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TRENDS IN SPATIAL FOREST PLANNING

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Abstract. Both mathematical and heuristic methods have advanced rapidly in spatial forest planning over the past 20 years. The review presented here is broader in both scope and depth (more analysis within spatial forest planning models). We conduct here a world-wide literature review and extensive analysis of the status and trends over the past two decades in spatial forest planning. In our investigation, we hope to understand the roles of objective and constraint functions in spatial forest planning. The literature review results suggest that methods used in forest planning have shifted somewhat from exact analytical solution techniques to heuristic techniques. In an effort to incorporate complex relationship into forest plans, other solution methods have also been evaluated for adoption in the planning process. Besides the economic and commodity production objectives, there is a noticeable increase in the proportion of ecological and social concerns in objective functions. In Europe, multi-parameter objective functions now seem to be in vogue, containing little or no constraints. In the U.S., single-parameter objective functions are still common, with multiple concerns recognized as constraints. In addition to the economic and commodity production constraints, adjacency and green-up relationships have recently been considered as important constraints in many areas of the world. Vector data are found to be more popular than raster data in the forest planning process, particularly in real-life applications of methods. In theoretical applications of methods, both vector and raster data are commonly used. Limitations in mixed integer programming, heuristic parameter selection processes, modification and enhancements to heuristics, and measurements of heuristic solution quality are some of the gaps we have identified.

Keywords: Spatial forest planning, Mathematical programming, Heuristics, Modeling techniques, GIS

1 Introduction

Although theoretically spatial order has always been a factor in the development of strategic and tactical forest plans, physically, incorporating spatial concerns into forest planning methods has advanced rapidly only over the past 20 years. This advance is coincident with the advances made in computer hardware and software technology, and satellite technology and geographic information systems (GIS), as well as changes in human values associated with forest conditions. Interestingly, while changes in forest structure occur globally, most of the concern related to the timing and juxtaposition of management activities is in developed countries. Forest regulations and voluntary efforts of managing forests for sustainability in these countries are the main areas of spatial forest planning concerns [29]. In addition, as many wildlife-habitat relationships continue to be better understood or advanced, the evaluation of these and other concerns has prompted advances in spatial forest planning concepts as well.

Certain laws and directives guide the use of spatial forest planning methods, and thus the need to adhere to regulations, to comply with the guidelines of voluntary certification programs, and to operate within published forest plans [29]. U.S. National Forests, for example, are regulated by the National Forest Management Act (United States Congress 1976), which provides guidance regarding the appropriate size of harvest units. In simply perusing the published forest plans, one can find information on the maximum sizes of clearcuts, the dispersion of the openings created, and guidance for the management of habitat patches on various national forest lands. Some U.S. states also have passed laws that limit the size of clearcutting activities on privately-owned land [29, 44]. Canadian provinces may also have regulations relating to the size, shape, and pattern of areas to be clearcut, as may other governments, such as Sweden, the United Kingdom, and Australia [44]. Further, voluntary certification programs and habitat conservation plans may contain inferences to compliance issues, such harvest planning strategies that contain goals related to the spatial management of forest land [29]. These laws and directives typically stem from the desire to alleviate the effects of forest management on forest fragmentation and other ecological processes, the creation of frost pockets that hinder reforestation, and public pressure related to aesthetic quality [44].

Over the last two decades, a number of researchers and practitioners have performed and reported reviews related to forest planning. For example, Church et al. (1998) describe how forest management issues are closely related to other similar issues in the location sciences. In addition, the quantitative basis for measuring spatial structure as a prerequisite to implementing forest landscape management has previously been characterized, and ecological goals assessed at the landscape level, especially those objectives concerning the negative effects of habitat fragmentation, have been discussed [11, 136]. Nowadays, in some areas of the world, forest landscape management uses an ecosystem-based approach, which requires different management paradigms, modeling approaches, and software engineering techniques. As a result, Baskent et al. (2000) discuss recently introduced planning methods one might use to design an ecosystem-based forest management plan. Although we recognize that others have also suggested that spatial forest planning is a trend in natural resources management. One review discussed the necessary factors that have led to its adoption and also describes why the planning process may be avoided [29].

