Bergmann's (1999) use of influence zones is very similar to what is described here with one notable exception. Bergmann (1999) only determines the stands contributing to an influence zone and the total area of that zone, i.e., the proportion of an influence zone residing within each of its constituent stands is not calculated. For the *ABCD* influence zone, Bergmann (1999) would not consider how much area of *ABCD* resides within C or within D. Knowing the amount of an influence zone within each of its constituent stands is critical for addressing the assumption that the buffer area for interior space need not meet the same stand age requirements as is required for the interior space area itself.

Interior space is defined as those areas that meet a certain vegetation condition and stand age and are surrounded by an adequate buffer – a buffer that makes it free of edge effects. Quality buffers will be referred to as areas that do not meet interior space condition requirements but still meet the requirements for providing adequate buffer conditions for interior space. Quality buffers are a mechanism for improving interior space modeling by recognizing that edge effects lessen gradually as the contrast between adjacent habitats decreases over time. For example, most would agree the extent of edge effects is different for an old forest, clearcut edge than for an old forest, mature forest edge.

Influence zone *AD* works well to demonstrate the role of quality buffers in modeling interior space. For brevity's sake, assume the stands in the example forest can exist in one of three condition classes: open, mature forest, or old forest. Stands must meet the old forest condition to be eligible for interior space and the mature forest condition for quality buffer. Table 2 summarizes the impacts of different condition classes for stands A and D on the state of influence zone *AD*

## Three Large-scale Test Cases

As stated earlier, the overall objective of this project is to explore how detailed site-specific forest management scheduling tools might be used to help better integrate environmental and economic objectives across public ownerships. The intent is to build off of the detailed baseline modeling work done by the USDA Forest Service and explore the potential gains from coordinated management planning across ownerships to better address spatial considerations. Three test cases are designed to examine potential gains from coordinating management of USDA Forest Service and Minnesota Department of Natural Resources (DNR) lands. The study area was comprised of Minnesota DNR managed lands in Itasca and Cass County and USDA Forest Service lands within the Chippewa National Forest. Approximately 747,000 thousand acres were modeled with 555,000 in federal ownership and 192,000 in state ownership. One case considered just Minnesota DNR lands, another case just the USDA Forest Service lands and a third case with these two ownerships combined. All three cases used multiple runs of the University of Minnesota's DPspace forest management scheduling model to examine trade-offs between timber production and interior space production. For each case, model runs varied only in terms of assumed values for old forest interior space. In effect, by placing higher values for older forest interior space, one is simply placing more emphasis on interior space production than timber production. Timber stumpage prices were assumed to be constant over time and equal to average prices received by the Chippewa National Forest in 1998. The only exception to this was for cedar as currently the USDA Forest Service does not consider cedar to be a commercial timber species on their lands. Considerable detail was included in tracking timber volume and values, recognizing 13 timber product classes: large red & white pine logs, small red & white pine logs, jack pine logs, spruce logs, hardwood logs, aspen pulp, hardwood pulp, balsam fir pulp, spruce pulp, tamarack pulp, pine pulp, cedar and firewood. Management cost estimates were those used by the USDA Forest Service and included sale administration costs, and a wide range of stand establishment and stand treatment costs that vary by forest cover type and treatment option. A 100-year planning horizon was used with ten 10-year planning periods. A four percent discount rate was used to compare net returns with all costs and revenues expressed in real terms (net of inflation).

Stand and substand level polygons were used as the basic modeling unit. Substand polygons were used because it was considered important to recognize both inner and outer riparian buffer areas within stands. Updated stand level inventories and ArcView GIS maps were obtained for both ownerships. Approximately 92,000 forested polygons were modeled. GIS technical staff for the Minnesota Forest Resource Council were instrumental in integrating the GIS polygon information for the two ownerships. Important map layers for the analysis included: (1) an ecological layer recognizing five upland landscape ecosystems and two lowland landscape ecosystems, (2) a riparian layer with inner and outer riparian areas, each 100 feet wide, (3) a management area layer using 18 management area classes as defined by the USDA Forest Service and (4) a visual quality layer identifying two classes of quarter-mile visual corridors along important roads and waters. All of these layers are quite detailed and were developed and used as part of the USDA Forest Service planning process.

Forest management scheduling models have the potential to consider a wide range of forest-wide constraints. This study focused on the spatial facets of the problem. It used estimates developed from the USDA Forest Service planning process to take into account forest-wide constraints. These other forest-wide constraints will be referred to as the aspatial objectives. They refer to forest-wide constraints such as: (1) even-flow harvest volume constraints, (2) forest cover type area targets for specific landscape ecosystems, (3) harvest area targets by decade for specific landscape ecosystems, and (4) demand constraints that place value on the biodiversity or mix of age classes for each forest cover type. Associated with each aspatial forest-wide constraint is a shadow price that estimates the marginal cost of achieving that constraint. The University of Minnesota's Dualplan model, the forest management scheduling model used by the USDA Forest Service in Minnesota, uses those shadow prices to value and compare specific management treatment options for each stand. The DPspace spatial model uses this same valuation process and also considers how the management of neighboring stands can be better coordinated to also produce interior space. Shadow price estimates for the aspatial constraints were taken from a draft Dualplan run done as part of the preliminary analyses for the Chippewa National Forest ongoing planning process. Generally, the forest-wide species targets reduce the area in the aspen forest cover type over time and increase the conifer types, especially white pine in landscape ecosystems where it occurred naturally. The shadow price estimates to produce a more balanced flow of timber over time show a trend in increasing shadow prices (timber values) over time, offsetting the older forest age imbalance that would otherwise suggest large yet unsustainable harvest levels in the first decade. With the spatial model it would be possible to use different shadow price estimates for each ownership, to also consider shadow prices for other forest-wide constraints or to even adjust shadow price estimates based on the forest-wide outputs of the spatial model schedule. Such considerations were considered beyond the scope of this study.

For each modeled polygon a large number of silvicultural treatment options were recognized as potential management choices or treatment options. With the Dualplan model, polygon treatment options are described in pieces, one piece for each rotation. In forest management scheduling terms, this approach of subdividing treatment options is referred to as a model II type of formulation (Johnson and Schuerman 1977). For each polygon over the planning horizon, the overall number of unique treatment options is large because of the combinatorial nature of rotations, with a number of treatment options possible for each rotation. Forest restoration options to change forest cover types were also an important consideration. Overall, this substantially increases the number of unique treatment options possible for individual polygons and generally has a much greater impact than recognizing more treatment options for the first rotation.

Forest management plans can only be as good as the treatment options they consider. With higher timber prices and more concern today than ever about the mix of forest types and ages in various landscape ecosystems, the number of plausible management options is large. The USDA Forest Service planning effort has put considerable effort into considering a wide range of silvicultural treatment options. This study paced emphasis on using them too. Seventeen silvicultural treatment types were recognized for possible use during the first rotation. Table 3 shows a breakdown of the specific treatment types considered for each forest cover type and the associated minimum rotation age possible. Treatment types are numbered with the lower numbered types generally being more intensive options. Treatment #17, the no harvest option, was considered for all forest cover types. The predominant forest cover type in the study area is aspen. Treatment type options for aspen received considerable attention by the USDA Forest Service because an important consideration in northern Minnesota is whether active forest management should be used to reduce the area in the aspen type. Treatment types 7 through 14 are partial cut options for the aspen and aspen-fir types designed specifically for helping accelerate the rate at which aspen cover types might be restored to other cover types that are natural to the corresponding landscape ecosystems.

Future rotations are assumed to start when management actions during the first rotation remove the most of the overstory and thus set the age of the stand age back to age zero. This occurs within the planning horizon only with the even-aged management systems (treatment types 1-5). Any active conversion (or restoration) of the stand to another forest type is assumed to occur either as part of the first rotation (treatment types 7-14) or at the start of the second rotation through active site conversion management actions.

Reforestation options for each stand depend on the location of the stand in terms of landscape ecosystem (LE). For example, in the Dry Pine LE, it was pre-determined that regenerating a jack pine stand as a hardwood stand is not desirable. Thus, modeling did not consider this choice for jack pine stands harvested in the dry pine LE. Generally, conversion options were eliminated if the desired future cover type conditions for the LE did not suggest a need for such conversion. To help simplify the analysis, once the second rotation forest cover type is established, forest conversion options were not considered for later periods. Second and subsequent rotations were thus limited to only the treatment types not designed to include site conversion (treatment types 1-6). Rotation ages for future rotations were in no way limited by the rotation selected for the first rotation. Conversion options were not considered for lowland cover types. These types may be harvested, but they can only be regenerated to their original stand component. Natural succession is also recognized for the early successional cover types: aspen, aspen-fir, birch and jack pine. The specific successional pathway followed depends on the landscape ecosystem in which the stand is located. Treatment types 15-16 involve uneven-aged management for stands that have succeeded to spruce-fir or mixed hardwoods.

Spatial modeling is complicated because emphasis shifts to how site-specific management decisions for individual stands are intertwined with the similar management decisions for neighboring and nearby stands. Unlike temporal concerns like sustaining timber flows over time, outcomes are not simply additive. Combinations of options for multiple polygons become a key consideration with emphasis on the spatial interdependencies of the outcome. For example, if 5 polygons all interact with each other and each has 100 treatment options, then there are $100^5$ or 10 billion unique ways of managing just those 5 polygons in combination. Much of the emphasis in this study focused on ways of simplifying the number of options for each polygon while looking critically at this simplification process to avoid eliminating potentially good choices. This will be explained in more detail when we look at the specific components of the overall modeling system.

The test cases represent a specific real world situation. The situation has many facets with an almost limitless combination of possible management choices. A thorough analysis of the cases involves an enormous amount of data. The modeling system provides a framework for organizing the data and sorting through the possible management choices. Much of the effort of this study involved refinement of computer software to help develop, address and integrate much of the associated data describing the stands in the forest and the associated site-specific management choices. Fortunately, the analysis could utilize much of the ongoing analytical work for the USDA Forest Service National Forest planning process in Minnesota. But that effort has not focused much yet on the spatial aspects of planning and all of the work necessary to address how site specific management decisions are interdependent. In the following section the modeling system will be described. Some of its components are much more refined than others with some components developed almost exclusively for this study.

## The Modeling System

Forest management scheduling models for addressing spatial management objectives are relatively new in forestry. Most applications reported in the literature involve small areas or hypothetical test cases. Prior to this study the DPspace model had only been applied to hypothetical test cases. Plans are underway to use it as part of the USDA National Forest planning process in Minnesota, but to this point those applications have not been fully developed. As such, the overall spatial modeling system is very much in a developmental stage. This study helped substantially with that development. Because of the enormous amount of detailed data involved in large-scale applied studies, a key for this study was linking the new modeling system with the existing aspatial modeling system used for USDA Forest Service planning in Minnesota

A challenging aspect of forest management planning is the need to integrate information from a wide range of disciplines. The modeling system presented here attempts to do that. Effort was made to modularize the system so that specific components could later be updated without changing the entire system. The overall system should be viewed as one that is dynamic with enhancements possible and even planned. Yet in its current state it is well defined and quite capable of producing meaningful results. It seems noteworthy that although the USDA Forest Service has invested heavily in developing new forest management scheduling tools, the USDA Forest Service has selected this system as the primary management scheduling system to use for analysis in revising the current forest plans for both National Forests in Minnesota.

A general overview of the model components and linkages between them are shown in Figure 4. Components have each been classified as either aspatial, spatial or integrated depending on which facets of the problem they focus. The following three sections describe the modeling system subcomponents based on this classification. A general understanding of the case studies as described in the previous section will be helping in better understanding linkages between the model components. Learning about the modeling system will hopefully add insight about the facets of the case studies and how the management decisions are interdependent.

## Aspatial Model Components

### Treatment Generator

The Treatment Generator develops all of the product flow information associated with all of the possible silvicultural treatment options for each polygon (analysis area) . For each option, this includes information on timber yields, associated management costs, and age and cover type characteristics of the stand. Detail was substantial with linkages with the USDA Forest Service planning process critical to make this amount of detail feasible for this study.

Each of the 17 silvicultural treatment types modeled by the Treatment Generator also has a range of possible timing options for each of the corresponding forest types for which it applies (Table 3). For example, for clearcutting red pine, rotation ages can vary anywhere from 60 years to more than 200 years. All possible clearcut timings were considered with harvests assumed to occur at the midpoint of each planning period. To keep timing options for thinning options from being too numerous to enumerate, simplifying assumptions were made. For example, with red pine thinning it was assumed that thinning intervals would be 20 years.

For each forest cover type, it was also important to take into account site quality impacts as growth rates vary substantially by forest cover type within the study area. Site index measurements for each polygon were used for this. For each of the forest cover types identified in Table 3, the Treatment Generator developed a set of treatment options for single year age classes ranging from age 0 to the oldest age of feasible harvest. The Treatment Generator is based on a Model II structure (Johnson and Scheurman 1977). The next model subcomponent, the Treatment Linker, combines treatment options from the Treatment Generator, to define options for the entire planning horizon.

### Treatment Linker

A key to developing a good forest management plan is to consider a range of treatment options for each management unit. Schedules can only be as good as the treatments considered. Generally, the objective is to consider a wide range of options for each stand. But there is also a need to limit treatment options to those appropriate for the specific characteristics of the stand. For example, in an inner riparian area, clearcutting is not considered to be a feasible option. The Treatment Linker links each polygon with those treatment options that are judged potentially appropriate for the polygon. It also adjusts associated timber growth and yield estimates for those treatments based on stand level inventory information describing the basal area and site quality of the stand. Important stand level factors in defining potential treatment options include (1) ecological area, (2) management area (3) riparian area, (4) visual quality area and (5) sensitive species considerations. The ecological area identifier is key in defining which forest cover type restoration activities are considered and how the stand is likely to change over time with succession if the stand is not treated. For USDA Forest Service planning a management area identifier is often a major driver in the planning process with approximately 15 types of management areas recognized. For applications for this study most of the study area was classified as general forestry with few treatment options eliminated because of an assigned management area classification. Riparian area classifications, visual quality classifications and sensitive species classifications generally eliminate clearcutting and force longer rotations for some forest types.

### Dualplan

Dualplan is a forest management scheduling model. It is similar to scheduling models based on linear programming like the USDA Forest Service models Forplan and Spectrum. The key difference between Dualplan and those models is that Dualplan uses a specialized solution technique that utilizes an understanding of the forestry problem to solve the problem (Hoganson and Rose 1984). Essentially the problem is decomposed and solved in parts using standard concepts of economic cash flow analysis. Estimates of the marginal costs of achieving forest-wide constraints are key to the process as these estimates are used like market prices in the analysis to compare treatment options for individual polygons. Initially the user must supply estimates of these marginal costs of production, but through an iterative process Dualplan re-estimates the marginal costs of each forest-wide constraint based on what can be learned about those costs from earlier estimates and the management schedules developed based on those estimates. In early applications like those for the Minnesota Generic Impact Statement on Timber Harvesting in Minnesota, emphasis was on satisfying forest-wide constraints associated with timber production. Recently, many options have been added to track and constrain forest conditions over time. Currently the USDA Forest Service is using Dualplan to analyze a range of forest-wide alternatives for the two National Forests in Minnesota. Besides constraints on timber production levels, these Dualplan applications are recognizing constraints that: (1) control the age distribution of the forest in each landscape ecosystem, (2) describe forest restoration objectives for each landscape ecosystem by setting area targets for selected forest cover types over time, and (3) recognize biodiversity values associated with having a mix of all forest cover types and ages whenever possible. This last set of constraints is similar to the concept of downward sloping demand curves for timber where less timber output in a given time period implies a higher price for timber in that period.

Dualplan marginal cost estimates for the forest-wide constraints used in modeling a scenario for the Chippewa National Forest were used to value forest-wide aspatial objectives for the test cases for this study. The scenario selected was just a preliminary and draft scenario in the USDA Forest Service's planning process and one with relatively few forest-wide constraints on old forest. The desire was to address the old forest objective in the spatial model using prices on old forest interior space. One could set aspatial old forest objectives using Dualplan, but that would not address how that old forest is arranged spatially, nor would it make it easier to later address trade-offs between timber production and old forest interior space. The forest-wide constraints used focused more on the timber side addressing the age class imbalance and the desire to better balance harvest flows over time.

## Spatial Components

### IZones

Earlier, the concept of influence zones was defined. Influence zones are key in that they describe the spatial arrangement of the forest in terms of how stand-level decisions for different stands are interdependent in terms of their impact on the forest's production of interior space. Substantial insight can be gained learned just by examining summaries describing the influence zones.

The Izones program determines the influence zones. The Izones program is the first in the series of spatial programs to be applied, with its results utilized by ISpaceCap and SubProblems (Figure 4). Izones considers ownership on the landscape as well as roads. Areas within the assumed interior space buffer distance from a road or from another ownership are assumed not capable of producing interior space.

The Izones program is grid based. All geographic data used by it must be rasterized before processing. The Izones program first performs a neighborhood analysis on a kernel template that is subsequently applied to the rasterized map of the forest. The buffering process for the template is illustrated in Figure 5. For a given buffer width and raster cell size, the kernel template must be a large enough map to include all of the raster cells that are within the buffer distance from the center raster cell. The template subdivides the center cell (labeled as E in Figure 5) into areas based on the combination of neighboring raster cells that are within the assumed buffer distance. Each of these subdivisions will each involve a different combination of neighboring raster cells. Subdivision boundaries within the center cell are determined using discrete means. A 1000 by 1000-point matrix is placed within the center cell E, and the distance is measured for each point of the matrix to the nearest border with every cell comprising the kernel. If the nearest border is closer than the buffer distance, then that cell influences that given point. This process is repeated for every point in the matrix, and the results are categorized and summed. The final product is a listing of all uniquely interacting regions within cell E and their corresponding areas.

The second step in Izones applies the template to the rasterized landscape. For each cell in the raster map, the template is overlaid and all uniquely interacting regions are resolved from placeholding letters, e.g., A, B, E, to analysis area (polygon) identifiers. A similar process used in creating the template is used to process the map. The results within and between each analyzed raster cell are condensed, categorized, and summed. The final product is a listing of uniquely interacting regions and their areas. These results from the Izones program are referred to as influence zones.

This study used a 1/16$^{th}$ acre raster cell size, which corresponds to cells with 52.18 feet (15.9 meter) sides. For this study, the road network is recognized explicitly by overlaying a roads map layer onto the base map. The roads layer consists of line features, and it is necessary to buffer the road network before overlaying in order to ensure the roads themselves appear in the raster map. A width of 50 feet is used for buffering the road network. After overlaying the roads and before rasterizing the map, an ownership and roads mask is applied to the stand to uniquely identify those stands that belong to roads or non-ownership.

In defining influence zones some specific rules were developed for dealing with small polygons. Specifically, for aquatic polygons less than one acre in size and terrestrial polygons less than .25 acres in size were assumed to have no impact on the production of interior space in any neighboring polygons.

### IspaceCap

The ISpaceCap program determines for each stand the maximum capability that the stand can have on the production of interior space in each of the periods of the planning horizon. This information is important for helping determine which management treatment options need to be considered in the scheduling model. Clearly, for stands not influencing any potential production of interior space, the optimal choice is simply the treatment option that maximizes aspatial values. The input data for IspaceCap is a complete list of influence zones, attribute information for modeled stands, and a definition of interior space and quality buffer. Table 4 provides the age definitions of interior space and quality buffer by landscape ecosystem used for this study. The ability exists within ISpaceCap to have a unique interior space and quality buffer age for each combination of forest type and landscape ecosystem; however, forest type differentiation is not used in this study.

The ISpaceCap program differentiates three different types of potential interior space for each stand for each planning period: SelfMin, SelfMax, and AdjMax. The SelfMin interior space measure is based solely on influence zones classified as a 1-way interaction. By definition, 1-way interactions exist solely within a single stand and are only influenced by that stand; therefore, the management of surrounding stands does not impact interior space production within 1-way interactions. Clearly, a stand can be managed to produce this amount of interior space regardless of how neighboring stands are managed. The SelfMax is the maximum amount of interior space the stand can produce within its borders less the SelfMin. The SelfMax is interior space that could be produced within the stand but its production still depends on the condition of other stands. The AdjMax is the maximum interior space potentially produced outside of the given analysis that depends on management of the stand. The AdjMax results are reported for each landscape ecosystem as stands in one landscape ecosystem potentially impact nearby stands that are in other landscape ecosystems. Each of these three interior space area estimates are determined by IspaceCap for each decade of the planning horizon. These values are key information to the Treatment Trimmer program.