A number of types of forest management problems related to the location sciences have been classified to emphasize the locational issues in forest management [58]. As early as 1990, researchers introduced the idea of heuristic simulation, and provided a brief review of its capabilities for accommodating spatial forest plans [71]. Besides North America and Europe, some developing countries also have accumulated significant research on spatial forest planning; for instance, Epstein et al. [72] provide a review on the application of operations research systems in Chilean forest industries. Besides the conventional single-objective plans, a review of multiple criteria decision support in forest management illustrates how these methods could be beneficial for one or more types of spatial forest planning problems [127]. Martell et al. (1998) review methods for strategic forest management, short-term forest planning, forest operations, and forest fire management, and discuss the opportunities and challenges for operational researchers. Nurullah et al. (2000) review the need for spatial stratification as a method to organize the geographical information. Murray (1999) reviews some specific constraint functions also have been reviewed, such as the unit and area restriction models, two basic kinds of adjacency constraints in harvest scheduling. One of the most common spatial constraints in forest planning is related to the adjacency and green-up of clearcut harvests, an area of research that has stimulated researchers and practitioners to find more efficient solution processes for spatial forest planning problems. As early as 1990, reviews concerning the analysis of adjacency constraints have been presented [217, 242]. Due to the combinatorial complexity of spatial forest planning problems, forest planning problems have become much more difficult to solve. Reviews of combinatorial problems induced by spatial forest harvest planning were presented by Weintraub et al. (2000a) and Weintraub and Murray (2006). Weintraub (2007) further reviews some traditional mathematic programming techniques, such as the use of integer programming for spatial forest planning.

A comprehensive review of mathematical forest planning in North American literature was presented by Bettinger and Chung (2004), providing forest managers and researchers who are involved in forest planning tasks with a good grasp of the trends in forest planning techniques associated with the change in the forest management planning environment. In contrast, the review presented here is broader in both scope (world-wide) and depth (more analysis within spatial forest planning models). Previous reviews have discussed the conceptual frameworks of spatial forest planning, and included a discussion of the spatial configuration related to the forest patches. In addition, various management approaches that could be used to conceptualize spatial forest planning problems were posed, along with a discussion of challenges related to spatial forest planning [14]. Compared to this, our forthcoming review considers a more extensive analysis of the status and trends over the past two decades. In our investigation, we hope to understand the roles of objective and constraint functions in spatial forest planning. The configuration of the objective function, for example, may provide information regarding shifts in what researchers and land managers want their spatial forest plans to accomplish. Constraint functions may also illustrate that more restrictions are being placed on forest plans, or that a different set of restrictions now applies, as opposed to twenty years ago. Thus, our objective is to expend a greater effort understanding the current status, trends, and gaps in the spatial forest planning literature.

2 Methods

We conducted an extensive literature review of peer-reviewed spatial forest planning research based on a full search of twenty-three international journals and a limited examination of 19 other journals whenever there was an indication, through the review, that relevant spatial forest planning literature might be located there. This review is mainly concerned with the use of techniques for problem-solving, and not necessarily about how problems are structured or about how models are built. These latter two concerns are more difficult to understand given the various manners in which research results are presented. Therefore, we developed a classification process and used it to categorize the papers in various ways, including (a) the methods used to accommodate the planning model, (b) the types of objectives and constraints that were recognized, and (c) the size of problems that were being addressed. The full classification that we used can be found in Tables 1 through 3. We examined papers published from January 1989 and through December 2007.

Because of the complexity of natural resource management problems today, and given our previous knowledge of the literature, we expected that much of the literature reported the development, testing, and analysis of new techniques for accommodating spatial forest planning issues. The two basic groups of techniques involve heuristic methods and traditional mathematical programming methods. In our assessment, mathematical programming methods were sub-divided (Table 1) into exact techniques (linear programming, goal programming, integer programming, mixed integer programming (MIP), and non-linear programming) and other techniques (dynamic programming, simulation, and others). We consider exact techniques as those that are generally deemed to guarantee the location of an optimal solution to a planning problem. Heuristics and other techniques generally cannot provide this guarantee. Heuristic techniques were subdivided into seven commonly used methods (genetic algorithms (GA), Monte Carlo integer programming (MCIP), simulated annealing (SA), tabu search (TS), threshold accepting (TA), the raindrop method, and other heuristic methods).

The type of forest planning methods applied to spatial planning problems is of interest from a number of perspectives: (a) some methods are more well-understood by practitioners than others, (b) some methods have been demonstrated over time to be robust or simply adequate, and (c) some methods are better for addressing certain problems than others, from both computational speed and computational complexity perspectives. We know that some research papers describe the use of up to eight planning techniques [24], while most describe only one or two. In these cases, a number of planning techniques may have been recorded as being used, all arising from a single paper. In cases where two or more techniques are present in a research paper, this usually suggests that a validation or comparison of techniques is performed. Further, in some instances a single technique (e.g., tabu search) may have been examined using several different formulations or modifications [201]. In cases such as these, the number of times a technique is noted as being used is limited to one instance. In other words, various modifications to techniques are not recorded beyond the fact that the type of technique is used.

Table 1: Categories for forest-level planning techniques described in peer-reviewed articles.

Major categories	Sub categories
Heuristics	Genetic algorithms
	Monte Carlo integer programming
	Stimulated annealing
	Tabu search
	Threshold accepting
	Raindrop
	Other heuristics
Exact techniques	Goal programming
	Integer programming
	Linear programming
	Mixed integer programming
	Non-linear programming
Other techniques	Dynamic programming
	Qualitative analysis
	Simulation
	Others

Deciphering the formulation of planning problems is relatively straightforward in most research papers, but this is not universally the case. While a formal description of a planning problem may seem requisite, a number of papers have been published where it is difficult to ascertain the objective or constraints under analysis. We began our assessment of the literature with a preliminary categorization of the elements within the objective and constraints. The categories evolved as our assessment grew, however. Table 2 represents the major categories and sub-categories of objective functions that we determined. As we suggested, we began with a smaller set, and found that it needed expansion as the literature search proceeded, since some objectives were not assumed *a priori*. For example, economic and commodity production objectives are the most obvious forest planning objectives. In addition, we assumed wildlife habitat objectives would be found in the literature. However, during our search, we located research that used measures commonly considered as constraints (e.g., adjacency) in the objective function of planning problems.

With each forest and landowner comes a different set

Table 2: Objective functions categories for forest-level planning peer-reviewed articles.

Major categories	Sub categories
Economic and commodity production	Maximize net present value
	Maximize revenue
	Minimize discounted costs
	Wood flow
Wildlife habitat	Maximize acres in habitat
	Maximize species
Forest structure	
Biodiversity	
Recreation	
Other objectives	Fire
	Entomology
	Adjacency
	Landscape metrics
	Minimize shape index or clustering
	Minimize site disturbance
	Regeneration area
	Water yield

Table 3: Constraint categories for forest-level planning peer-reviewed articles.

Major categories	Sub categories
Economic and commodity production	Net present value
	Revenue
	Budget
	Wood flow
Aquatics	Stream sediment
	Stream temperature
	Water yield
Forest structure or inventory	
Adjacency	
Road-related	
Wildlife	
Minimum or maxaximum harvest age	
Other constraints	Fire
	Entomology
	Biodiversity
	Carbon
	Optimal bucking
	Processing capacity or materials

of objectives and constraints. The ideal situation of each landowner behaving rationally with economic or ecological objectives and institutional constraints on budgets and timing considerations does not necessarily hold. As a result, a wide variety of constraints were anticipated in the assessment of the literature. For example, we planned to locate economic and commodity production constraints as well as those related to habitat, adjacency, and forest structure (e.g. ending inventory). Some forest-level constraints were unexpected (entomology, carbon) and were represented by few papers; therefore the "other" category contains several diverse natural resource planning constraints. In a number of cases the constraints used in various research papers were embedded informally as thoughts within the text, and therefore required a careful reading of the methodology of each paper.

Over a period of six months, the main 23 journals we targeted were systematically reviewed by first viewing the titles of manuscripts to determine whether further analysis was necessary. The reference work within the literature we located led to other sources of research outside of our initial area of search. We also consulted the vitae of numerous scientists working in this field, if those vitae were available over the Internet. When we felt we had exhausted our search, we began to synthesize the contributions made thus far in spatial forest planning.

3 Results

Developing a comprehensive review of spatial forest planning literature is somewhat difficult given all of the potential venues in which peer-reviewed literature might be located. Some journals provide efficient access through the Internet, while others do not. In addition, our organization (University of Georgia) does not necessarily provide researchers direct, no-cost access to every journal. Undeterred, 245 papers were located that report results or discussion on spatial forest planning activities. We found over half of the papers on spatial forest plannings in either *Forest Science* (27.1%), the *Canadian Journal of Forest Research* (16.5%), *Forest Ecology and Management* (7.6%), or the *European Journal of Operational Research* (5.1%). These results were not unexpected since spatial forest planning approaches represent advances or new developments in operations research methods applied to natural resource management. These advances are better suited to journals that accommodate theoretical research, rather than journals that accommodate applied research transfer to forest managers. A number of other journals contained several papers on spatial forest planning, including *Silva Fennica*, *Scandinavian Journal of Forest Research*, *The Forestry Chronicle*, and *Ecological Modelling*. These findings were expected, since these journals have forestry or natural resource management as their main emphasis. A few other journals that do not have forestry or natural resource management as their main emphasis contained as many papers as these, however, including *Operations Research*, *Journal of Environmental Management*, and *Annals of Operations Research*. Some papers were located through limited searches in journals such as *Tree Physiology*, *Water Resources Bulletin*, *Location Science*, *Nonlinear Analysis*, and *Discrete Applied Mathematics*. The difficulty for researchers and managers new to the field is that at least 42 journals serve as sources for spatial forest planning literature. As a result, the ability to locate pertinent research may require a considerable commitment of time.