### SubProblems

For large-scale applications, the management scheduling problem will be easiest to solve by dividing it into small subproblems. To keep subproblems of manageable size, generally one cannot assume that all subproblems are spatially independent. To overcome potential problems of not ignoring spatial interactions between subproblems, overlapping subproblems are used so that all spatial interactions are still recognized.

Three steps were used in this study for defining the subproblems. First, the major roads and large lakes were used to divide the study area into eleven subforests of roughly similar size. These breaks in the landscape subdivide the study area into subsets that are independent in terms of the potential for producing interior space. For each of these subforests the interior space interdependencies of management decisions between component stands are defined by the influence zone information. This information was analyzed for each subforest using the Subproblems program. This program tabulates all of the influence zone interactions and based on those interactions identifies as many independent subsets within each subforest as possible. These subsets are referred to as subdivisions. For each subdivision, the stands involved are analyzed spatially to determine an axis for defining the moving-windows subproblems. The intent is to define a coordinate system such the width of the subdivision is narrow so that fewer overlapping windows will be needed to move the windows across the width of the subdivision.. Key output from program Subproblems is the list of stands in each subdivision and the amount to rotate the x-y axis for defining the overlapping windows for the subdivision. This output is used by program DPform to define the overlapping windows. This step is an optimization problem in itself and will be explained briefly in the following section.

### DPform

As described above, the forest was first divided into subforests and then each subforest was divided into spatially independent subdivisions. For each subdivision, DPform defines a series of overlapping subproblems (moving windows). DPform sequentially adds more stands to each window and keeps an updated dynamic programming formulation of the problem as it builds each window. As each stand is added, an important modeling question from a modeling efficiency standpoint is: in what order should the stands be sequenced in the dynamic programming (DP) formation to help keep decision trees smaller. Hoganson and Borges (1998) describe this concern in detail. As more stands are added, DPform revaluates the sequencing of stands in the DP by considering options to swap stand locations in the sequence. Generally, stands are sequenced such that the sequence begins at one end of the window and proceeds down the length of the window. The associated size of the DP decision tree increases in size as the window becomes wider. The decision trees grow in size because the tree must create more nodes (states) for each stand (stage) because it is necessary to remember how neighboring stands are treated. Each stand must remain as a state variable until all its neighbors have been represented in the decision tree. The size of the decision trees tends to grow exponentially with the width of the window. For example, if the window is 5 stands wide and each stands has 10 treatment options, then there would likely be 100,000 ($10^5$) states throughout much of the tree, but varying some depending on the sizes and shapes of the polygons.

DPform also defines the specific overlap in the subproblems . For this study, there was generally about an 80 percent overlap between successive subproblems (moving windows). This overlap relates to the fact that for each DP formulation solved, a portion of the solution is accepted as the scheduled solution. The portion accepted is for that portion of the window that is along the outside edge length of the window. The "outside" of the window is that part of the window that is farthest from that portion of the forest (subdivision) that has yet to be included in the window. For example, if the windows are moving from west to east, then the stands on the outside edge of the forest are those on the west edge of the windows.

A complicating factor that is dealt with in substantial detail within DPform is the irregular size and shape of most polygons. The range is size and shape is substantial, as for this study sizes there were many substands smaller than 1 acre and also many stands larger than 100 acres. With buffering of lakes and streams also used to define stands, many stands are long and slender and run at different angles with respect to the axis of the moving window.

## Integrated Spatial & Aspatial Components

### Treatment Trimmer

The purpose of the Treatment Trimmer program is to simplify the problem formulation used to modeling interior space production while maintaining optimality characteristics of the system. The Treatment Trimmer program is responsible for translating the Model II treatment options from the Treatment Linker into a Model I structure and eliminating (trimming out) those treatments that are clearly not optimal for the problem formulation. The Treatment Trimmer uses data from the ISpaceCap, Treatment Linker, and Dualplan programs. The results from Treatment Trimmer are used by DPspace to select a management schedule for the forest while considering explicitly the value of interior space.

The modeling uses dynamic programming as a solution technique. Dynamic programming has the benefit of being an optimization technique and generally substantially more efficient than linear programming, thus making larger problem formulations feasible in practice. But problem size can still be a concern with the technique suffering from what is commonly referred to as "the curse of dimensionality." The application of dynamic programming to adjacency constraints (Hoganson and Borges 1998) and interior space production (Bergmann 1999) has demonstrated the potential of the technique in solving spatial management problems; however, dynamic programming is untested for spatial problems of the size considered in this study. One way of potentially reducing problem size substantially is to reduce the number of treatment options considered for each stand. The decision tree nodes at any one point in the DP decision tree enumerate all combinations of decision combinations for a set of stands with interdependent decisions. For example, if 5 stands are involved and each stand has 10 potential treatment options then there would be $10^5$ or 100,000 nodes. Reducing the number per stand by 20 percent (10 to 8) would reduce the number of nodes to 32,768 ($8^5$), an almost 70 percent reduction. Treatment Trimmer analyzes the list of treatment options for each stand to see if there are options that are clearly one that are suboptimal for the problem.

The input to Treatment Trimmer consists of the Model II treatment options from the Treatment Linker, the maximum interior space data from ISpaceCap, and a set of shadow prices from Dualplan to value aspatial product flows. In addition to the aforementioned data, Treatment Trimmer requires a definition of interior space and a set of interior space prices. An explanation of interior space definitions is found in the previous section describing ISpaceCap. The main output from Treatment Trimmer is a list of trimmed Model I treatment options that is subsequently used by DPspace for each modeled polygon.

A flowchart diagram helps to describe the process used by Treatment Trimmer (Figure 6). The process described in the flow chart involves a series of independent steps to facilitate the explanation of the logical tests; however, the implementation of the process in computer code does not have such a degree of separation and never needs to enumerate the typical large number of potential model I treatment options for each polygon.

The first step in the Treatment Trimmer program involves finding the treatment option for the stand that has the greatest NPVself. NPVself represents the sum of aspatial and spatial values that result from managing the stand using that treatment, ignoring additional interior space production that could result by better coordinating management decisions with neighboring stands. This value is guaranteed because the spatial contribution for this estimate comes from just the stand itself. For each stand treatment option NPVself is simply the sum of two terms, NPVsptMin and NPVaspt. The estimate for NPVsptMin uses the assumed interior space prices and the SelfMin area estimate determined by the IspaceCap component of the modeling system (a description of SelfMin, is found in the previous section on ISpaceCap). NPVaspt is the NPV of all aspatial benefits derived from managing the stand according to this option. This aspatial value is the estimate of the treatment option based on the results of the Dualplan model. It incorporates all of the cost estimates from Dualplan associated with aspatial constraints such as constraints for even-flow or constraints defining targeted age class distributions. After NPVself has been determined for all treatment options, the highest NPVself over all options is stored as NPVlbnd. This value is a lower bound on the value for the stand expressed. Regardless of the management of surrounding stands, the stand can at least be managed to achieve this value. Any treatment option that cannot possible achieve this value need not be considered in the spatial analysis.

The second stage of the trimming process re-estimates the value all of the treatment options for the stand, but this time does so assuming that all other neighboring stands will be managed to help maximize any interior space production that is associated with the stand. For this stage of the trimming process, all potential interior space production in areas outside the stand that are influenced by the stand are credited to the treatment option. Although this is likely an overly optimistic estimate of the treatment option's value, it is done to give the treatment option the benefit of the doubt so as not to potentially underestimate it and then trim (remove) it from further consideration when it fact it could possibly be optimal. In Figure 6 this estimate of the stand treatment option that also includes potential benefits in other stands is labeled NPVother. If this value is still less than the greatest NPVlbnd estimate for the stand then this treatment option can be discarded from further consideration because the treatment option associated with the maximum NPVlbnd would clearly be a better choice.

The third stage of the trimming process involves a concept referred to here as spatial dominance. Spatial dominance involves the situation where the series of spatial benefits from one treatment option completely meets or surpasses the series of spatial benefits from another treatment option. A simplified example is where Treatment option A produces interior space only in decade 5 of the planning horizon while Treatment option B produces interior space in decade 5 and decade 6. In this example, Treatment option B is spatially dominant over Treatment option A because Treatment option B produces interior space in at least the same decades Treatment option A does. It is impossible for Treatment option A to produce a higher spatial value than Treatment option B because any spatial value derived from Treatment option A is also derived from Treatment option B. The series of spatial benefits over the planning horizon is classified as a series (vector) of spatial conditions represented by what is labeled the ISeries vector in Figure 6. The ISeries vector simply flags whether or not a stand is in an interior space condition for each period of the planning horizon.

For the third stage of the trimming process, only treatment options that passed the test of stage two of the trimming process are considered. For each treatment option, the ISeries corresponding to the interior space definition and vegetation conditions of the current treatment option is calculated along with NPVaspt. The ISeries of the current treatment option is compared against the ISeries of all stored treatment options. If the current ISeries spatially dominates any stored ISeries, then the values of NPVaspt are compared. If the current NPVaspt is greater than the stored NPVaspt, then the stored treatment option is discarded and the process continues until all treatment options have been checked against each other. A treatment option can be discarded if both its ISeries and NPVaspt is dominated because DPspace will never chose it because another treatment option for that stand exists that is guaranteed to produce higher spatial and aspatial values.

**DPspace**

DPspace solves the dynamic programming formulations for each of the moving windows as formulated by DPform for each of the overlapping subproblems. Input from Treatment Trimmer lists the set of management treatment options to consider for each polygon. Shadow price estimates from Dualplan for the aspatial forest-wide constraints are used in valuing stand-level treatment options to account for stand level impacts on the forest-wide constraints. The size of the DP formulation in DPspace varies from that estimated by DPform because of the variation in number of treatment options considered for each stand. Interior space values are incorporated into the formulation by first identifying which stand in each influence zone is addressed last in the DP decision tree. At that point, interior space values are incorporated into the process of valuing each arc of the decision tree. These values vary by arc depending on the stand level treatments associated with the arc and its position in the decision tree. Options can be evaluated because the decision trees are designed by DPform with the recognition that the decision tree must be structured such that it can identify the decisions implied for stands with interrelated decisions as described by the influence zone definitions. It is the need to track those interrelationships that can potentially make the decision large.

Figure 7 illustrates an example of a portion of a DP decision tree using a simple 8-stand rectangular forest where stands are all the same size and shape and each stand is assumed to have just two treatment options, option a and option b. The portion of the DP decision tree shown in Figure 7 represents the decision for stand 6. Decisions for lower numbered stands are addressed earlier in the network and decisions for higher numbered stands are addressed later in the network. At this stage where the decision is addressed for stand 6, the beginning nodes all show the conditions for stands 3, 4, and 5 because stand 6 is next to all three of those stands with management decisions potentially interdependent. The status for any influence zone involving stand 6 and any combination of stands 3, 4 or 5 could be evaluated for any arc because each arc has an implied management decision about the treatment option associated with all of those stands. The decision tree also represents all combinations of decisions for those stands so that all options will be considered. For the ending nodes in Figure 7 the status for stand 3 and stand 4 are no longer explicitly identified because those stands do not neighbor stand 7 or stand 8, the two remaining stands to be addressed in later stages of the decision tree.

Addressing the production of interior space in the DP network is complicated by the assumption that the buffer area surrounding interior space may not need to meet the required age of interior space to provide adequate buffering for the portions of the influence zone that are in other stands and do meet interior space age requirements. In effect, this means that each subcomponent of each influence zone (subcomponents defined in terms of the parent stand in which the it resides) must be examined separately. For all stands making up the influence zone, its portion of the influence zone will produce interior space if the stand meets the age requirements of interior space and all other stands in the influence zone meet the minimum buffer age requirements. When addressing each influence zone in the DP network, these checks must be made for all subcomponent portions of the influence zone. It is not simply an all or none answer as to whether an influence zone produces interior space each period. Recognizing that the number of influence zones in a forest is generally substantially larger than the number of stands, this adds substantially to the overall computation requirements. In terms of the DP decision tree, the calculations are still all associated with each arc where the influence zone is addressed.

Once each decision tree is analyzed for a moving window, DPspace traces back through the through the decision tree to identify the optimal treatment option for each polygon. This is a straightforward process but complicated a bit by the size of most problems. For most formulations this requires storing node information on disk and then tracking back via disk to identify the optimal schedule. Once the optimal solution is identified for a given moving window, DPspace accepts the schedule for that portion of the window that is not to be included in the next moving window. Window overlap between the subproblems helps overcome potential problems associated with recognizing spatial interactions that would result if one tried to divide the forest into many subproblems without recognizing the spatial interdependencies that cross subproblem boundaries.

### Dualscape

Dualscape is a model component currently under development. It integrates the spatial features of DPspace with the forest-wide constraint capabilities of Dualplan. DPspace currently uses prices to value interior space and shadow prices from Dualplan to value aspatial forest condition targets and timber flows. With Dualscape, the intent is to offer the ability to set target flow constraints for interior space production and to also adjust the DPspace solution to also achieve the aspatial forest-wide constraints used in DualPlan. With constraints on interior space production, shadow prices will be used to value interior space with these prices determined in an iterative manner much like that used by

Dualplan for forest-wide aspatial constraints. In other words, DPspace will be used iteratively to search for appropriate shadow prices. Similarly this search for shadow price estimates will also re-estimate shadow prices for aspatial forest-wide constraints, taking into account the impact that spatial objectives have on forest-wide aspatial constraints. Feedback in an iterative manner will also be needed with the Treatment Trimmer component, as the results of trimming treatment options depending on the shadow prices assumed. In other words, as shadow price estimates change, repeated runs of the treatment trimmer will be needed to help assure that good treatment options are not lost. This aspect of the problem will unlikely be needed in every iteration of the shadow price search process because small changes in shadow prices are unlikely to cause large errors in the treatment trimmer process.

Developing and applying Dualscape is beyond the scope of this study. But the iterative process to be automated can be applied in a general sense manually using the existing system components. It would be unrealistic to think that manual applications could be repeated enough times to address many constraints or to satisfy even just a few forest-wide constraints precisely. Nonetheless, much can likely be learned about the general forest situation without forcing a model to achieve constraints exactly. Many would agree that most of the forest-wide constraints modeled in forestry are not hard constraints that must be met precisely, especially when considered in a broad and strategic forest-wide planning perspective. Certainly one would expect some interactions between aspatial and spatial objectives. For example, if we take a solution to an aspatial simplification of the problem as done in this study and then recognize additional spatial values for old forest like is done with DPspace we would expect that harvest levels will no longer remain constant over time. Solutions can still likely be enlightening adding insight about options for better addressing spatial objectives in forest planning. Generally much can likely be learned just by using assumed values for the different outputs and then comparing results for a number of model runs that vary these values.

## Results of Test Cases

This section highlights some of the key results of the three test cases. For each of the three test cases, several scenarios were analyzed with each based on a different value assumed for acres of old forest interior space. More scenarios were developed for the largest test case, the case that modeled both federal and state lands at the same time to explore potential opportunities to coordinate management for the production of old forest interior space. This case is referred to as the "Both" or "combined" case. For the "Both" case, interior space prices considered were $0, $100, $300, $500, $700 and $1000 per acre per decade. These values were assumed to occur at the end of each decade with discounting used to translate all value flows to a net present value. Interior space values of $0, $100, $500 and $1000 per acre per decade were used for the "Federal only" and "State only" test cases.

Although the overall results of the scheduling model is a primary interest, success of the system for practical application depends on the results of each component of the overall system. Some of those intermediate results also offer important insight about the test cases. An overview of those results is presented first, generally in the order that they were developed in the analysis process.

### Influence Zones

Table 5 lists the total area in influence zones by subforest for each test case assuming a 150-ft buffer for interior space. Table 6 lists the same information for a 300-ft buffer. Areas of the forest that are not in an influence zone are not capable of producing interior space. From these two tables it is clear that most of the eleven subforests involve both state and federal ownerships capable of producing old forest interior space. The column labeled "State + Fed" is simply the sum of the area of influences zones for the two cases where these two ownerships were modeled separately. It is interesting to compare this column with the column labeled "Both." The "Both" case combines the two ownerships for analysis and thus considers explicitly the interdependencies between stand management decisions for the different ownership. The difference between the values in these two columns represents the maximum potential area of interior space gain that could be obtained from coordinating management across ownerships.

Table 7 and Table 8 provide influence zone information for each test case. Each influence zone is classified in terms of a numeric interaction type – the number represents the number of stands interacting to define the zone. For example, an interaction type of 3 represents influence zones that are each impacted by the management decisions for three stands. This impact is in terms of the requirements for the influence zone area to produce interior space. For the test cases the highest degree of interaction for a 150-ft buffer is 14-way interaction. The combined and federal test cases have 28-way interactions for a 300-ft buffer and the state case has a maximum 27-way interaction. With a 150 ft buffer less than 1% of the total influence zone area is in influence zones involving more than 7 stands. With a 300 ft buffer this percentage increases to about 9 percent with less than one percent of the influence zone area involving more than 12-way interactions. Influence zone areas that involve more interactions typically are located in or near riparian areas where small substands are recognized to consider riparian buffers.

For the study area, a total of approximately 192,000 acres of state forest land was modeled. The total for Federal lands for the study area was approximately 555,000 acres. Comparing these totals with the totals in Table 7 and Table 8 one can see that approximately 62% of the forest land for the "Both" case can produce interior space assuming a 150-ft buffer is used for interior space. Only about 40% of the forest can produce it if a 300-ft buffer is used.

Much can be learned just from the influence zone summary information about the potential gains from coordinating management to produce interior space. With a 150-foot buffer, Table 7 shows that the potential area for producing interior spaces increases from 449,600 acres to 464,200 when it is assumed that management of the two ownerships can be coordinated. The gain is only about 3.2% of the total area. With a 300 foot buffer for interior space this area increase is approximately 6.6%. For this specific study with the MN DNR and USDA Forest Service lands, ownership fragmentation between each other is small compared to other factors: private ownership, roads, lakes, and vegetation conditions. Although the benefit of coordination appears to improve with larger buffer distances, the total amount of land available for producing interior space (modeled acres) drops by approximately 150,000 acres as seen by comparing Table 7 and Table 8.

Table 7 and Table 8 also help show the enormous amount of detail that was modeled in this study. With a 150 foot buffer, there are almost 240,000 influence zones that were addressed individually in the scheduling model. Not only that, but to recognize the concept of different buffer age requirements than the actual age requirements for interior space, each stand subcomponent of each influence zone must be addressed separately when each influence zone is addressed in the scheduling model. The size of the scheduling model formulations used in this study was exceptionally large because of the detail recognized.

## Overlapping Moving-Windows Subproblems

For each of the three test cases, the SubProblems model and the DPform model were used to define the moving windows subproblems. In this process DPform was applied twice to develop two sets of formulations that use different sizes of the overlapping subproblems (windows). Both applications for each test case assumed that each stand would have 10 unique treatment options. The number of treatment options will vary by stand, and those numbers will depend on the prices assumed for interior space production. A key was identifying a simple process that could work well across various interior space price assumptions. With this assumption overlapping subproblems were limited in size in terms of the maximum number of decision tree nodes at any one stage (column) in the decision tree. There is one stage in the decision tree for each stand in the moving window. One application used 10,000 nodes per stage as the limit and the other used one million nodes per stage. With the "10 treatment options per stand assumption," this resulted in one application with overlapping windows no more than 4 stands wide and another with windows no more than 6 stands wide.