The number of peer-reviewed forest planning papers increased at a rate of about 1.5 papers per year during the 1990s (see Figure 1). The largest number of papers appearing in our literature review occurred in 2000. The rate of publication of papers has declined slightly since 2000. With the exception of a few odd years (e.g., in 2004, only 5 papers were located in the journals.), the rate of publication seems to be between 10 and 15 papers per year. While implementation of these techniques into real-world planning effects remains a challenge, we may be seeing the end of the exploratory phase of spatial forest planning. A number of the early papers on this subject described new methods for incorporating spatial concerns in a forest plan or described new problem-solving methods for spatial forest planning problems. Advances in these areas may continue, however many further example applications may not be seen as novel. In essence, we may be transitioning into a phase of competitive testing and analysis, which may require an expanded effort of a research team to produce a peer-reviewed manuscript.

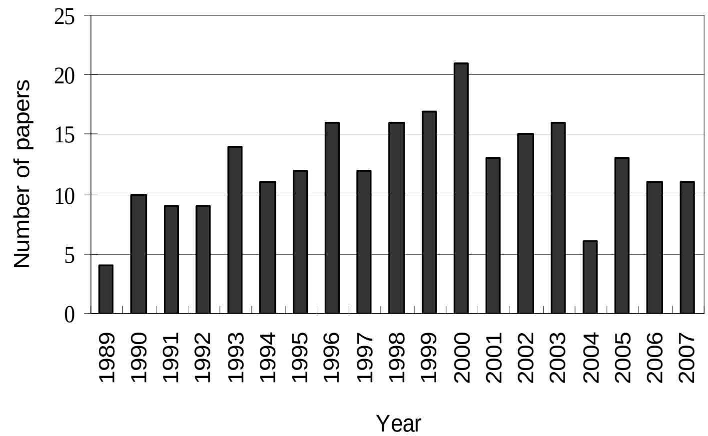

Figure 1: Number of publications in the spatial forest planning literature, by year.

3.1 Solution Techniques for Spatial Forest Planning Problems

The results from our survey show that during the 1990s, exact methods were mainly used for problem solving or validation purposes (Figure 2). However, since about 2000, heuristics have become just as frequently used. Although linear programming and its derivatives are still illustrated in recently published papers, they are generally used to generate the exact or the "relaxed" solutions to a problem in order to validate heuristic methods (and other methods as well), or are limited to solving various small-size problems. Simulation methods are used consistently in research papers throughout this time span, however to a much lesser extent than heuristics. The results also show that dynamic programming has shown value as a forest-level planning technique, rather than simply as a stand-level optimization technique. It is important to realize that dynamic programming produces optimal solution to individual subproblem in some specific paper [107], and its combination with other approaches to get a non-exact solution to the master problem in the same paper.

It is well known that one of the disadvantages of heuristic methods is that one cannot prove the solution located is the best solution to the problem, whereas exact methods provide a guarantee of optimality. However, as problem sizes increase, it may be impossible to solve large problems using tractable analytical methods [150]. In addition to the common exact and heuristic methods, researchers have continuously attempted to solve spatial forest planning problems with new methods. Each year several of these new methods appear in journals. However, in some cases these new techniques cannot be applied to the wider range of forest planning problems without encountering some computational issues (e.g., [20]). For example, an optimized method based on cellular automata has been applied to solve spatial forest planning problem [93]; fuzzy multicriteria approval method which is based on approval voting has been used in forestry decision support [122], and ant colony optimization has been adopted for the risk management of wind damage in forest planning [247].

Researchers initially considered exact techniques (table 4) as the most appropriate way to solve spatial forest planning problems. Goal programming (8 papers), integer programming (14 papers), mixed integer programming (29 papers), linear programming (64 papers) and non-linear programming (6 papers) have been used to solve economic and commodity production objective function problems, yet the problem size is usually limited to less than about 1,000 management units. Large and more complicated problems may require use of heuristics

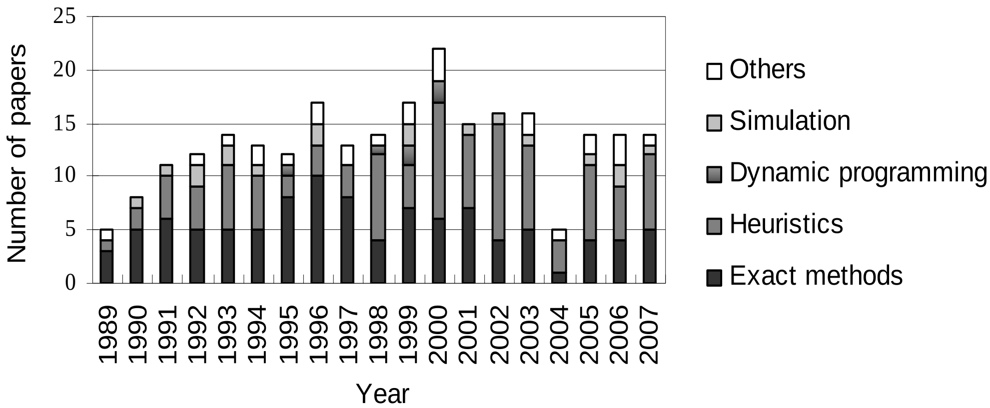

Figure 2: Type of mathematical programming technique in the spatial forest planning literature, by year.

such as GA (15 papers), MCIP (17 papers), SA (33 papers), TS (25 papers), TA (4 papers), and the raindrop method 32].

MCIP is one of the earliest heuristic methods used in forest planning and it helped illustrate the importance of heuristic methods to the forest managers by allowing the solution of spatial forest planning problems that could not be solved using traditional exact methods. Some advantages of MCIP are that it is computationally fast, conceptually simple, and easy to program and modify [174]. Thus, it is not uncommon to find that about 70% of forest planning problems used the MCIP method on real (not theoretical) data. Within forest planning, it has been applied to problems related to economic [8] and commodity production problems [61, 117, 200], and those involving adjacency constraints [67, 139, 175], wildlife habitat [89], and road system management issues [174]. The literature indicates that around 65% of the MCIP examples were published before 2000. After that, MCIP has typically been used as a method with which to compare against other recently developed heuristic methods.

The concepts that form the basis for SA were first published by Metropolis et al. (1953) and are based on an algorithm that simulates the cooling of materials in a heat bath, a process known as annealing [24]. Generally speaking, SA is implemented as a 1-opt process, where changes to a single decision variable are considered. If the changes lead to a less desirable solution, the SA criterion is employed to determine whether or not to accept the proposed change in the solution. We determined that the number of papers describing SA for solving spatial forest planning problems is 33, which is the largest group among all the heuristic methods. Within forest planning, SA has been applied to problems related to economics [186, 220], commodity production [12, 150, 206], recreation [40], landscape design [54, 187, 188], adjacency issues [65, 213], road system management issues [66], regeneration [120], biodiversity [146], forest structure [149, 185], and wildlife habitat [224]. These results also illustrate that SA is widely used throughout the world, thus one of the most common heuristic techniques in natural resource planning and research. The locations of the work include Oceania, Asia, U.S.A., Europe, and Canada. Most papers, however, involve the latter three areas of the world.

TA is similar to simulated annealing in how it operates. However, TA accepts every new (proposed) solution that is not much worse (within a threshold) than the previous current solution, whereas in SA there is only a probability that a less desirable proposed solution would replace the current solution [24]. We only located four TA papers in the literature, and three of them [24, 50, 191] are used to compare with other heuristic methods. Only one paper [25] relied on the unique TA method to assess the ecological and economic goals in a forest plan.

Tabu search, which is one of the most extensively used heuristic methods for solving forestry-related problems, is a hill-climbing algorithm and combinatorial optimization technique. The search process arrives at the best solution by incrementally adding (or removing) decision choices to (or from) a solution, yet avoiding a continual re-selection of a subset of these choices based on their influence on the objective function [21]. Tabu search is also generally implemented as a 1-opt process, however improvements have been noted with the addition of intensification (2-opt) or diversification (frequency analysis or strategic oscillation) processes. Tabu search analyzes a "neighborhood" of proposed changes to a solution prior to selecting one, changes are then considered off-

Table 4: Related papers for forest-level planning techniques described in peer-reviewed articles.

Technique categories	Literature
Genetic algorithms	24, 42-45, 70, 75, 76, 148, 152, 163, 194, 225, 246, 247
Monte Carlo integer programming	8, 24, 41-43, 61, 67, 76, 89, 117, 139, 174, 177, 200, 201, 227
Stimulated annealing	12, 15, 24, 40, 41, 50, 54, 65, 66, 92, 93, 120, 146, 149, 150, 166, 172, 185-188, 191, 194, 206, 208, 213, 220, 222-224, 246, 247
Tabu search	17, 20-22, 24, 27, 30, 31, 41-45, 47, 52, 92, 134, 142, 164, 166, 172, 191, 194, 201, 246
Threshold accepting	24, 25, 50, 91, 191
Raindrop	32
Other heuristics	2, 5, 7, 24, 57, 60, 63, 66, 74, 84, 92, 93, 103, 121, 125, 130-132, 134, 137, 140, 148, 152, 156, 166, 170, 178, 184, 191, 192, 194, 204, 207, 226, 230, 231, 233, 234, 238, 241, 243, 244, 247
Goal programming	19, 38, 56, 69, 133, 138, 181, 237
Integer programming	7, 17, 21, 64, 82, 83, 156, 168, 169, 210-212, 240, 241
Linear programming	5, 15, 18, 20, 21, 33, 34, 39, 42, 45, 46, 48, 49, 55-57, 62, 64, 67, 68, 77, 79, 81, 88, 95, 98, 100, 103-106, 109, 115, 118, 141, 147, 153, 160, 162, 167, 168, 171, 173, 175, 177, 184, 186, 196, 199, 200, 202, 203, 205, 213, 215, 220, 226, 227, 229, 230, 233, 236, 238, 243
Mixed integer programming	2, 33, 35, 53, 60, 62, 73, 74, 96, 97, 101, 142, 157-159, 167, 174, 179, 180, 198, 218, 219, 230, 231, 233, 234, 238, 243, 245
Non-linear programming	99, 100, 102, 104, 106, 237
Dynamic programming	36-38, 107, 108, 110, 189
Qualitative analysis	114
Simulation	3, 10, 26, 28, 59, 85-88, 110, 113, 115, 119, 144, 162, 173, 182, 216, 239
Others	1, 4, 6, 9, 51, 80, 81, 90, 94, 122-126, 128, 143, 151, 154, 161, 176, 193, 195, 197, 214, 218, 221