A summary of the moving windows for each test case shows the large size of the overall problem and the extent to which it was subdivided for each of the three test cases (Table 9). Of interest is the number of independent subdivisions for each of the test cases. Each subdivision is possible because it can be separated from the rest of the forest as independent in terms of any stands that have interacting management with the rest of the forest in terms of the potential to impact the production of interior space.   The almost twice as many subdivisions for the “Federal only” test case (920 subdivisions) than the “State only” test case (497 subdivisions) reflects the dominance of Federal lands over the overall study area.  It is interesting and perhaps not surprising that when the two ownerships are combined, there are fewer subdivisions for the combined case (861 subdivisions) than with “Federal only case.” This reflects the fact that State lands tend to fill in the patches and make for larger blocks of interdependent stand management decisions.  However, it is of interest how for some subforests the number of subdivisions for the combined case is larger than that for the Federal only case.  In these subforests there are some larger blocks with relatively few acres of Federal lands.

As one would expect, using larger moving window sizes results in fewer windows (subproblems). Using larger windows results in much larger dynamic programming decision trees.   Generally the 100-fold increase in the decision tree size limit reduced the number of windows by only a factor of two.  It should not be surprising that using these larger windows resulted in substantially larger computation times.  In general, computer computation time was not an issue in determining the subproblems or formulating the windows.  Once developed these windows were used for each of the scenarios that varied in terms of assumed interior space prices.

## Trimming treatment options

The results from the Treatment Trimmer indicate that enormous gains can be achieved in simplifying model formulations without causing a loss in terms of the optimality characteristics of the model formulation.  Treatment Trimmer is a critical component of the modeling system as many potential management treatment options are generally plausible for most stands.   The goal of the Treatment Trimmer is to enumerate and trim the number of Model I treatment options so that the DPspace program does not need to consider stand-level treatment options that are clearly suboptimal.  Table 10 summarizes the results from applying Treatment Trimmer for the “Both” case with a 150-foot buffer. It lists both the total number of treatment options and average number of treatment options per stand (polygon) for different assumed values for old-forest interior space.  For many stands, the number of possible Model I treatment options considered in the aspatial model (Dualplan) totaled in the hundreds if not thousands.  So many treatment options were possible because treatment options are defined by the combination of treatment type, rotation age and regeneration option for multiple rotations.  For most stands,  at least some type of site conversion was considered.  Site conversion options increase greatly the number of unique treatment options.  Table 11 groups stands by the number of treatment options that were still necessary to consider after applying Treatment Trimmer for the “Both” case with a 150-foot buffer for the different interior space prices used.

The average number of treatment options per stand increases roughly logarithmically with increases in the price of interior space.  This outcome strongly supports the use of spatial dominance in trimming treatment options for each stand..  As the price of interior space increases, the best aspatial treatment has less on an impact on trimming because the benefits of managing spatially begin to outweigh aspatial benefits.  With higher interior space prices, highly suboptimal aspatial treatment options are show enough upside potential to merit their consideration.  However, spatial dominance considerations contribute to dropping some of these options, keeping the average number of modeled treatment options from rising to an unmanageable level.  Another contributing factor relates to influence zones. Due to a variety of factors, stands have varying potential to produce interior space.  For stands with little to no potential to produce interior space, increasing interior space price has little effect on their average number of modeled treatment options. This explanation is supported by the results of Table 11. As the price of interior space increases, the variation in the number of modeled treatment options per stand increases with a large group of stands still trimmed to a single modeled treatment option.

The distribution of the number of modeled treatment options per stand illustrates a remaining challenge with modeling interior space production with dynamic programming. Although the average is slow to increase, a non-trivial number of stands have twenty or more treatment options that are potentially optimal. Even with a completely random spatial distribution of stands having twenty or more modeled treatment options, there are chances that enough of these stands will be ones that interact directly with each other. When this occurs, a small portion of the dynamic programming network can become quite large. For example, if decisions for seven stands all interact directly and each has twenty treatment options, then to address all seven in a single DP formulation requires at least one stage of the DP network with 64 million nodes.

## Trade-offs: Timber Production & Interior Space

For each of the three cases, multiple model runs of DPspace were performed where the only model parameter varied between runs was the price of interior space. Each run still required a separate run of the Treatment Trimmer model to select the set of management treatment options to consider for each stand based on the assumed value for interior space. All model runs used overlapping windows that generally kept the number of nodes in the dynamic programming decision tree less than 10,000 at any one stage (column) of the tree. The impact of this simplification was tested by also using larger windows for several of the test cases where up to one million nodes were allowed per stage. This was a guide on window size and not an absolute limit with the moving windows formulation process not considering the specific number of alternatives for each polygon. Using the larger windows, very little gain was found in the net present value of the optimal solution, thus supporting the hypothesis that the solutions found with the smaller windows are near-optimal solutions. All model runs were performed on a Dell 530 Precision workstation with a 1.4 GHz processor. Run times varied from approximately 7 minutes for the test cases considering only DNR lands to almost 1 hour for test cases considering both State and Federal lands.

In presenting results on timber production and interior space trade-offs, focus is on the test case that considered both Federal and State lands. More scenarios (interior space prices) were modeled for that test case, giving more information about tradeoffs. For each of the two individual ownership scenarios results, in general, parallel those of the combined ownerships or “Both” test case. Unless otherwise specified, results in this section refer to the test case that considers both ownerships.

With this study valuing only older forest interior space, it should not be surprising that higher values for interior space results in management schedules that produce less timber in most all planning periods (Figure 8). Of interest is how the impact on harvest levels tends to be cyclical with the greatest impacts in earlier periods. Generally, recognizing interior space value impacts stand-level management in one of four ways: (1) no impact on harvest timings or type, (2) rotation lengths are lengthened, (3) management shifts from even-aged management to uneven-aged management, or (4) old forest interior space values dominate making harvesting undesirable. Greater impacts on harvest levels in earlier periods are fairly easy to explain. Harvest levels in decade 1 drop because some stands otherwise harvested in decade 1 are shifting to either longer rotations or to uneven-aged management. Net harvest levels in later decades are generally not impacted as much as earlier decades because some of the shifts in harvest timings for stands otherwise cut in early decades are shifting harvests into later decades. The overall decline in harvest levels for the planning horizon is explained by the fact that some timber stands are more valuable to hold harvest because of their interior space values. The cycle in harvest levels over time is a direct result of the large portion of aspen in the study area. With less regeneration harvesting of aspen in the first decade, less is available to harvest in the second rotation. Figure 8 shows about a 50-year cycle in harvest levels as interior space prices are increased, and this cycle corresponds with the predominant rotation length for aspen.

Interior space production levels are summarized for each of the seven landscape ecosystems in Figure 9 thru Figure 15 for the "Both" test case over a wide range of interior space prices. Interior space production levels associated with $0 per acre per decade price show the results from planning as if interior space production is not considered. Without recognizing interior space values, interior space production does not decline over the long-term for any of the landscape ecosystems. For most, there is at least a small increase by the end of the planning horizon. This result can be explained by several factors. First, the harvest levels modeled are sustainable over time; if no harvesting was modeled for the forest, then interior space levels would increase over time. Second, some areas of the study area are at least somewhat limited in terms of harvesting options assumed available. For example, riparian areas cannot use harvesting options that set the overstory age back to age zero.

With no interior space production values recognized (value $0/acre in Figure 9 thru Figure 15) there are still some periods in the shorter term where interior space production drops below interior production levels at the start of the planning horizon (period 0) levels. These drops are likely a result of the age imbalance of the forest with average rotation ages likely dropping temporarily for the first 20 to 40 years.

As expected, the higher the value assumed for interior space, the greater the amount of interior space produced. Of interest is how interior space production changes over time, how its production varies by landscape ecosystem and how responsive production levels are to changes in assumed interior space values. Several general trends in all of these graphs are important to note. First, it takes time for interior space production to increase in response to recognizing a higher but constant value for interior space over time. With high interior space values this lagged response is most pronounced. For all landscape ecosystems it takes at least several decades for interior space production levels to rise to what might appear to be a more constant level closer to what might be a longer-term steady state for the assumed interior space value. In general, this reflects the time required to create interior space and the fact that interior space production has not been valued in the this area in the past. This second fact is evident from the much lower interior space production levels for period 0, the start of the planning horizon (Figure 9 thru Figure 15). Basically, options are much more limited for increasing old forest interior space in the short term. This thus suggests that managers may need to exercise caution before destroying what options are available for producing more old forest interior space in the short term. Longer term, by planning ahead, higher levels can be produced without perhaps the need to assume as high of interior space values for the long term as might be needed for the short term to keep short term levels to a desirable level.

From the general trends observed above it is clear that a simple management guide like cut today in large blocks is oversimplified and potentially detrimental to short-term production of interior space. Harvesting today in large blocks potentially helps for long-term production, but it reduces the potential to produce interior space in the short term by harvesting large blocks that could produce interior space in the shorter term. For the long term, interior space can likely be produced effectively without the need to harvest today in large blocks.

Differences in interior space production by landscape ecosystem are interesting to note but difficult to explain in great detail. Generalizations are difficult because each landscape ecosystem is complex with a real mix of forest cover types involved. Results are also somewhat confounded by the natural succession that is also occurring. Succession was modeled in this study as assumed by the USDA Forest Service for their ongoing planning process. Succession rules vary by landscape ecosystem both in terms of specific forest type changes and the reduction in the age of the overstory when the succession is assumed to occur. Interior space production from a landscape ecosystem tends to show less of a change with high interior space prices if it currently contains relatively more older stands or relatively more stands in forest cover types with longer rotation lengths or relatively more acres in forest cover types suitable for uneven-aged management. These landscape ecosystems are already (period 0) producing relatively more interior space, and interior space prices need not be as large to shift more of these acres to schedules more conducive to interior space production. The mesic northern hardwoods (Figure 12) and the tamarack lowlands (Figure 15) are examples of these landscape ecosystems. In the mesic northern hardwoods ecosystem (Figure 12) large increases in interior space production are realized with only a $100/acre decade price assumed for interior space. In contrast the dry mesic pine landscape ecosystem (Figure 11) shows a large response to valuing interior space with much of the response not happening until interior space prices are raised to the higher interior space price levels considered. This landscape ecosystem has a greater percentage of stands with more valuable timber species, thus explaining why higher interior space values are needed to move more acres to schedules that produce interior space.

Also of interest is the reduction in net present value of timber production with the increasing value of interior space for each of the three test cases (Figure 16). Perhaps not surprising is the relatively low cost associated with the $100 per acre per decade interior space value and the relatively high cost associated with the $1000 per acre value. It is also interesting to see how these losses compare to overall aspatial value of the forest as measured by the model results (Figure 17). Of interest is the much higher average values for the Federal lands compared to the State lands. Figure 17 also suggests that the relative losses in aspatial value may not be all that large. However it is important to realize that these losses apply for the entire area modeled. For example, a $1 per acre loss for the “combined” test case translates to approximate a $750,000 loss in absolute terms. Clearly there is much at stake and real opportunities for improving solutions through modeling.

Results show clearly that there are substantial trade-offs between timber production and old forest interior space production. Obviously, there is subjective value judgment involved in selecting a balance for implementation. It is likely unrealistic that all interest groups could agree on the best choice. The learning tools demonstrated here can help for better understanding the trade-offs involved and the management schedules appropriate for the different value assumptions. There are likely real opportunity costs if inefficient strategies are undertaken.

## Gains from Coordination Across Ownerships

Three test cases were use in this study so that insight could be gained about the potential gains from better coordinating management across ownerships. Of interest is comparing the results from coordinated planning test case with the sum of outcomes from the other two cases involving the same study area where planning was done separately for state and federal lands. Results show clearly that for the problem as it was defined, the real gains from landscape planning are not dependent on the combined analysis. By far most of the site-level spatial interactions are a due to spatial interactions involving stands of the same public ownership.

A comparison of harvest levels for the combined and separate analyses shows very little differences in outcome over the entire planning horizon for the four price levels compared (Figure 18). As one would expect, with an interior space price of $0 per acre per decade the results should be the same as there is no value assumed in coordinating any areas to produce interior space. The fact the model results found identical solutions helped verify that the model was working correctly. The similarity in results across all price levels is perhaps more of a surprise (Figure 18) considering the mixed ownership appearance of the study area as illustrated in Figure 1. A comparison of interior space production across test cases for each price assumption also shows very similar results. For example, little differences are found in the interior space production levels over time for the dry mesic pine oak (Figure 19), boreal hardwood conifer (Figure 20) and tamarack lowlands ecosystems (Figure 21). Comparisons of these ecosystems show clearly that state lands to be much more prevalent in the lowland landscape ecosystems.

The degree of site-specific spatial interactions across ownerships is perhaps fairly misleading from looking at a large-scale map of ownership patterns (Figure 1). An understanding of the site-specific interactions is best understood by looking carefully at the specific spatial interactions as identified by the influence zones data layer developed for the analyses. A summary of the influence zones shows that only about 3 percent of the total area in influence zones involves stands of both federal and state ownership (Table 7). This amounts to less than 15,000 acres of the approximately 464,000 capable of producing interior space. Also, approximately 35 percent of the area capable of producing interior space (164,000 acres) is in influence zones involve only 1 stand. Influence zones with just one stand are modeled the same in both separate and combined analyses, and because they are areas not influenced by other stands, they tend to be areas more conducive to interior space production.

## Patch Sizes

Of interest is the tendency of the DPspace model to aggregate interior space production in blocks, thus producing larger older forest patches on the landscape. MFRC staff was instrumental in helping analyze patch size characteristics of solutions. Results are easy to link with GIS systems yet there are numerous spatial details that could be examined in each of the different planning periods. High interior space prices clearly lead to more forest area in larger forest patches by the end of the planning horizon (Figure 22). Clearly, with high interior space prices the model moves large areas into large patches. Such a trend is not as obvious between the $0 per acre per decade price and the $100 per acre per decade price at the end of the planning horizon (Figure 22). This is likely explained by the dynamics of the situation associated with trade-offs and cycles over time in terms of interior space production.   For example, with a $100/acre/decade price for interior space, much of the older forest is held to longer rotations to produce more interior space in earlier decades.  Later some of these stands are harvested leaving a younger forest in later decades than the $0 price where more stands are harvested earlier.  With higher interior space prices, interior space production becomes more of an overriding objective for more stands, thus explaining the increase in old forest patch sizes for the last decade with high prices.

## Discussion

Spatial aspects of the modeling situation certainly complicate the forest management situation. The situation is quite dynamic with more expected from the forest than ever before. More is constantly being learned about additional spatial facets that are important for environmental objectives. Increasing populations with increasing per capita consumption will likely increase timber demands over time. Higher timber prices make many new silvicultural treatment options potentially affordable and worth considering. Results from this study certainly suggest that there is potentially much at stake. Study results suggest potentially substantial reductions in timber production if substantial increases in old forest interior space are desired. Interior space production is also quite complicated as it involves many interdependent decisions. To manage effectively it is important to understand these interdependencies and address them in the decision-making process. Unfortunately, this is a huge challenge facing forest managers today.

This study showed how potential areas for producing interior space can be identified as influence zones with each influence zone identified by a unique combination of stands that influence that area. In total, the number of influence zones substantially outnumbered the large number of stands recognized in the study area. One would almost certainly expect that this would be the case for most forests.

Models can play a key role in helping forest management organizations explore potential management strategies and understand trade-offs associated with general management policies. Management scheduling models can also likely help guide specific site-level management schedules. Plans from the past did not focus on interior space production so it is not surprising that forests today are not necessarily capable of achieving these objectives in the short term. It takes time to achieve these conditions. Furthermore, areas capable of producing substantial areas of older forest interior space in the shorter term could easily lose much of that potential fairly rapidly without careful planning of current harvests. Simple management guides like “cut oldest stands first” or “cut in large blocks” are unlikely good management strategies. With good planning and planning ahead, it is likely that the costs of achieving desirable spatial conditions need not be a major issue in the long-term.

It was not within the scope of this study to explore a wide range of definitions of interior space. Clearly, the appropriate definition depends on the specific spatial concern. The modeling approach could almost certainly be expanded to consider multiple types of interior space for each landscape ecosystem. Multiple types could be used fairly easily to consider multiple buffer widths and various age requirements for its production. Probably the biggest difficulty in this enhancement relates to the potential of trimming management options so that one can be confident that potentially good management strategies are not lost for specific stands. Silvicultural options to convert or restore cover types are generally important and such considerations can greatly expand the number of treatment options per stand. If these considerations become more spatial in nature with interior space definitions dependent on specific forest cover types, then the treatment trimming process will become substantially more complicated. It will be simpler if forest cover type objectives can be treated primarily as aspatial targets that could vary by landscape ecosystem. There is also a concern about whether old forest objectives should be considered aspatially or primarily as a component of spatial management objectives.

As described earlier, the plan is to integrate DPspace and Dualplan in a model currently referred to as Dualscape. This modeling system will be complicated in that multiple iterations of the DPspace model will be needed to help search for appropriate shadow price values for the forest-wide constraints. For example, the Dualplan formulation used constraints that forced timber harvest levels to be within even-flow guidelines. Because the study area has an imbalanced age distribution with more older stands, Dualplan shadow prices for timber production penalized harvesting in the first decade to help balance harvest volumes over time. Recognizing interior space values in DPspace shifted harvests to later periods and thus reduced harvesting in early decades. This result suggests that the Dualplan penalties are too large for harvesting in early decades if interior space values are also considered. The intent with Dualscape would be to better integrate the aspatial constraints with the spatial objectives by refining the estimates of the shadow prices for the aspatial constraints. Once found, these re-estimates would essentially smooth out the periodic variation in the harvest volumes over time. Impacts of valuing interior space would thus not have much of an immediate impact in the early decades as suggested by the harvest levels shown in Figure 8. More harvesting would be scheduled for the earlier decades. This, in turn, may lower interior space production levels for early periods and perhaps suggest using higher interior space values for earlier periods.

Dualscape model applications could require substantial computation time if many iterations of the shadow price re-estimation process are needed. Results of this study suggest some improvements that might be helpful in this process. First, much of the computer power used in this study involved in solving much larger DP formulations than were estimated in the model formulation process. Specifically, in the formulation process it was assumed that all stands would have ten treatment options. Although ten options is well above the average that was achieved using the Treatment Trimmer component, with so many polygons involved it is not surprising that there were areas where there were many neighboring polygons that substantially exceeded this average. For example, in the DP formulations that assumed an approximate size of 10,000 nodes ($10^4$) per stand, this number becomes almost 400,000 in areas where the window is four stands wide with 25 treatment options per stand ($25^4$). Within DPform, it is relatively easy to overcome this problem by recognizing the specific number of options per polygon. Size limits of DP networks could thus be better controlled if the results of the Treatment Trimmer were linked directly with DPform. Initially this linkage was not developed as it was assumed that it would not be desirable to rerun the formulation model any more than necessary. There is likely some balance needed in this strategy for use with Dualscape. Rerunning of DPform is likely necessary only after the number of treatment options has changed substantially for a substantial number of polygons,

Another option in developing Dualscape relates to the size of the moving windows to use. It is likely that quite small window sizes could be used in early iterations of the process. These iterations are done only to help estimate the values of the forest-wide shadow prices. Early applications of the moving windows process for the adjacency constraint problem found that even window widths two stands wide could consistently outperform other heuristic techniques (Hoganson and Borges 1998). This will be a relatively easy option to test now that large test cases have been developed.

It is also important to understand some of the potential limitations about the model as it has been developed to date and some of the potential problems these could cause in future applications:

1) Forest management scheduling models are data intensive with success of applications dependent on providing the model with a set of potentially good management treatment options for the individual stands. Some pre-analysis work is likely needed to reduce the number of treatment options considered in the model for each stand. Although this pre-analysis worked well for this study, it may be more difficult when additional spatial measures are also valued or constrained. Heuristic rules for reducing treatment option may then be needed with some concern about potential loss in optimality.

2) In modeling interior space, many stand-level decisions become quite interdependent. Substantial data prep work is needed to identify interdependencies. This process would likely benefit from more work. Developing influence zone data was one of the most difficult steps of this study. Computation time involved overnight runs for each of the eleven subforests. The methods used focused on developing very precise estimates of each influence zone area. Such estimates likely exceed the precision of the data as the estimation process uses a rasterization process that reduces the precision in stand boundaries and the related spatial interdependencies. A weakness also identified related to the accuracy of the GIS data layer itself. In merging the State and Federal GIS databases some very small "non ownership" polygons resulted that are simply locations where stand boundary information did not match precisely for the two data sets. In the modeling process some of these "non ownership" polygons were buffered outward, reducing the potential area for interior space by a small amount. In the future, it would seem appropriate to set a minimum size limit for "non ownership" polygons to be buffered outward.

3) The model itself is fairly technical with a substantial number of components. It requires a background in forest management, basic operations research techniques, and computer systems. Its modular design may help make it easier understand and improve specific components and add new dimensions.

4) The model currently uses the same buffer distance for all types of interior space. Recognizing multiple distances will require more data pre-processing and will increase model run times. It will also complicate the pre-analysis process done to keep the number of management options at the stand level to a workable number. Wider buffers will mean more interdependent decisions with influence zones tending to involve more stands.

5) The model does not address explicitly objectives related to very large patches or specific distributions of patch sizes. Large patch objectives are addressed only by using larger buffer distances for interior space, larger interior space values, or pre-allocating some areas for large patch production by planning period.

6) The model is deterministic. It does not recognize natural disturbances. Clearly, losses from natural disturbances would have some impact on the forest-wide output levels if schedules were implemented exactly as modeled. It is erroneous to assume that the management schedules developed will be implemented precisely over the long term. It is assumed that the planning process is dynamic with schedules updated on a fairly regular basis to adjust to uncontrollable events, changing market conditions and changing values. It is assumed that schedules in the short term would need to be adjusted to integrate responses to natural disturbance events.

## Conclusions

Integrating ecological, economic and social objectives in forest management is a challenge facing decision-makers today. Models can play an important role in developing good management plans. Results from the large test cases suggest that:

1) The DPspace model, a tool for better integrating spatial objectives into forest management plans, can be applied successfully to problems involving 100,000 or more stands. Initial screenings of stand-level treatment options by the system make it possible to consider substantial detail involving a wide range and number of silvicultural treatment options. The system decomposes large problems into linked smaller problems of manageable size. This characteristic makes it likely that model enhancements can be developed to address additional spatial facets of the management situation.

2) Providing adequate older forest interior space is likely more of a short-term problem than a long-term one. Interior space levels are likely low today simply because spatial arrangement of the forest received little consideration in past forest planning efforts. In the short-term, forest conditions cannot change rapidly so focus may need to be on the more limited interior space production options for the short-term. Short-term actions have potential long-term impacts so both short term and long term impacts need to be considered simultaneously. With good planning and the lead-time associated with long-term planning, spatial conditions can be improved over the long-term.

3) Patches of older forest can be produced in a variety of ways over the long-term. Effective and efficient strategies likely involve a variety of harvest block sizes with analysis likely key for identifying good spatial and temporal strategies that fit well with existing landscape patterns. Simple management guides like "harvest today in larger patches" will increase patches of older forest for the very long term, but such guides are very simplified guide and potentially quite detrimental to short-term objectives. Such a guide would tend to destroy large patches of forest that are potentially very important for producing older forest over the short-term which might be for fifty years or more.

4) The study area has perhaps as much of an intermixed public ownership pattern as anywhere in Minnesota. Yet for the two ownerships considered, most of the area capable of providing interior space involves areas of single ownership. Assuming 150-foot buffers for interior space, over 95 percent of the study area capable of producing interior space is in blocks of single ownership. With larger buffer widths, interactions between the large public landowners increase, but even with 300 foot buffers, over 90 percent of the area capable of producing interior space is in blocks of single ownership. In effect, much can likely be gained from just good planning for each ownership. While coordination doesn't seem critical for increasing interior space as defined in the study, there are caveats to this finding. The study did not consider directly the patch sizes associated with interior space areas. From a biodiversity perspective, some very large patches of older forest interior area (500 acres +) are likely critical with ownership coordination potentially important for their production.

5) Although the model does not address directly the size of patches developed to produce older forest interior space, results showed a strong tendency to schedule interior space production in patches that are substantially larger than what is currently present on the landscape.  Smaller patches are generally more inefficient because larger proportions of them only qualify for producing buffer conditions, not interior space.  As one would expect, patches of older forest tended to be larger when larger values were assumed for interior space.

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Table 1. Influence zone summary for the five-stand example forest.

| **Zone Type** | **Influence Zone** | Area (acres) | Potential interior space area influenced by each stand (acres) Stand A | Stand B | Stand C | Stand D | Stand E |
|---|---|---|---|---|---|---|---|
| 1-way interactions | A | 17.82 | 17.82 | | | | |
| | *B* | 6.75 | | 6.75 | | | |
| | *C* | 1.57 | | | 1.57 | | |
| | *D* | 5.58 | | | | 5.58 | |
| | *E* | 63.32 | | | | | 63.32 |
| | subtotal area | 95.04 | | | | | |
| 2-way interactions | AB | 3.71 | 3.71 | 3.71 | | | |
| | *AC* | 0.10 | 0.10 | | 0.10 | | |
| | *AD* | 8.29 | 8.29 | | | 8.29 | |
| | *AE* | 4.63 | 4.63 | | | | 4.63 |
| | *BC* | 3.47 | | 3.47 | 3.47 | | |
| | *CD* | 4.04 | | | 4.04 | | 4.04 |
| | *DE* | 11.36 | | | | 11.36 | 11.36 |
| | subtotal area | 35.6 | | | | | |
| 3-way interactions | ABC | 2.01 | 2.01 | 2.01 | 2.01 | | |
| | *ACD* | 1.41 | 1.41 | | 1.41 | 1.41 | |
| | *ADE* | 2.81 | 2.81 | | | 2.81 | 2.81 |
| | subtotal area | 6.23 | | | | | |
| 4-way interactions | ABCD | 0.37 | 0.37 | 0.37 | 0.37 | 0.37 | |
| | subtotal area | 0.37 | | | | | |
| Total area | | 137.24 | 41.15 | 16.31 | 12.97 | 33.86 | 82.12 |

Table 2. Impact of stand condition on components of influence zone AD for the five-stand example forest (N/A indicates not applicable in terms of interior space production).

| Stand Condition Class | | Condition of Influence Zone Component in | |
|---|---|---|---|
| Stand A | Stand D | Stand A | Stand D |
| Open | Open | N/A | N/A |
| Open | Mature | N/A | N/A |
| Open | Old | N/A | N/A |
| Mature | Open | N/A | N/A |
| Mature | Mature | N/A | N/A |
| Mature | Old | Quality Buffer | Interior Space |
| Old | Open | N/A | N/A |
| Old | Mature | Interior Space | Quality Buffer |
| Old | Old | Interior Space | Interior Space |

Table 3. Summary of silvicultural treatment options by forest cover type (xxx's indicates feasible options).

| | Forest Cover type | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Jack Pine | Red Pine | White Pine | Spruce Fir | Oak | N. Hdwd | Aspen | Aspen -fir | Birch | Low Spruce | Tamar ack | Low Hdwd | Cedar |
| **Minimum Rotation age (years)** | 50 | 60 | 60 | 50 | 60 | 90 | 40 | 40 | 50 | 90 | 90 | NA | NA |
| **Treatment Type** | | | | | | | | | | | | | |
| 1. Clearcut with thinning | | XXX | | | | | | | | | | | |
| 2. Clearcut | XXX | XXX | | XXX | XXX | | XXX | XXX | XXX | XXX | XXX | | |
| 3. Shelterwood with thinning | | XXX | XXX | | | | | | | | | | |
| 4. Shelterwood | | XXX | XXX | | XXX | XXX | | | | | | | |
| 5. Heavy Selection Cut | XXX | | | XXX | | | XXX | XXX | XXX | XXX | XXX | | |
| 6. Uneven-aged Management | | XXX | XXX | XXX | XXX | XXX | | | | | | XXX | |
| 7. Selection Cut & plant white pine for uneven aged mgmt | | | | | | | XXX | XXX | | | | | |
| 8. Selection Cut & underplant white pine. No later harvesting | | | | | | | XXX | XXX | | | | | |
| 9. Selection Cut & underplant spruce/ fir for uneven aged mgmt | | | | | | | XXX | XXX | | | | | |
| 10. Selection Cut & underplant spruce/ fir. No later harvesting | | | | | | | XXX | XXX | | | | | |
| 11. Selection Cut & underplant hdwds for uneven aged mgmt | | | | | | | XXX | XXX | | | | | |
| 12. Selection Cut & underplant hdwds No later harvesting | | | | | | | XXX | XXX | | | | | |
| 13. No initial harvest. Underplant white pine for uneven aged mgmt. l | | | | | | | XXX | XXX | | | | | |
| 14. No initial harvest. Underplant white pine. No harvesting later. | | | | | | | XXX | XXX | | | | | |
| 15. Succeed to spruce/fir with uneven aged mgmt later | XXX | | | | | | XXX | XXX | XXX | | | | |
| 16. Succeed to hdwds with uneven aged mgmt later | | | | | | | XXX | | XXX | | | | |
| 17. No Harvesting | XXX | XXX | XXX | XXX | XXX | XXX | XXX | XXX | XXX | XXX | XXX | XXX | XXX |

Table 4. Interior space and quality buffer age requirements by Landscape Ecosystem

| Landscape Ecosystem | Quality buffer age (years) | Interior Space age (years) |
|---|---|---|
| Dry Pine | 35 | 75 |
| Dry Mesic Pine Oak | 35 | 75 |
| Dry Mesic Pine | 35 | 75 |
| Mesic Northern Hardwoods | 35 | 75 |
| Boreal Hardwood Conifer | 35 | 75 |
| White Cedar Lowlands | 55 | 75 |
| Tamarak Swamp | 20 | 55 |

Table 5. Influence zone area by subforest for 150-ft buffer for each of the three test cases.

| Subforest | Potential interior space (acres) | | | |
|---|---|---|---|---|
| | State | Fed | State + Fed | Both |
| 01 | 8 | 15,532 | 15,540 | 15,541 |
| 02 | 18,348 | 29,165 | 47,513 | 48,845 |
| 03 | 20,172 | 21,124 | 41,296 | 43,601 |
| 04 | 21,384 | 34,089 | 55,473 | 57,632 |
| 05 | 16,773 | 33,823 | 50,596 | 51,992 |
| 06 | 2,996 | 24,064 | 27,060 | 27,600 |
| 07 | 9,891 | 41,522 | 51,413 | 53,551 |
| 08 | 12,980 | 35,191 | 48,171 | 49,559 |
| 09 | 19,602 | 34,186 | 53,788 | 56,116 |
| 10 | 1,206 | 10,864 | 12,070 | 12,183 |
| 11 | 5,458 | 41,237 | 46,695 | 47,616 |
| All | 128,818 | 320,797 | 449,615 | 464,236 |

Table 6. Influence zone area by subforest for a 300-ft buffer for each of the three test cases

| | Potential interior space (acres) | | | |
|---|---|---|---|---|
| Subforest | State | Fed | State + Fed | Both |
| 01 | 0 | 8,523 | 8,523 | 8,523 |
| 02 | 13,134 | 17,087 | 30,221 | 31,827 |
| 03 | 14,318 | 12,450 | 26,768 | 30,048 |
| 04 | 15,026 | 20,508 | 35,534 | 38,355 |
| 05 | 13,235 | 21,703 | 34,938 | 36,777 |
| 06 | 1,696 | 13,856 | 15,552 | 16,126 |
| 07 | 6,226 | 25,209 | 31,435 | 34,049 |
| 08 | 9,908 | 23,867 | 33,775 | 35,584 |
| 09 | 13,752 | 19,838 | 33,590 | 36,536 |
| 10 | 780 | 5,193 | 5,973 | 6,080 |
| 11 | 3,212 | 23,675 | 26,887 | 28,003 |
| All | 91,287 | 191,909 | 283,195 | 301,908 |

Table 7. Influence zone area by interaction type for 150-ft buffer

| Interaction Type | Potential interior space (acres) State Area | State Count | Fed Area | Fed Count | State + Fed Area | State + Fed Count | Both Area | Both Count |
|---|---|---|---|---|---|---|---|---|
| 1 | 49,103 | 7,342 | 115,106 | 21,418 | 164,209 | 28,760 | 164,209 | 28,760 |
| 2 | 54,776 | 14,942 | 139,995 | 47,250 | 194,771 | 62,192 | 201,599 | 65,779 |
| 3 | 17,503 | 16,103 | 45,954 | 48,473 | 63,457 | 64,576 | 68,730 | 70,577 |
| 4 | 4,766 | 9,042 | 12,894 | 26,489 | 17,660 | 35,531 | 19,456 | 38,962 |
| 5 | 1,634 | 4,786 | 4,303 | 13,692 | 5,937 | 18,478 | 6,412 | 19,917 |
| 6 | 688 | 2,484 | 1,769 | 6,698 | 2,457 | 9,182 | 2,610 | 9,783 |
| 7 | 213 | 1,028 | 532 | 2,497 | 745 | 3,525 | 807 | 3,785 |
| 8 | 85 | 451 | 162 | 868 | 247 | 1,319 | 269 | 1,434 |
| 9 | 28 | 165 | 56 | 322 | 84 | 487 | 92 | 528 |
| 10 | 15 | 94 | 19 | 126 | 34 | 220 | 38 | 239 |
| >10 | 6 | 43 | 8 | 52 | 14 | 95 | 15 | 103 |
| All | 128,817 | 56,480 | 320,798 | 167,885 | 449,615 | 224,365 | 464,237 | 239,867 |

Table 8. Influence zone area by interaction type for 300-ft buffer

| Interaction Type | Potential interior space (acres): State Area | State Count | Fed Area | Fed Count | State + Fed Area | State + Fed Count | Both Area | Both Count |
|---|---|---|---|---|---|---|---|---|
| 1 | 15,179 | 1,933 | 22,883 | 5,916 | 38,062 | 7,849 | 38,062 | 7,849 |
| 2 | 30,420 | 7,082 | 63,529 | 20,668 | 93,949 | 27,750 | 96,927 | 29,134 |
| 3 | 23,711 | 11,390 | 55,144 | 32,142 | 78,855 | 43,532 | 84,927 | 47,874 |
| 4 | 12,200 | 10,518 | 27,580 | 28,281 | 39,780 | 38,799 | 44,987 | 44,003 |
| 5 | 4,829 | 6,996 | 11,382 | 18,411 | 16,211 | 25,407 | 18,764 | 29,071 |
| 6 | 2,295 | 4,246 | 5,403 | 11,500 | 7,698 | 15,746 | 8,687 | 17,754 |
| 7 | 1,075 | 2,600 | 2,690 | 7,108 | 3,765 | 9,708 | 4,199 | 10,807 |
| 8 | 600 | 1,789 | 1,426 | 4,417 | 2,026 | 6,206 | 2,236 | 6,827 |
| 9 | 375 | 1,232 | 778 | 2,814 | 1,153 | 4,046 | 1,268 | 4,439 |
| 10 | 231 | 852 | 467 | 1,819 | 698 | 2,671 | 759 | 2,916 |
| 11 | 135 | 590 | 273 | 1,151 | 408 | 1,741 | 446 | 1,905 |
| 12 | 88 | 402 | 148 | 681 | 236 | 1,083 | 256 | 1,177 |
| 13 | 54 | 255 | 91 | 449 | 145 | 704 | 157 | 762 |
| 14 | 37 | 183 | 54 | 290 | 91 | 473 | 99 | 511 |
| 15 | 24 | 122 | 28 | 144 | 52 | 266 | 57 | 295 |
| >15 | 35 | 214 | 33 | 207 | 68 | 421 | 77 | 477 |
| All | 91,288 | 50,404 | 191,909 | 135,998 | 283,197 | 186,402 | 301,908 | 205,801 |

Table 9. Summary of the subproblems for the three large-scale test cases

| Subforest | FEDERAL | | | STATE | | | BOTH | | |
|---|---|---|---|---|---|---|---|---|---|
| | Number of SubDivisions | Number of subproblems with 10,000 Node/stage guide | Number of subproblems with 1,000,000 Node/stage guide | Number of SubDivisions | Number of subproblems with 10,000 Node/stage guide | Number of subproblems with 1,000,000 Node/stage guide | Number of SubDivisions | Number of subproblems with 10,000 Node/stage guide | Number of subproblems with 1,000,000 Node/stage guide |
| 1 | 67 | 187 | 109 | 1 | 2 | 2 | 67 | 188 | 109 |
| 2 | 98 | 319 | 176 | 44 | 164 | 96 | 83 | 380 | 222 |
| 3 | 73 | 214 | 115 | 79 | 238 | 142 | 66 | 315 | 191 |
| 4 | 114 | 409 | 237 | 81 | 281 | 171 | 111 | 601 | 359 |
| 5 | 61 | 312 | 192 | 49 | 120 | 74 | 59 | 347 | 201 |
| 6 | 68 | 358 | 208 | 26 | 57 | 34 | 71 | 372 | 229 |
| 7 | 96 | 458 | 242 | 56 | 137 | 85 | 61 | 453 | 239 |
| 8 | 45 | 220 | 113 | 34 | 102 | 56 | 45 | 269 | 137 |
| 9 | 100 | 299 | 182 | 70 | 188 | 114 | 89 | 388 | 235 |
| 10 | 62 | 157 | 100 | 10 | 23 | 15 | 66 | 178 | 117 |
| 11 | 136 | 384 | 223 | 47 | 78 | 54 | 143 | 456 | 266 |
| Total | 920 | 3317 | 1897 | 497 | 1390 | 843 | 861 | 3947 | 2305 |

Table 10. Impact of interior space price on the number of modeled prescriptions considered after applying the Treatment Trimmer.

| Interior Space Price ($/acre/decade) | Model I prescriptions from Treatment Trimmer<br>Modeled polygons | Total number of prescriptions | Average number of prescriptions |
|---|---|---|---|
| 0 | 91,951 | 91,955 | 1.00 |
| 100 | 91,951 | 212,013 | 2.31 |
| 300 | 91,951 | 297,817 | 3.24 |
| 500 | 91,951 | 341,597 | 3.71 |
| 700 | 91,951 | 366,259 | 3.98 |
| 1,000 | 91,951 | 387,028 | 4.21 |
| 100,000 | 91,951 | 408,862 | 4.45 |

**Table 11. Variation in the number of modeled prescriptions per polygon after applying the Treatment Trimmer.**

| Prescriptions per polygon | Interior space price ($/acre/period) 0 | 100 | 300 | 500 | 700 | 1000 | 100,000 |
|---|---|---|---|---|---|---|---|
| 1 | 91947 | 64779 | 58551 | 56792 | 56036 | 55517 | 54683 |
| 2 | 4 | 6756 | 4329 | 3219 | 2652 | 2245 | 1838 |
| 3 | 0 | 4009 | 3661 | 2988 | 2695 | 2377 | 2230 |
| 4 | 0 | 2756 | 3058 | 2774 | 2560 | 2355 | 2280 |
| 5 | 0 | 2171 | 2881 | 2794 | 2586 | 2437 | 2456 |
| 6 | 0 | 2177 | 2805 | 2865 | 2825 | 2810 | 2715 |
| 7 | 0 | 2482 | 2964 | 3097 | 3071 | 2933 | 2763 |
| 8 | 0 | 1780 | 2707 | 3004 | 3096 | 3201 | 3217 |
| 9 | 0 | 2046 | 2802 | 3147 | 3212 | 3258 | 3277 |
| 10 | 0 | 1052 | 1941 | 2311 | 2607 | 2726 | 2903 |
| 11 | 0 | 469 | 1166 | 1583 | 1863 | 2003 | 2315 |
| 12 | 0 | 370 | 1134 | 1543 | 1718 | 1910 | 2044 |
| 13 | 0 | 303 | 839 | 1153 | 1260 | 1421 | 1543 |
| 14 | 0 | 186 | 584 | 806 | 999 | 1171 | 1223 |
| 15 | 0 | 306 | 758 | 1005 | 1195 | 1366 | 1489 |
| 16 | 0 | 116 | 558 | 845 | 987 | 1109 | 1262 |
| 17 | 0 | 65 | 352 | 538 | 683 | 790 | 878 |
| 18 | 0 | 47 | 209 | 344 | 423 | 525 | 617 |
| 19 | 0 | 32 | 234 | 411 | 529 | 621 | 745 |
| 20 | 0 | 22 | 155 | 248 | 310 | 380 | 456 |
| >20 | 0 | 27 | 263 | 484 | 644 | 796 | 1017 |