limits for a number of iterations of the model. Within forest planning it has been applied to problems related to economics [17, 45, 172, 194], commodity production [20, 21, 164, 191], stream sediment and temperature [27], adjacency issues [41, 43, 44, 47, 92], wildlife habitat [22, 30, 43], road system management issues [135, 201], and forest structure [52]. The literature illustrates that the size of the planning problems in the 25 tabu search papers we located are larger than 100 management units (75% of them among 100 to 1,000 units, others were larger than 1,000 units). There are usually two types of decision procedures in tabu search: a change to single-decision choices (1-opt moves) and changes to two-decision choices (2-opt moves). Since 1999, almost half of tabu search papers have discussed the advantages and disadvantages of using combinations of 1-opt and 2-opt. The use of 2-opt moves allowed the tabu search procedure to find better solutions because the changes in the objective function value are not as severe as with using a 1-opt neighborhood alone, where changes are made simply to the status of individual harvest units [21].

Genetic algorithms are a population-based, nature-inspired random search technique, and were first developed by Holland (1975) in an attempt to locate global optimal solutions to complex problems. With genetic algorithms, a population (set) of solutions is generated. These are then combined randomly or deterministically to create new solutions. The new solutions are then modified slightly through "mutations." The population is then updated, and the search continues until stoppings criteria have been recognized. In concept, the method is not very appropriate for solving spatial forest-planning problems unless limited amounts of genetic material (pieces of forest plans) are incorporated into new solutions. However, as its development proceeded and given successful application in other areas, such as strategic planning, machine learning and so on, since about 2000, researchers and practitioners have successfully applied GAs to spatial forest planning problems. Within forest planning, it has been applied to problems related to economics [152], commodity production [75], adjacency issues [148], forest structure [76], wildlife habitat [163], and landscape design [225]. Some researchers have conducted comparisons between GA and other heuristic methods, such as SA, and TS. For each iteration of a GA model, there may be multiple changes to a forest plan, and thus GA is relatively slow compared to some of the other heuristic methods. Opinions vary on the application of GAs to spatial forest planning problems. In the study of Bettinger et al. (2002), it was concluded that a basic GA was not as good as SA and TS. The same conclusion was attained by Liu et al. (2006), who suggest that simulated annealing is more efficient than genetic algorithms for forest harvest scheduling problems. However, Pukkala and Kurttila (2005) pointed out that GA might be better than SA and TS in spatial problems. However, they also concluded that GA was not good in very simple problems, and the improved performance of GA in the most difficult problems can result from the fact that it was the only technique where a move could imply more than one change in the solution [194]. For spatial problems, the best GA algorithms may be those that transfer limited genetic material in the development of new (child) solutions. There still exist fertile areas of subjects to research, including variable mutation rates and crossover probabilities, or the use of dynamic penalty functions, with parameters self-modified with the convergence process [75].

3.2 Objective Function Components The economic and commodity production concerns of landowners continue to account for the majority of objectives in spatial forest planning problems presented in the literature (Figure 3). However, long-term sustainable forest management challenges have prompted researchers to pay more attention to wildlife habitat, forest structure, biodiversity, recreation, and other objectives. As a result, about one-third of the spatial forest planning papers accommodate other goals in the objective function of the problems presented. These are either single-objective optimization problems, or more commonly, goal programming problems that use various forms of utility functions. Interestingly, in Europe, utility functions have become common aspects of spatial forest planning [143], yet in North America, penalties are more commonly added to single parameter objective functions [12]. Why this is the case has yet to be understood, but may be related to the goals and objectives of both the planners and the land managers.

The maximization of net present value (97 papers), revenue (28 papers), and wood production (76 papers) are still the highest-level issues of researchers and practitioners, as is the minimization of discounted costs (20 papers). Policy makers and private landowners continue to balance economic and commodity production objectives with other non-product objectives, however. Objectives which include maximizing area in habitat (19 papers) and maximizing wildlife species populations (9 papers) dominate the non-product objectives that researchers and practitioners have considered (table 5). The population and habitat of a wildlife species is mostly affected by the landscape features and spatial distribution factors that are considered in a spatial forest planning process. Forest structure (16 papers), biodiversity (11 papers), recreation (12 papers) are also hot topics in spatial forest planning. Other objective function components have included those related to entomology (Hof et al. 1997), adjacency of harvests (8 papers), landscape metrics (6 papers), shape indexes or clustering (3 papers), site disturbances (3 papers), regeneration areas (Jorgensen et al. 1992), and water yield (4 papers). Papers that describe single-objective problems represented about 69.1% of the literature. Papers describing two-parameter objective functions represented about 19.1% of the literature, and the rest of the literature include more than three components in the objective function. As a result, we have seen an increase in the use of multiple objective function problems in spatial forest planning over the past ten years.