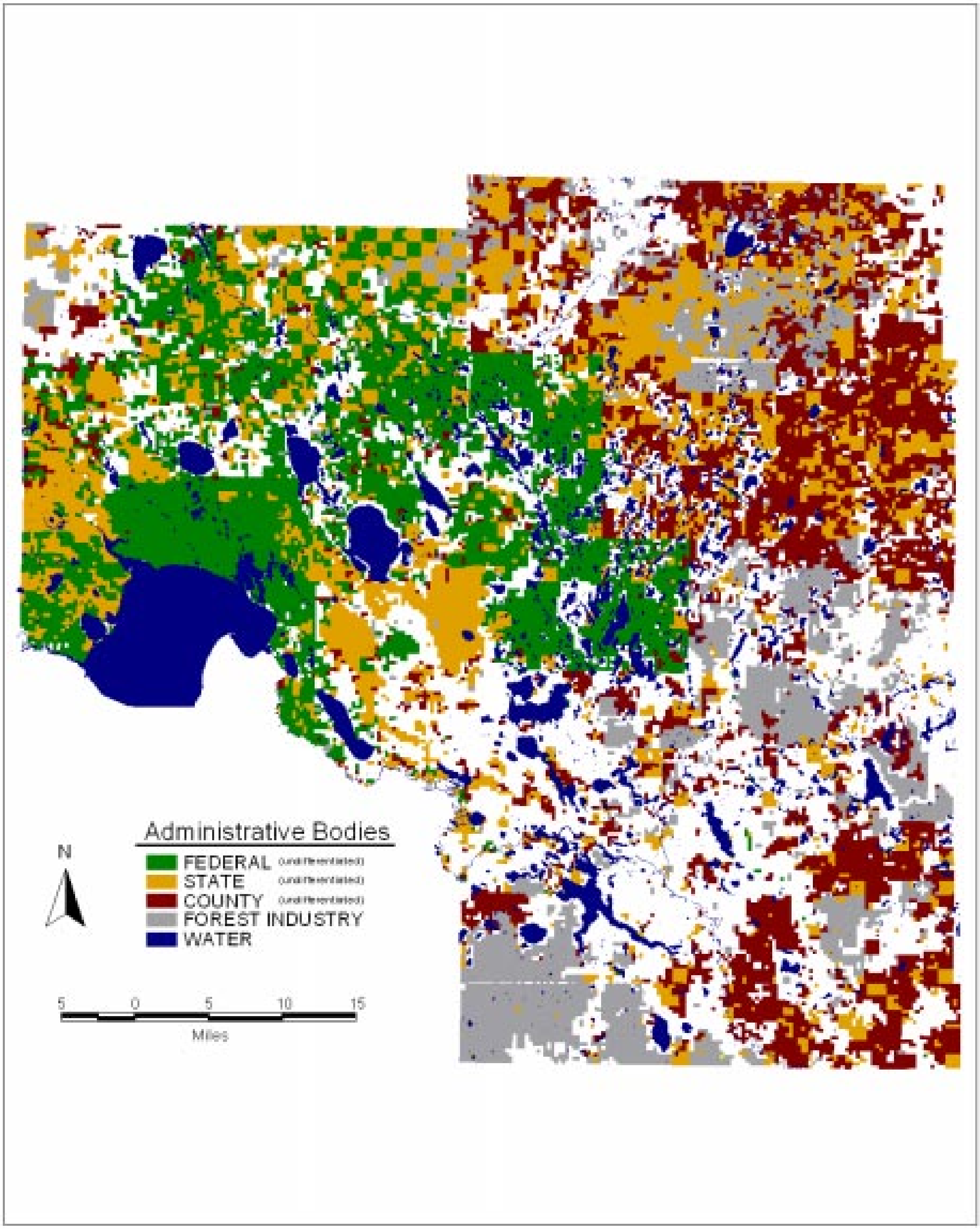


Figure 1. Administration of public lands in
Itasca County, Minnesota

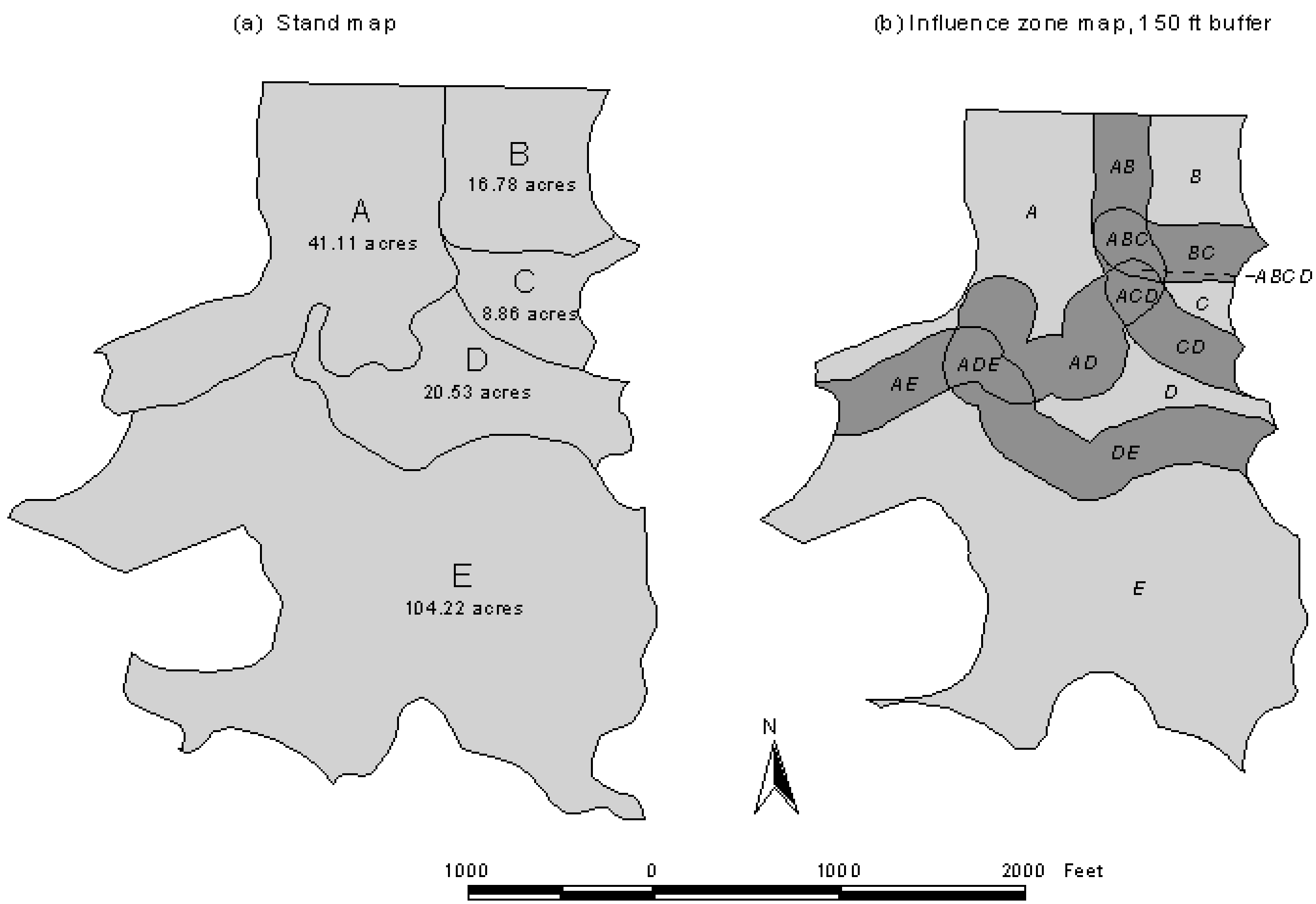


Figure 2. Stands and influence zones for the five-stand example forest.

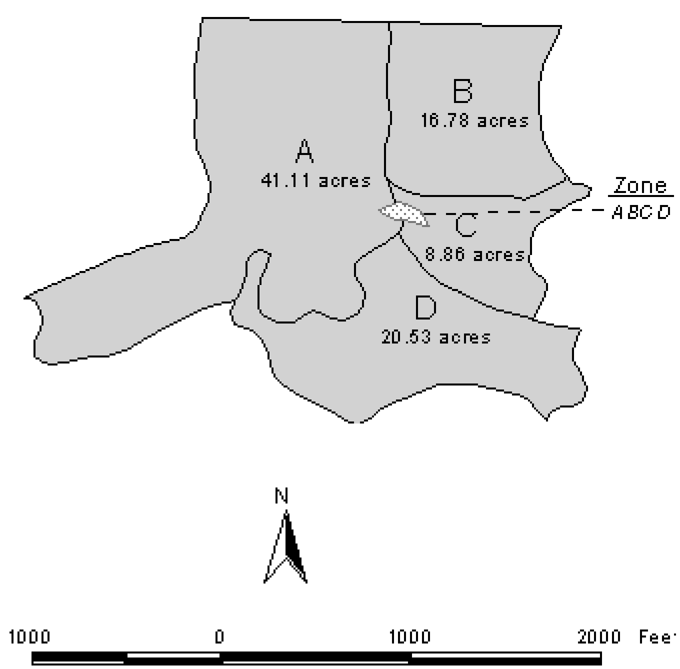


Figure 3. A four-way interaction for the five-stand example forest

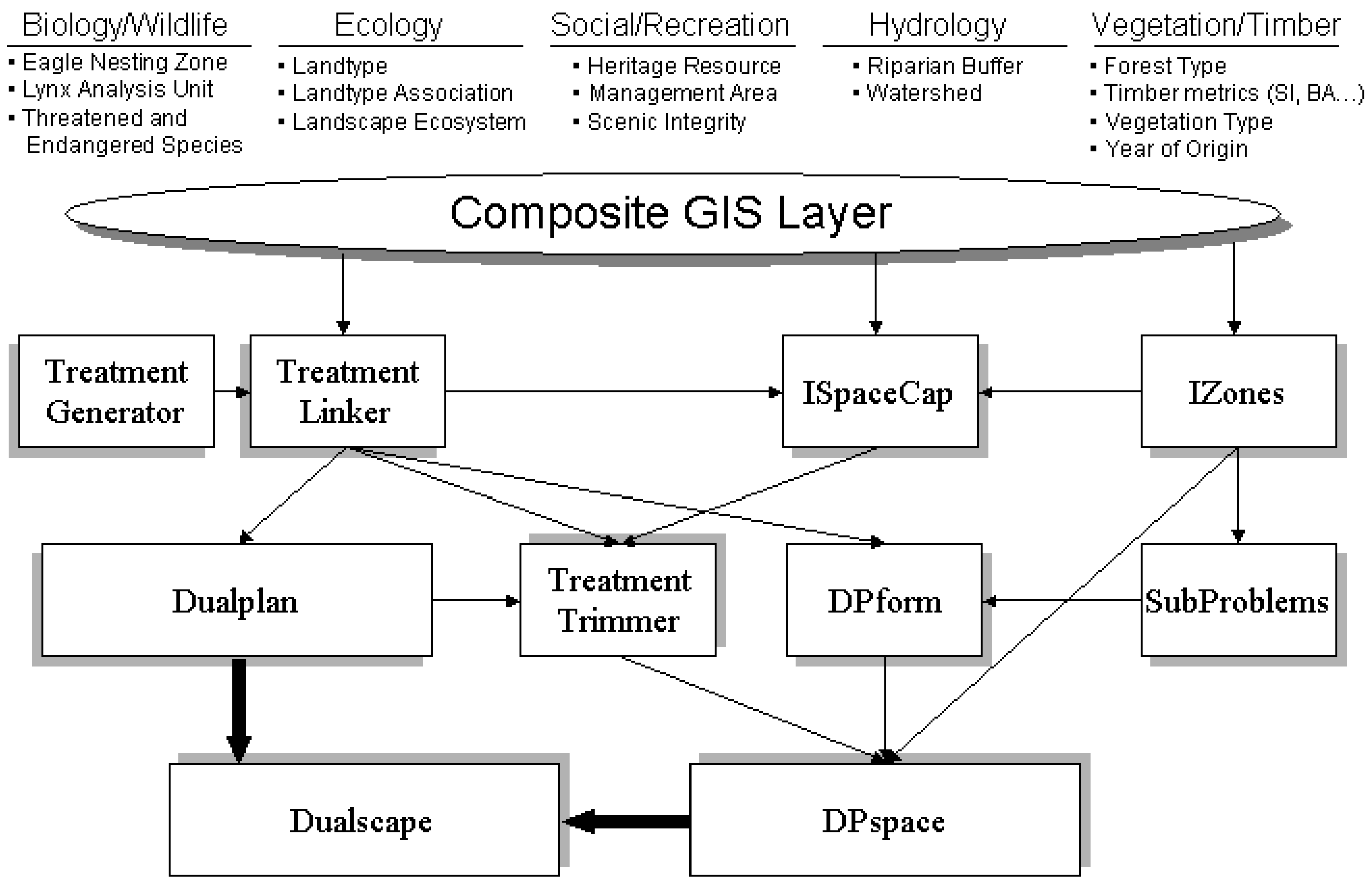


Figure 4. Overview of the modeling system.

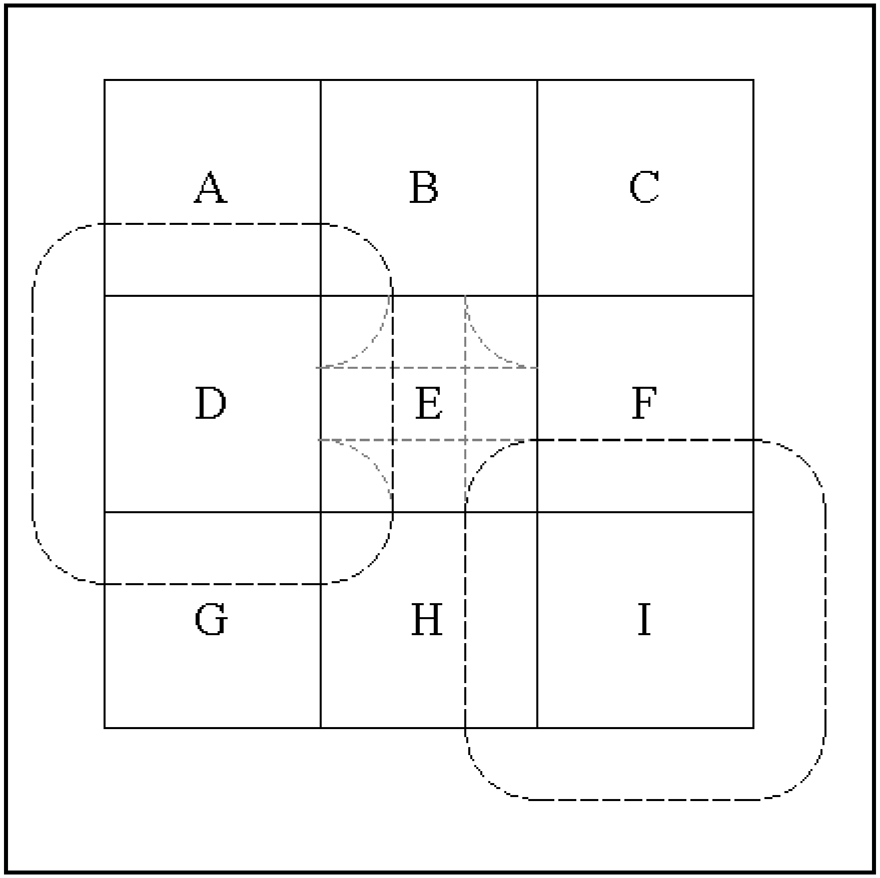


Figure 5.  Illustration of buffering for an IZones kernel

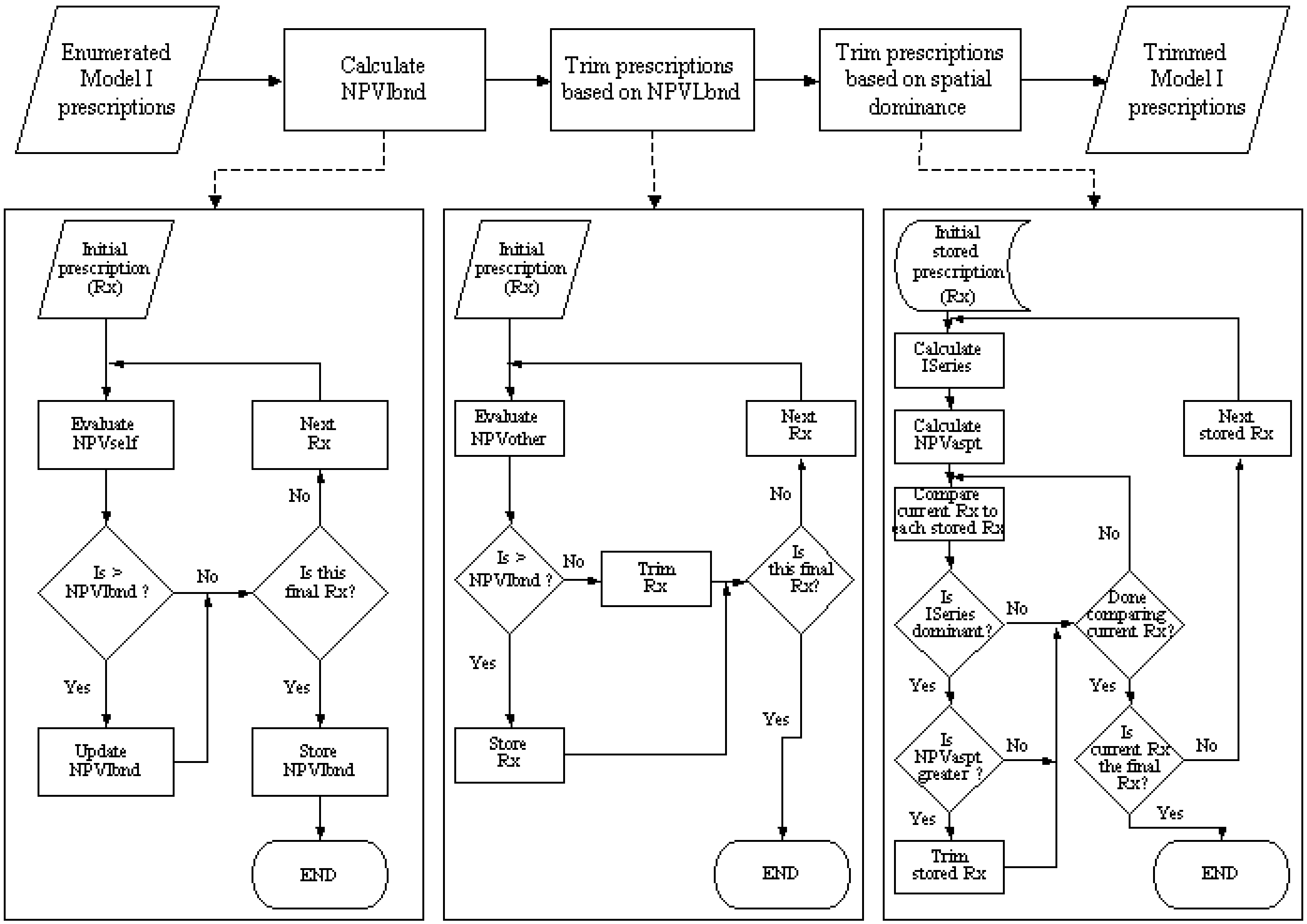


Figure 6. Flow chart summarizing the analysis process used for each polygon in Treatment Trimmer

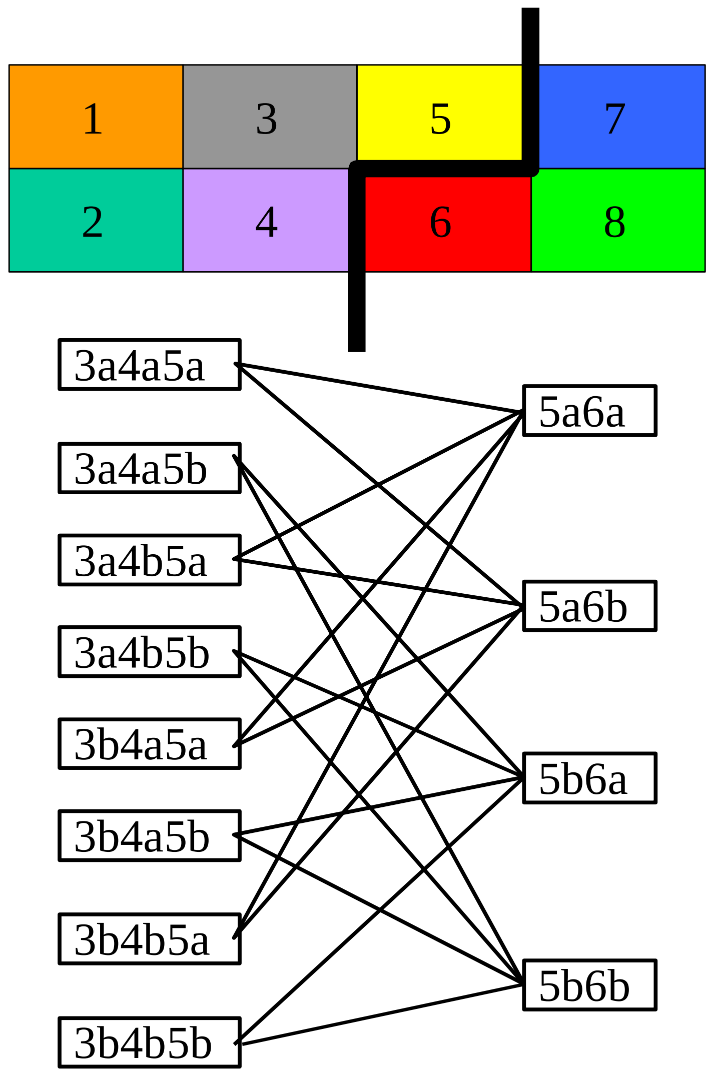


Figure 7. Example of a portion of a DP decision tree used to represent interdependent decisions for an 8-stand forest. Each stand has just two management choices (treatment a or treatment b). The portion of the tree shown represents the decision choices for stand 6.

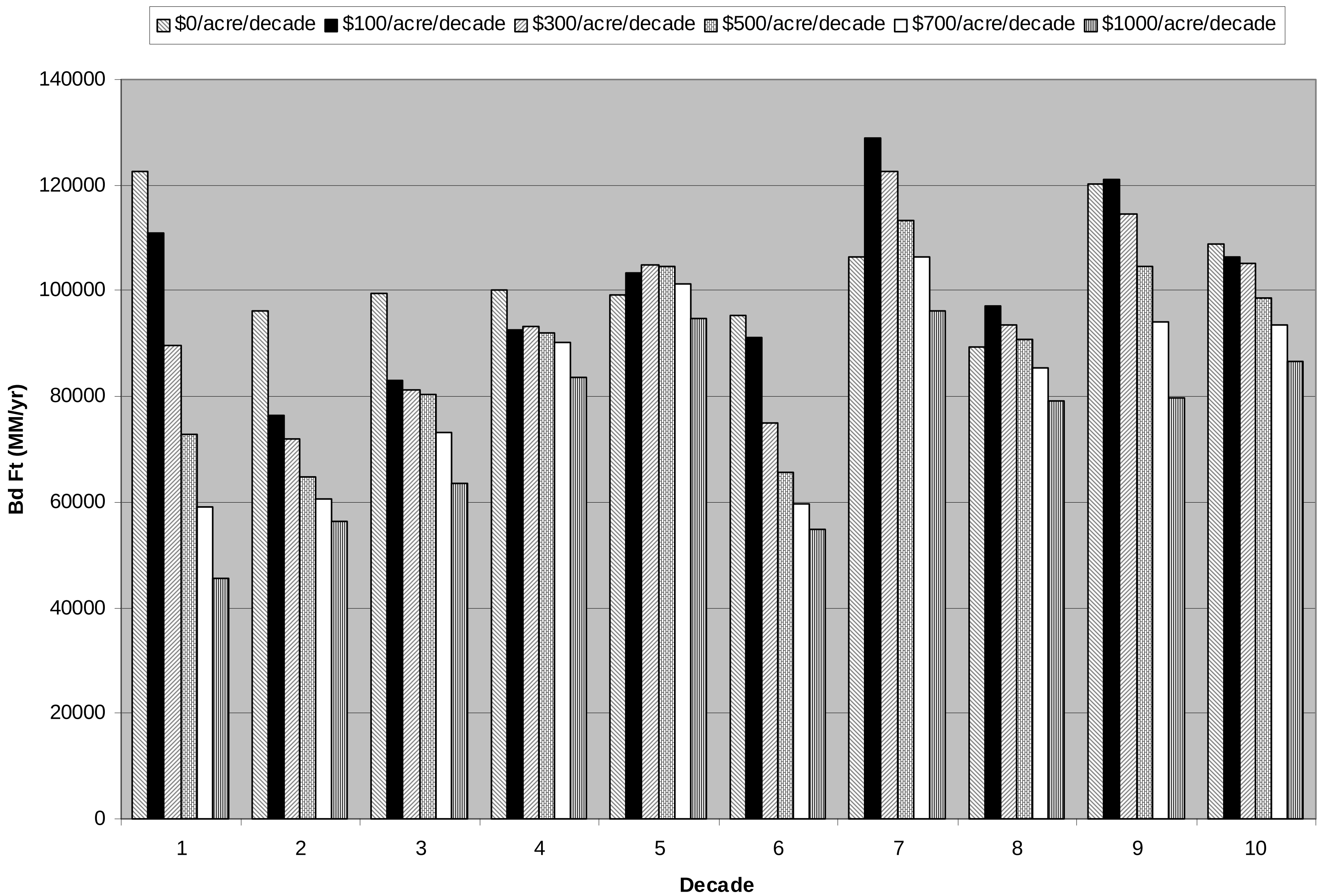


Figure 8. Impact of interior space value on timber production for the “Both” test case.

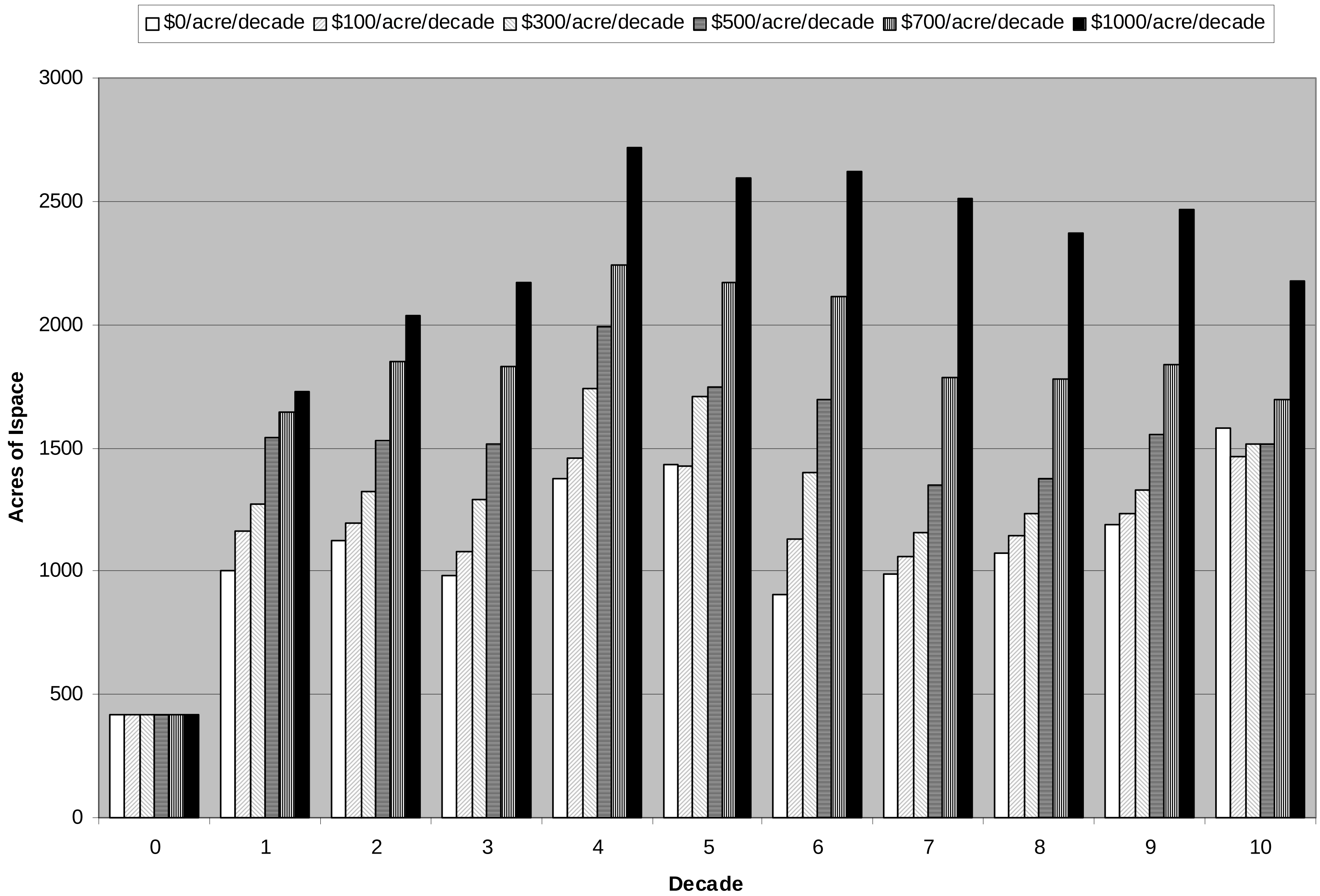


Figure 9. Impact of interior space value on interior space production in the dry pine LE for the "Both" test case.

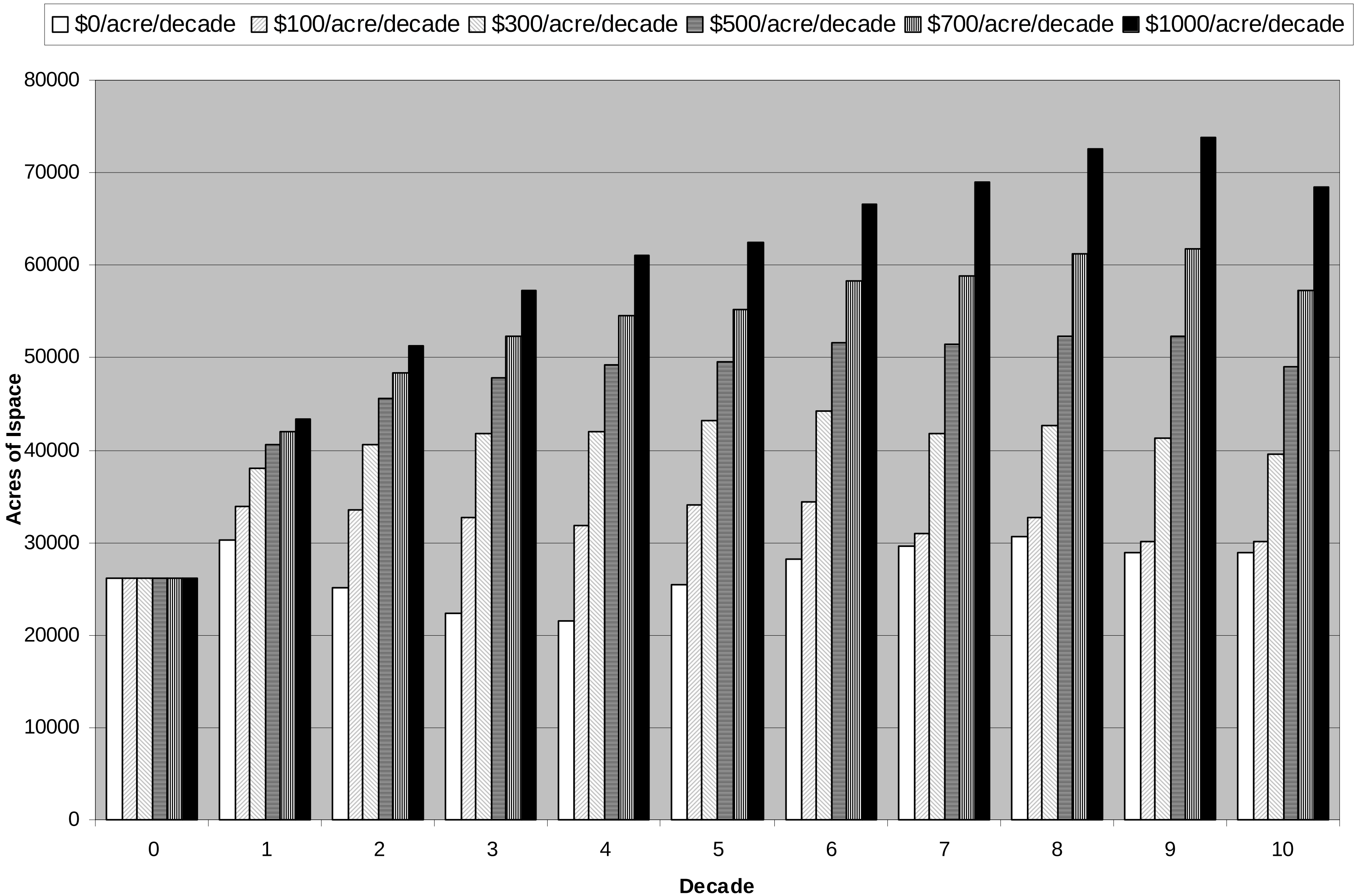


Figure 10. Impact of interior space value on interior space production in the dry mesic pine oak LE for the “Both” test case.

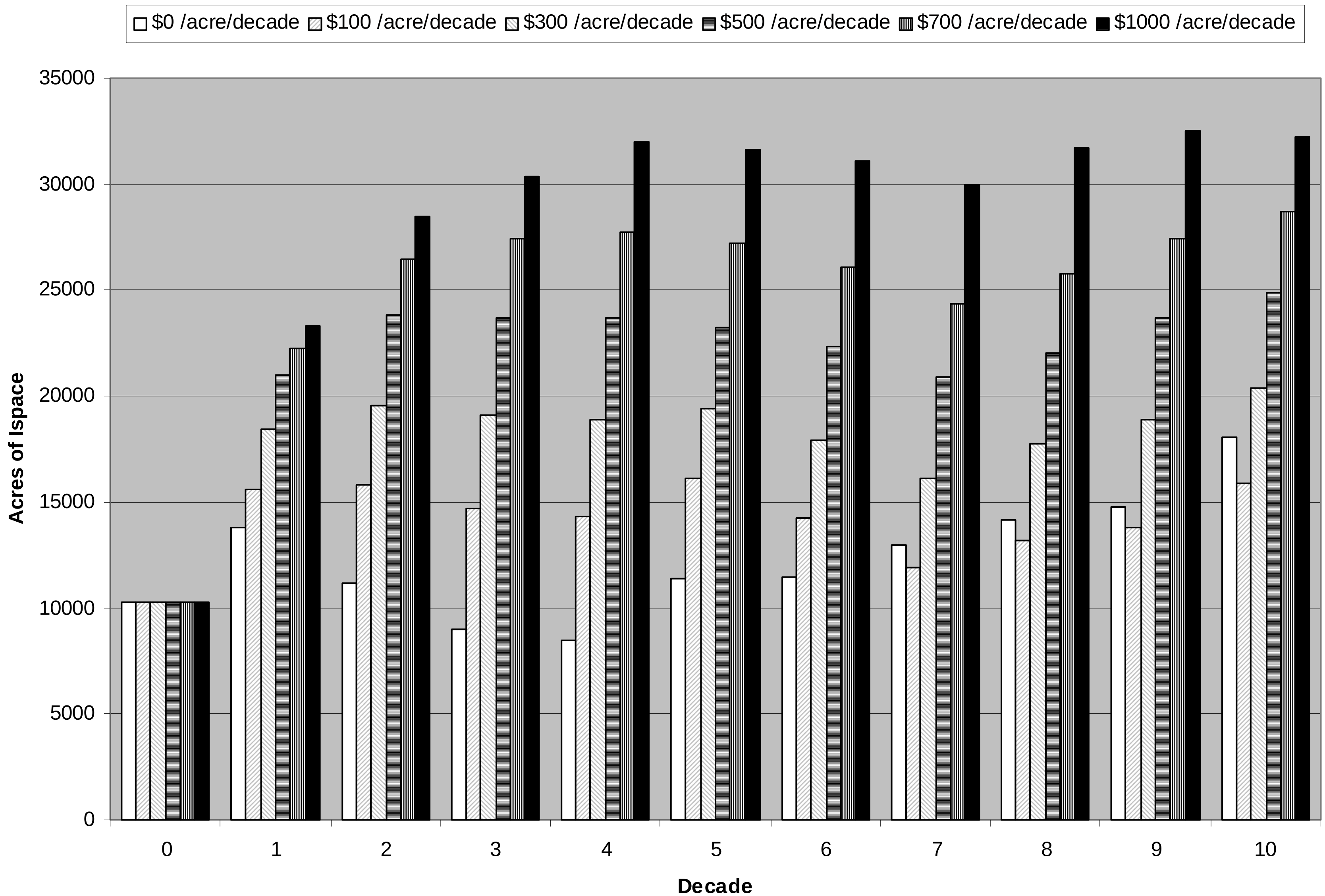


Figure 11. Impact of interior space value on interior space production in the dry mesic pine LE for the “Both” test case.

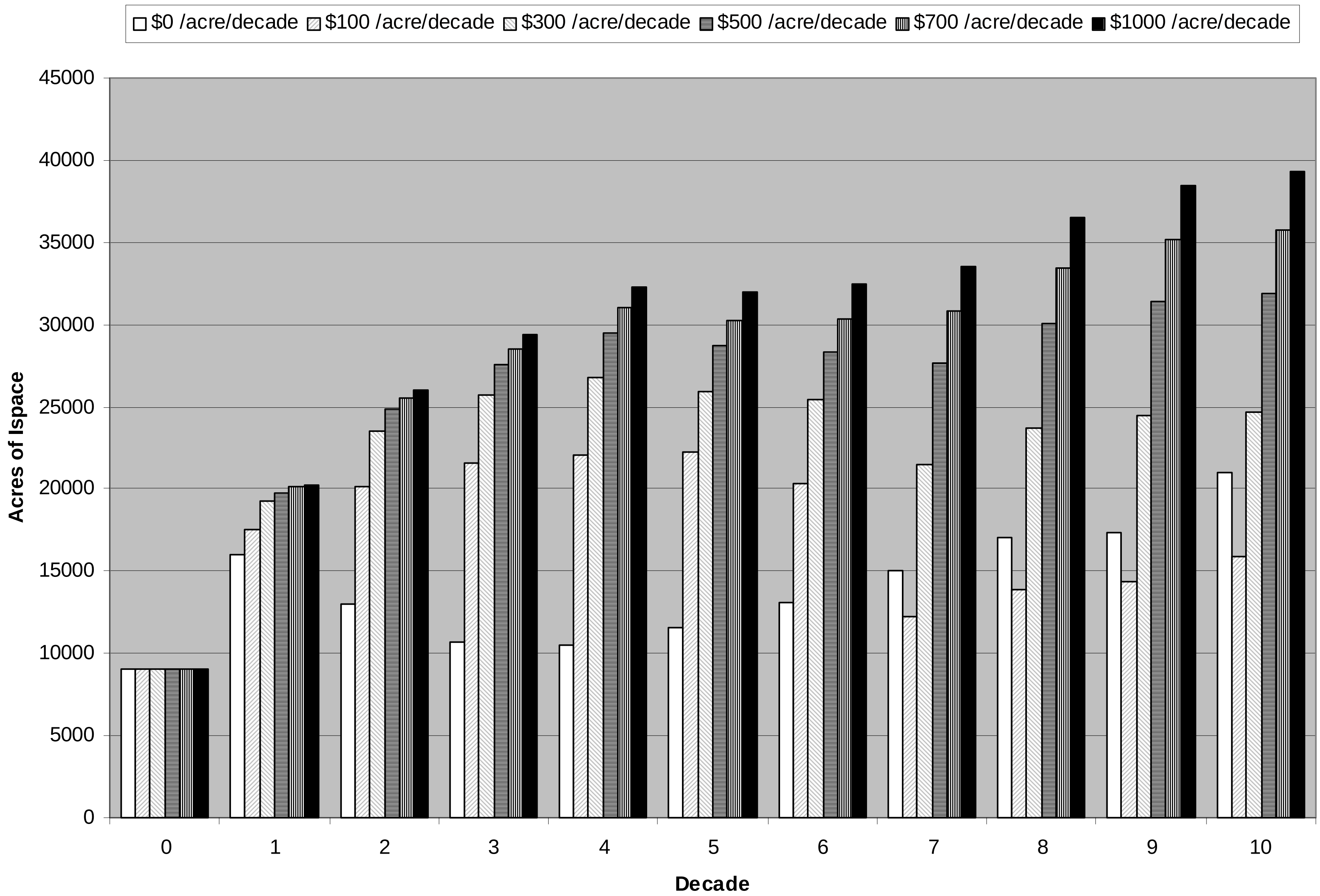


Figure 12. Impact of interior space value on interior space production in the mesic northern hardwoods LE for the “Both” test case.