3.3 Constraint Components Two constraints have dominated forest-planning problems over the last twenty years: (1) those that are fragmentation related, or involve harvest size or adjacency issues; and (2) those that involve economic measures or commodity production goals (Figure 4). The economic and commodity production constraints represent some of the more traditional constraints in forest plans. Economic and commodity production constraints (table 6) include those related to net present value [51], revenue (10 papers), budgets (9 papers), and even wood-flow (113 papers). Adjacency and green-up relationships, which address the juxtaposition of harvests and habitat, are perhaps the single most widely used spatial constraints in forest planning today [32]. The papers that involve adjacency relationships are numerous (90 papers). While we are unable to determine cause or effect, spatial forest planning problems seem to have become more complex as time proceeded through our analysis, and there has been a shift from a reliance on exact techniques or Monte Carlo simulation to the use of various heuristics. In addition, the constraints incorporated into these manuscripts have become more complex in recent years, using functional relationships related to wildlife habitat, biodiversity, aquatic resources and others. We assume the need to incorporate the complex relationships prompted the exploration of alternative solution methods, however, one could argue that the use of alternative solution methods allows a more extensive set of resource evaluation rules to be incorporated into forest plans. In addition, validating these problems (when solved with heuristics) becomes problematic because exact methods often are incapable of solving the full problem.

Other constraint functions (table 6) that have been considered include those related to forest structure or inventory (60 papers), road management (20 papers), wildlife (30 papers), minimum or maximum harvest ages (40 papers), and aquatics, which includes stream sediment (7 papers), stream temperature (2 papers), water

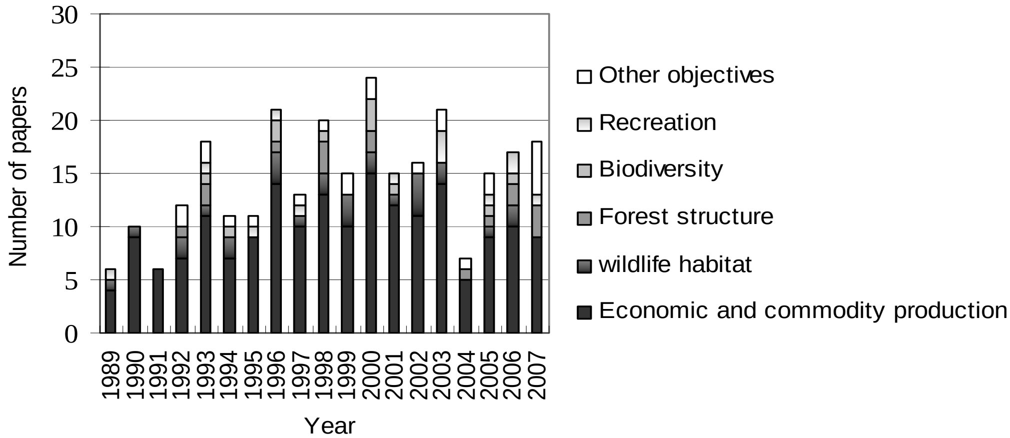

Figure 3: Objectives contained in the spatial forest planning literature, by year.

Table 5: Related papers for objective functions categories in forest-level planning peer-reviewed articles.