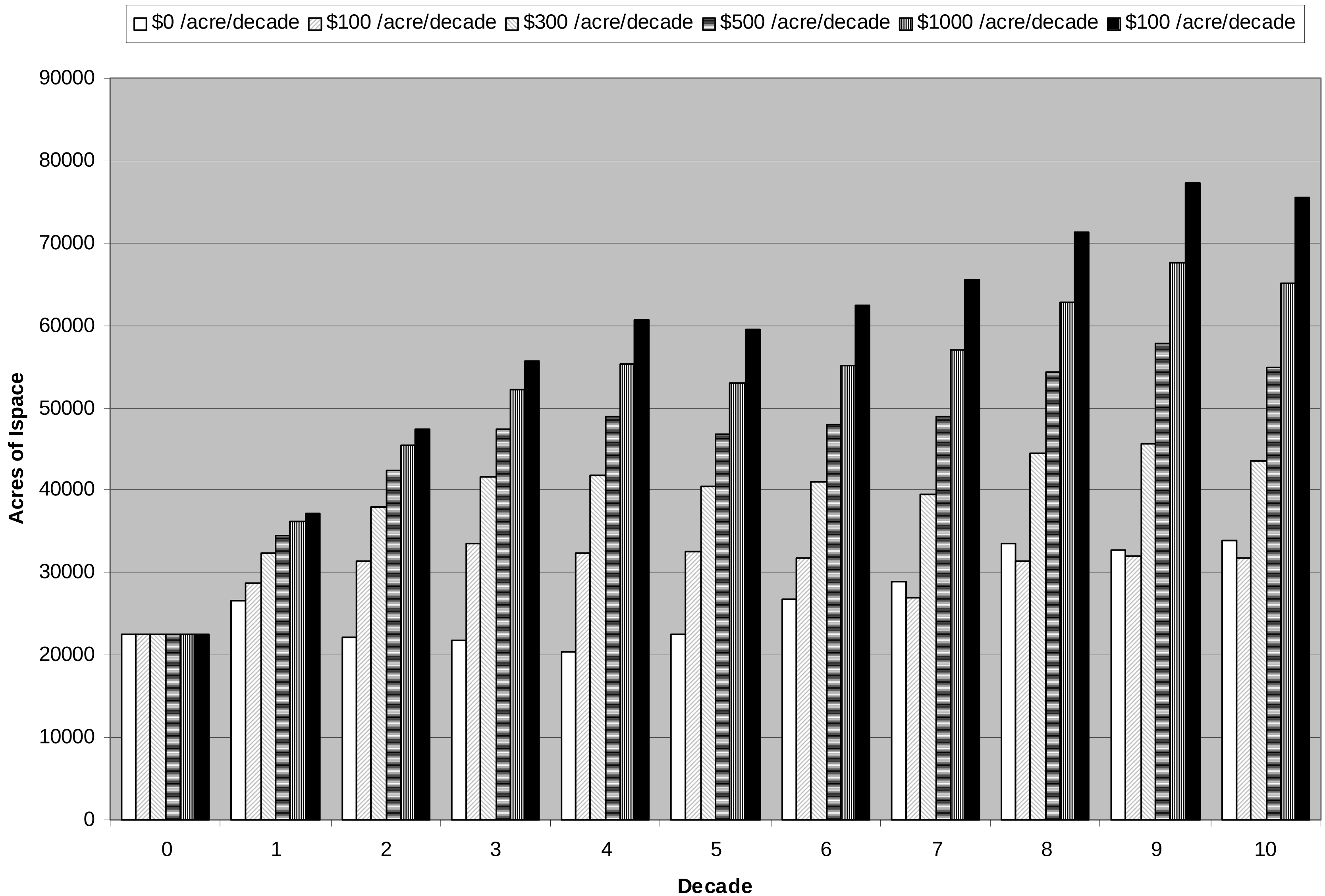


Figure 13. Impact of interior space value on interior space production in the boreal hardwood conifer LE for the "Both" test case.

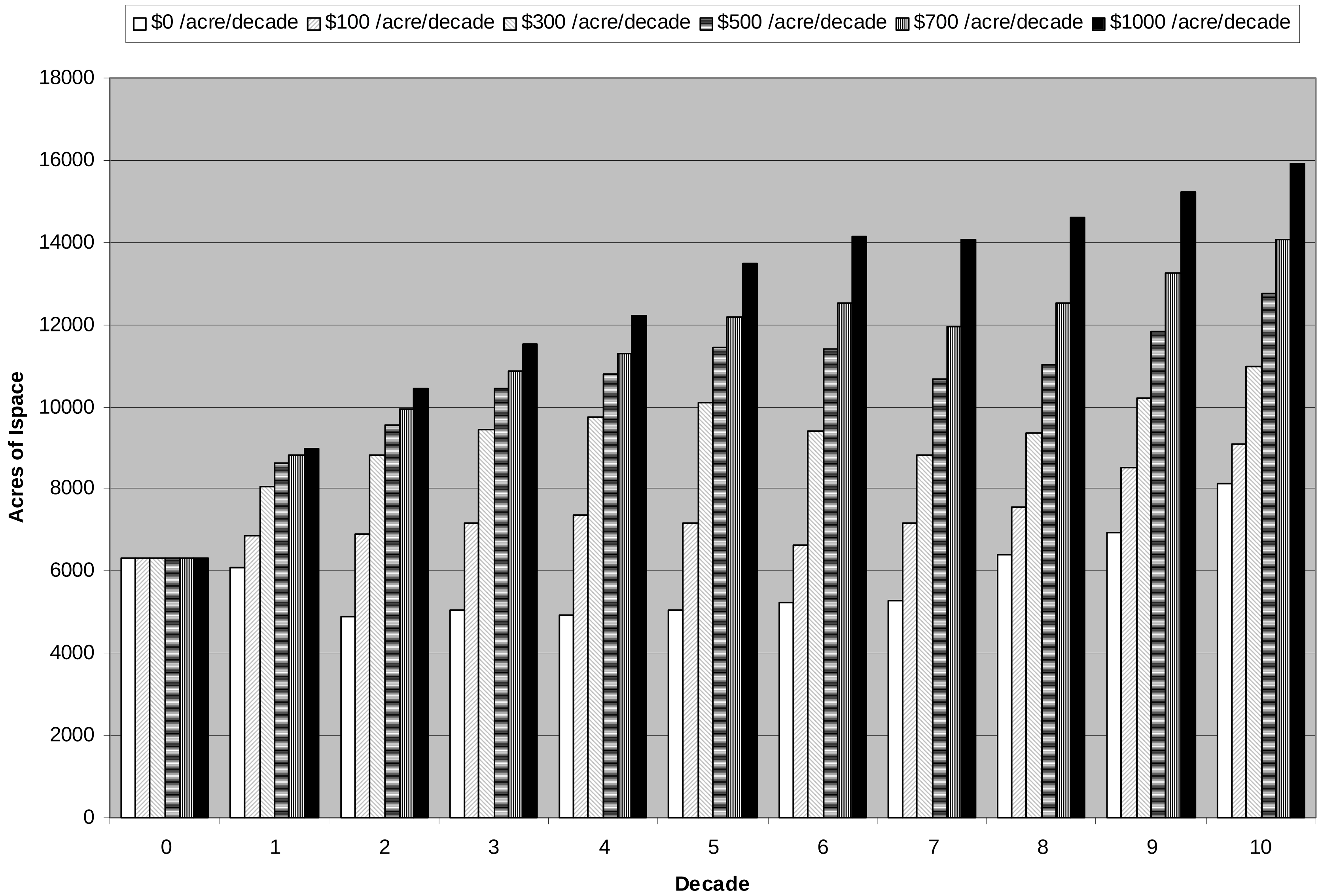


Figure 14. Impact of interior space value on interior space production in the white cedar lowlands LE for the “Both” test case.

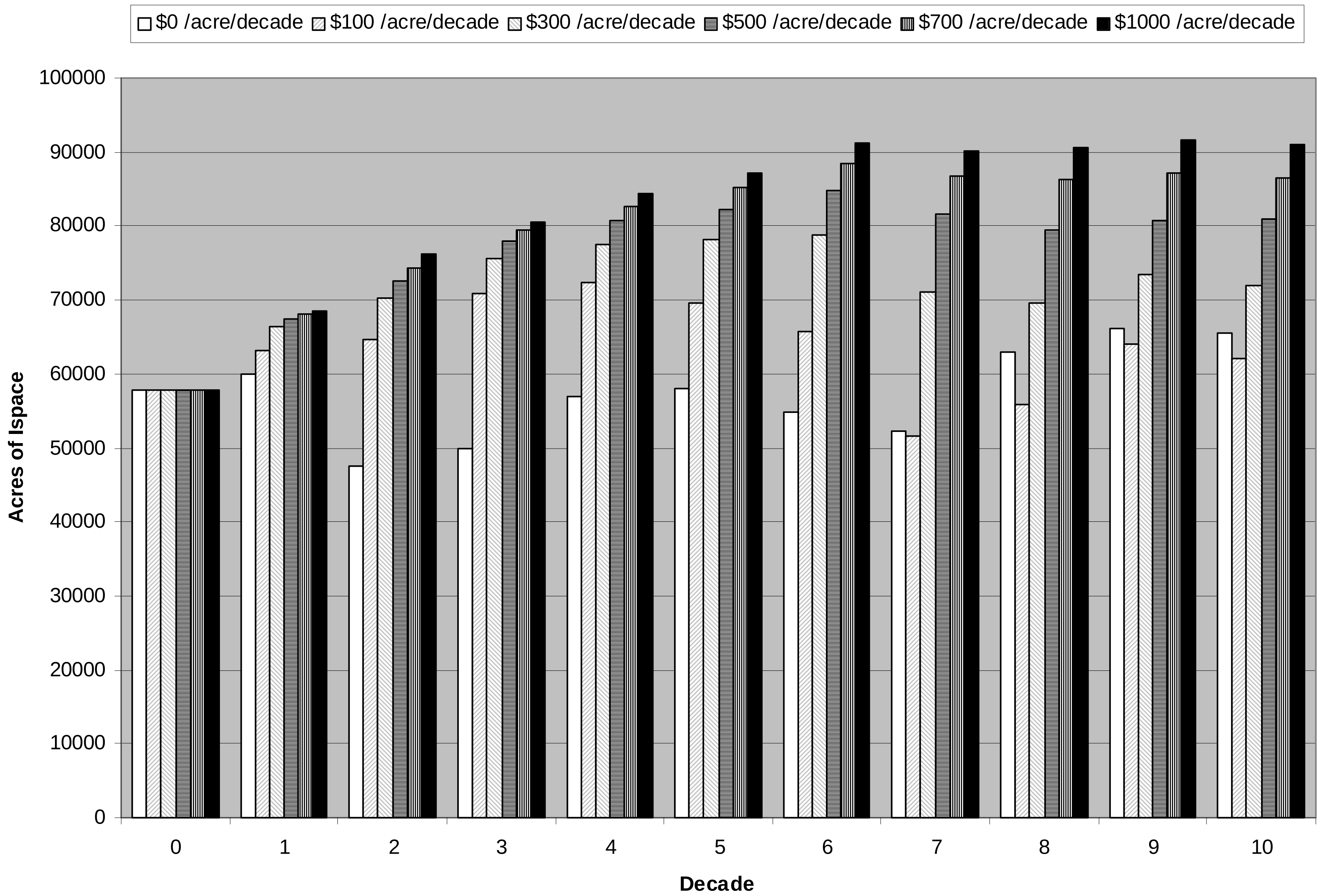


Figure 15. Impact of interior space value on interior space production in the tamarack lowlands LE for the "Both" test case.

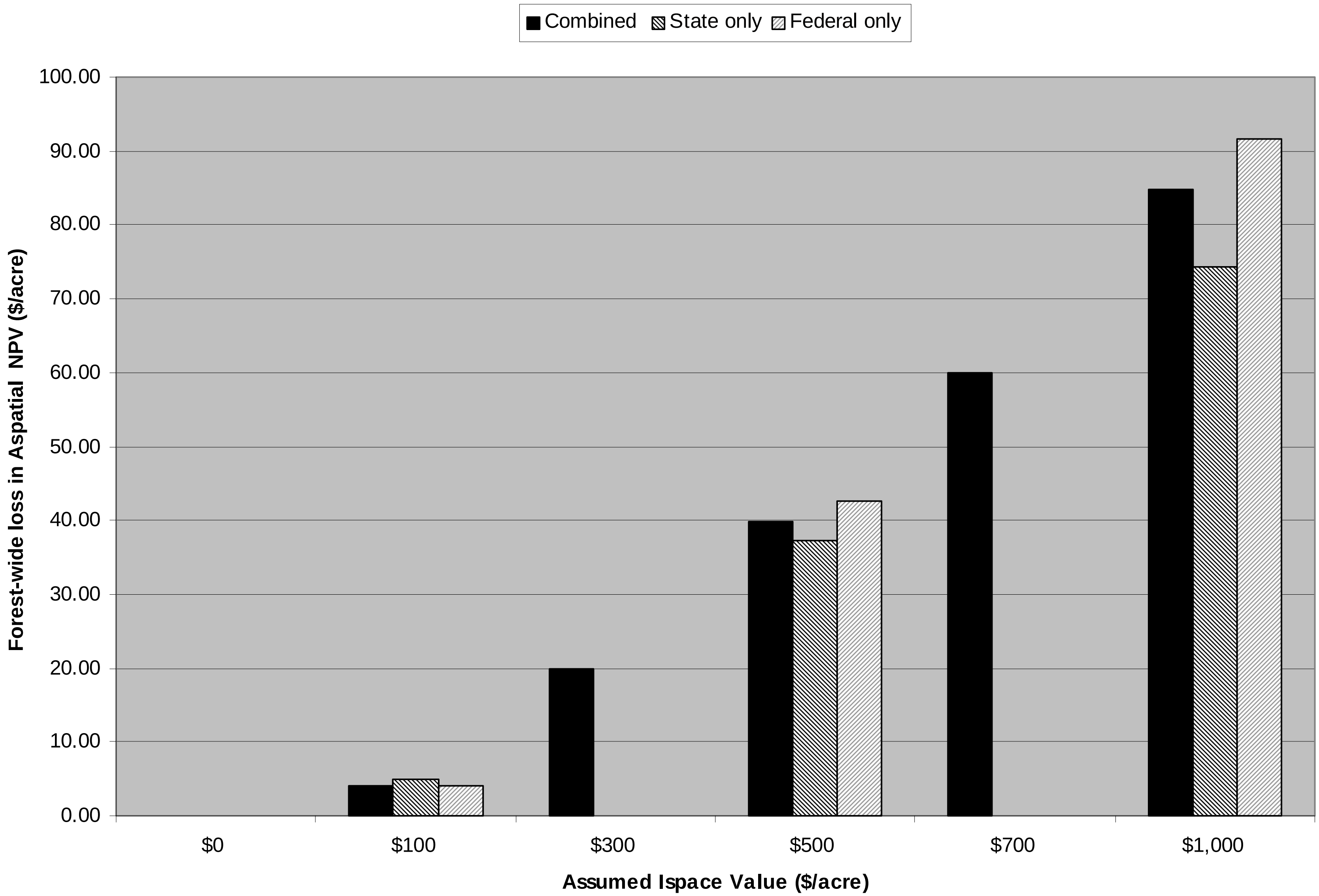


Figure 16. Loss in aspatial NPV($/acre) for the three large-scale test cases for alternative interior space values

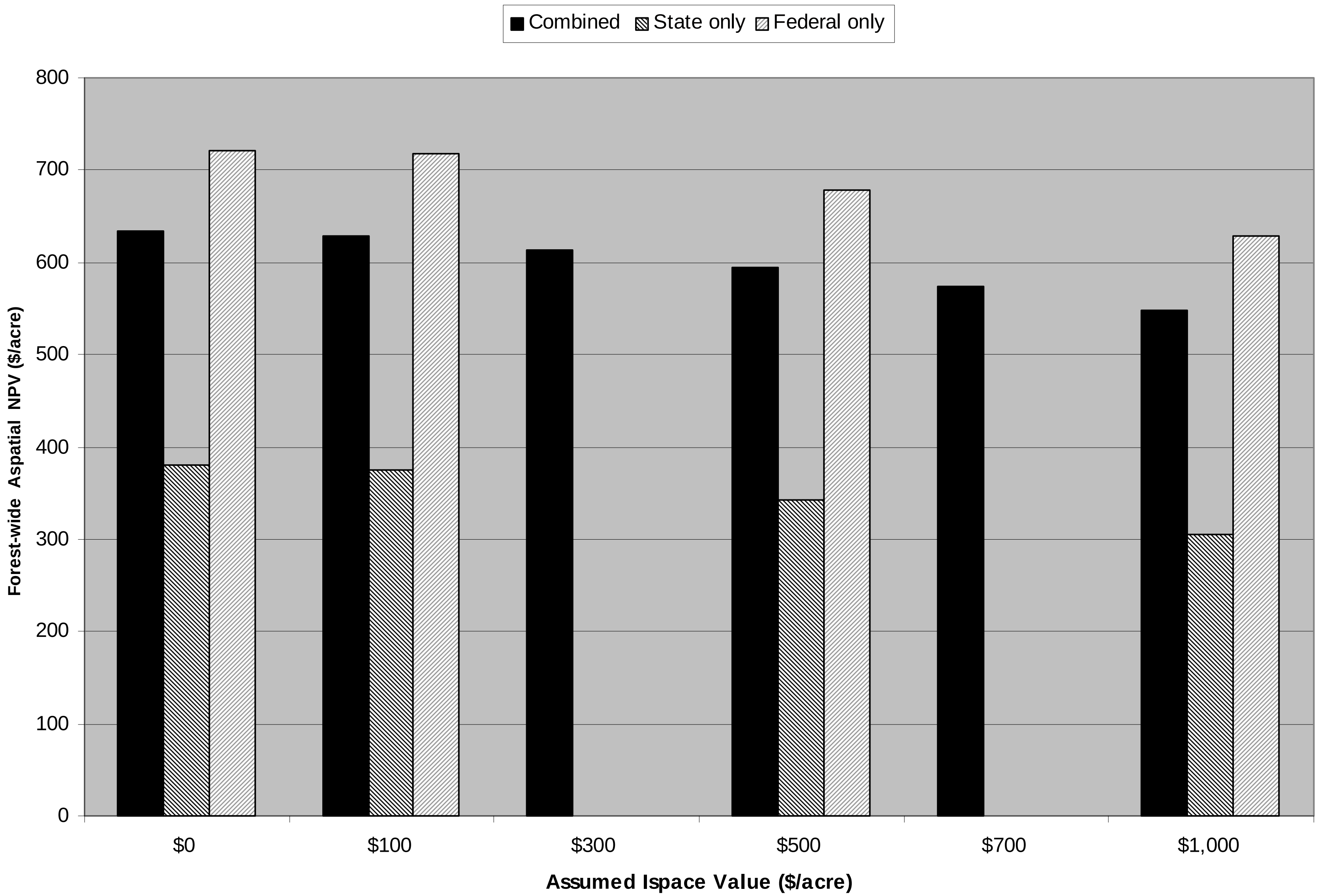


Figure 17. Aspatial NPV($/acre) for the three large-scale test cases for alternative interior space values

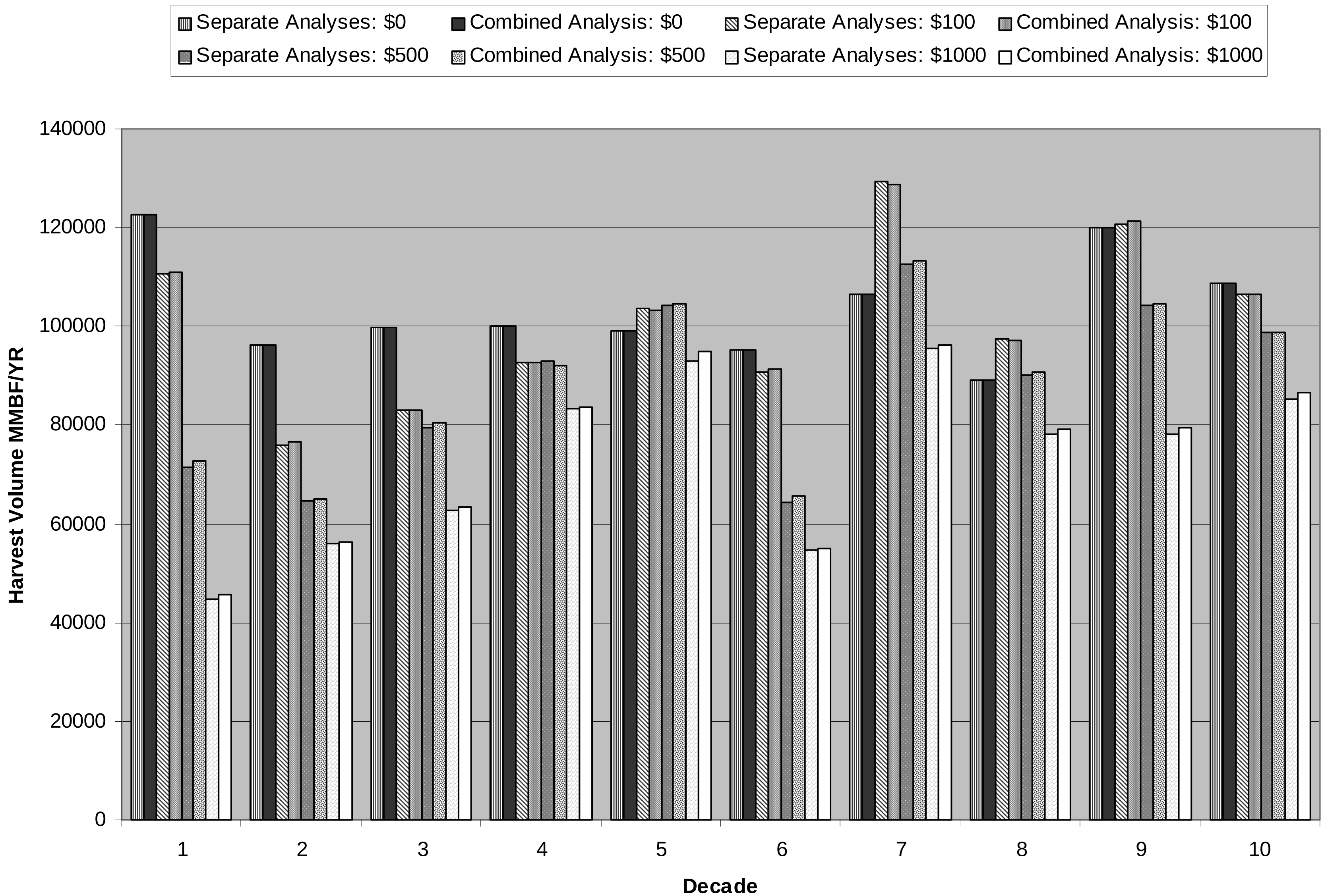


Figure 18. A comparison of timber harvest levels for the "Both" test case with the total harvest levels when federal and state lands are analyzed separately. Prices refer to the prices assumed for interior space.

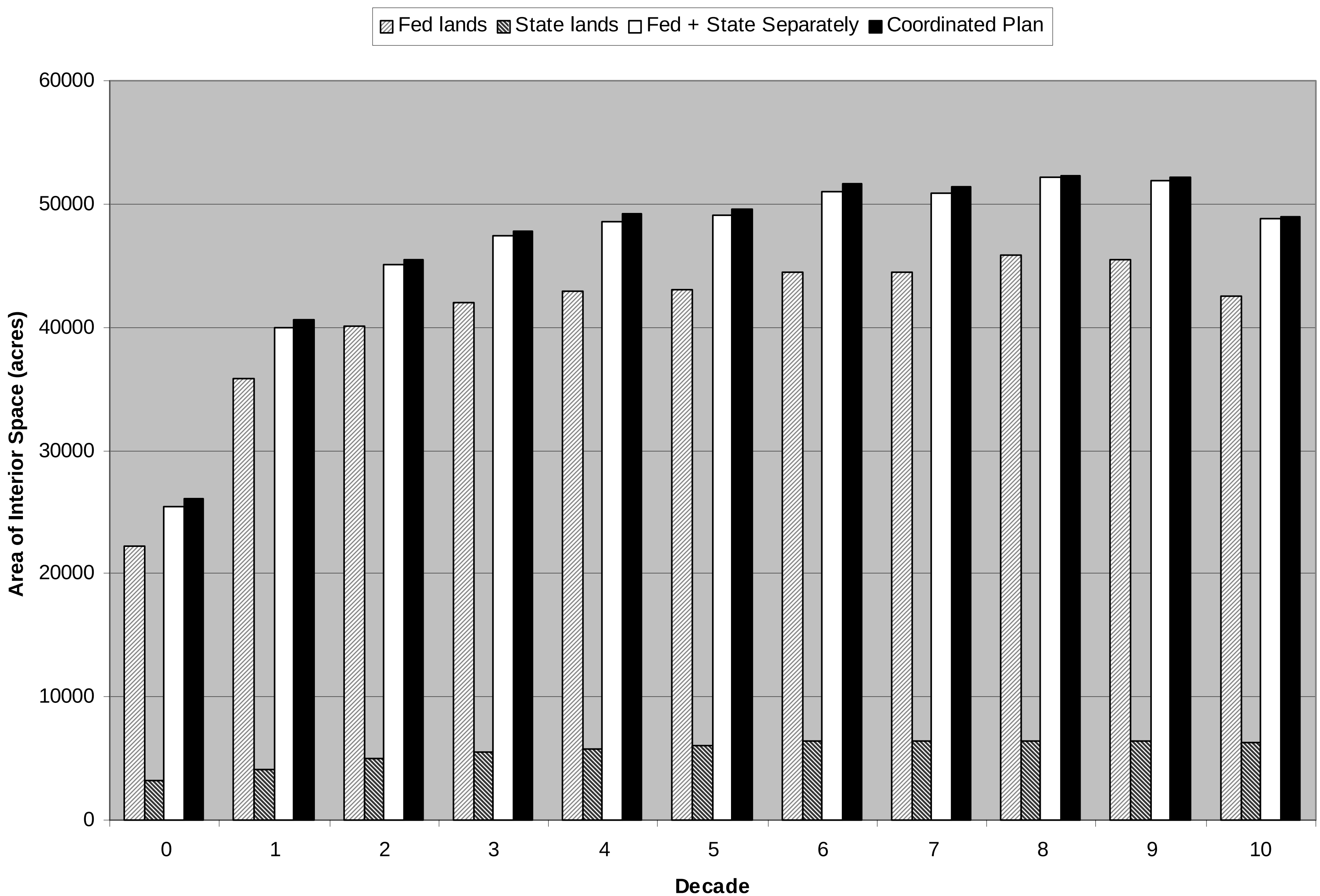


Figure 19. Comparison of interior space area for the "Both" test case with the interior space area when federal and state lands are planned separately and then summed: Dry mesic pine oak landscape ecosystem (Interior space price = $500/acre/decade).

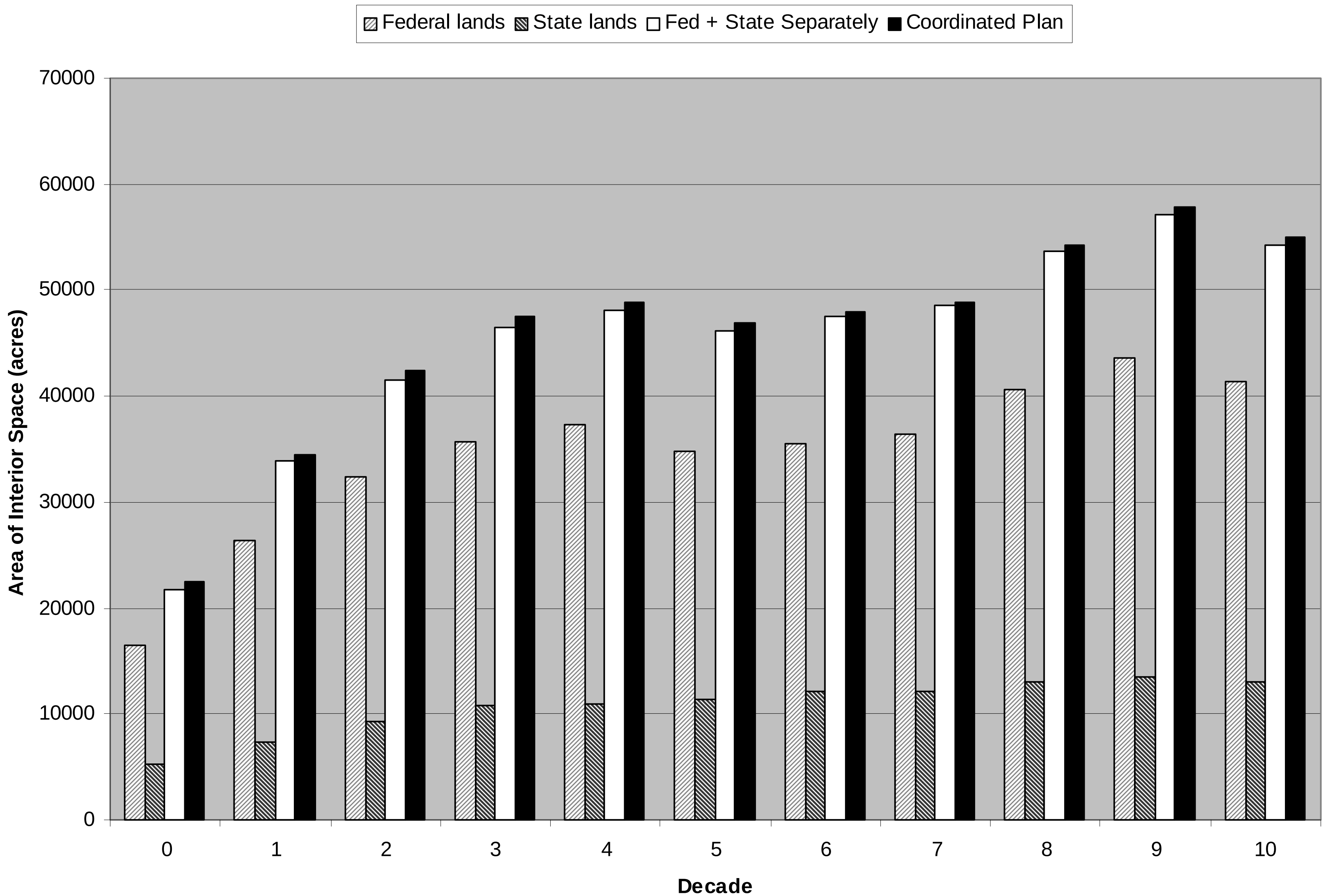


Figure 20. Comparison of interior space area for the “Both” test case with the interior space area when federal and state lands are planned separately and then summed: Boreal hardwood conifer landscape ecosystem (Interior space price = $500/acre/decade).

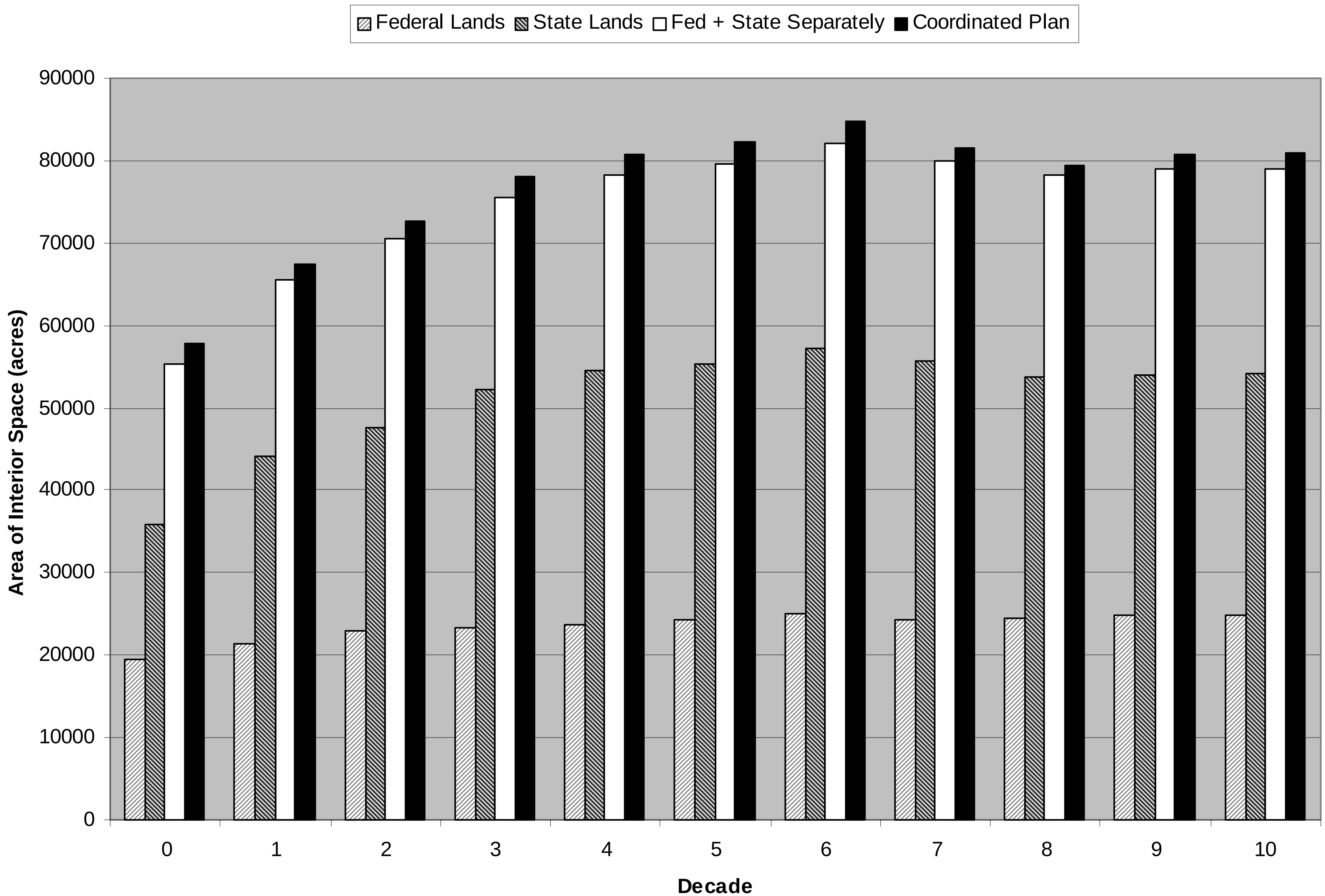


Figure 21. Comparison of interior space area for the “Both” test case with the interior space area when federal and state lands are planned separately and then summed: Tamarack lowlands conifer landscape ecosystem (Interior space price = $500/acre/decade).

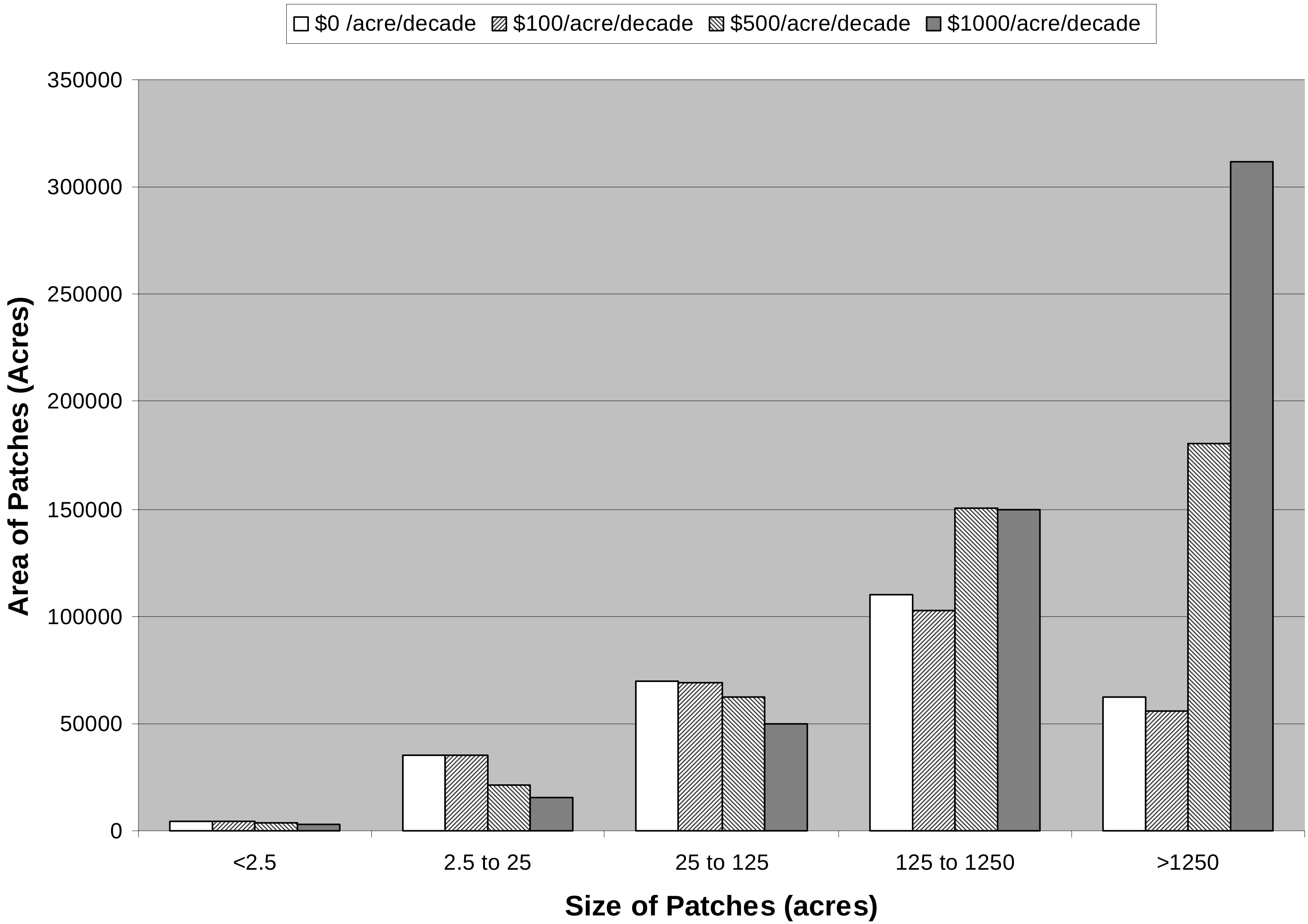


Figure 22. Patch size distribution of older forest at the end of the planning horizon for varying older forest interior space prices.