Objective categories	Literature
Maximize net present value	2, 4-8, 17-20, 27, 31, 36-39, 41-46, 50, 52, 53, 56, 57, 60, 62-64, 66, 69, 70, 73, 75-77, 80, 81, 90, 93, 107-109, 116, 122, 123, 126, 130, 134, 135, 140, 141, 143, 150, 152, 153, 157, 162, 164, 166, 169-173, 175, 185-188, 190, 194, 198-200, 202, 205, 206, 209, 213, 214, 219-221, 223, 230, 231, 233, 234, 236, 238, 241, 243-245
Maximize revenue	1, 32, 33, 48, 56, 65, 83, 102, 104, 105, 110, 121, 128, 138, 146, 158, 159, 161, 168, 174, 192-194, 196, 208, 218, 221, 227
Minimize discounted costs	20, 48, 61, 74, 89, 98, 99, 102, 103, 110, 113, 142, 154, 179, 180, 189, 201, 214,233, 234, 240
Wood flow	10, 15, 20-22, 26, 30, 32, 34, 40, 47, 54, 55, 61, 67-70, 79, 82, 84-88, 91, 100-102, 115, 117, 119, 121, 123-126, 128, 130-133, 137, 142, 148-151, 156, 160, 176, 177, 181, 182, 184, 195-197, 199, 200, 206, 211, 212, 215, 216, 221, 224, 229, 238,243, 246, 247
Maximize acres in habitat	1, 4, 22, 24, 49, 100, 137, 161, 163, 179, 180, 191, 194, 196, 197, 202, 203, 207, 240
Maximize species	33, 88, 96, 101, 126, 181, 186, 191, 204
Forest structure	40, 69, 91-93, 100, 125, 143, 149, 185, 191-193, 197, 221, 245
Biodiversity	19, 106, 122, 125, 131, 132, 140, 149, 194, 197, 222
Recreation	1, 40, 122, 123, 126, 128, 133, 143, 161, 181, 194, 195
Fire	214
Entomology	97
Adjacency	3, 9, 92, 93, 144, 150, 239, 247
Landscape metrics	54, 91, 100, 225, 246, 247
Minimize shape index or clustering	187, 188, 219
Minimize site disturbance	3, 126, 134
Regeneration area	93, 120
Water yield	95, 151, 197, 234

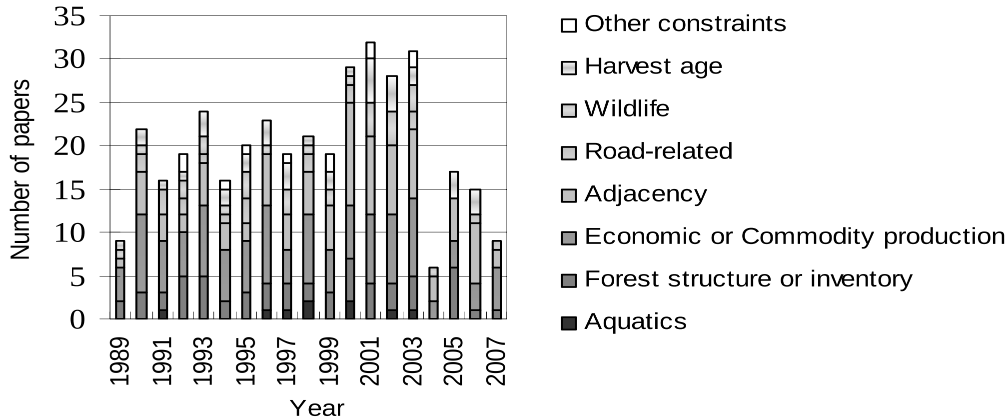

Figure 4: Constraints contained in the spatial forest planning literature, by year.

yield (5 papers). In addition, other noteworthy constraints include fire, entomology, biodiversity, carbon, optimal bucking, processing capacity or materials.

3.4 Type of Data used in Forest Planning Research The type of the data that has been used in spatial forest planning research is characterized as hypothetical and real, and raster and vector. We used our best judgment, where necessary, to make these determinations. Raster data and vector data are the two basic GIS data structures that we considered in the review. Raster data is characterized by regular-shaped grid cells (pixels) obtained from satellites or other geoprocessing methods. This data structure can be manipulated quickly by a computer, thus computations are generally more efficient. Vector data includes points, lines, and polygons (irregularly shaped), which are derived from air photo image interpretation, digitizing, and land surveys. Since this data is relatively easy to obtain and use, it is not uncommon to find that vector data is more prevalent in forest planning problems compared to raster data (Figure 5). Within the 245 papers we located, we determined that 50 used raster data, 107 used vector data, and 10 used both, which means that about one-third of the papers did not explicitly refer to one of these two data structures (we considered the review papers to not mention either of them). Although it is hard to argue against the fact that vector data is prevalent in the planning process, the trends indicate that researchers and practitioners may be suggesting that a single data structure is not enough to satisfy the needs of complex spatial forest planning and research. In order to further describe the type of data used, we classified it as real or hypothetical (Figure 6). It seems obvious that researchers would want to test their methods on real data, but due to the complexity of the planning problems, researchers at many times resort to testing their methods on hypothetical data. Among the 245 papers we reviewed, 140 used real data, 72 used hypothetical data, and 5 used both. Through our interpretation of the literature, we concluded that 143 of the papers represent applications and 87 lacks an example of the use of the techniques in applied spatial forest planning, and of course 18 are review papers (Figure 7). As a result, many of the applied research papers utilize hypothetical data. Two reasons for this include the difficulty in obtaining large databases describing actual landscapes, and the inability to obtain permission to illustrate an organization's data in a published research paper.

3.5 Geographic Location of the Problems While the importance of forest planning has been realized worldwide, research on forest planning is costly and the objectives nowadays do not concern economic or commodity production. Thus, developing countries may be short of such funds for conducting forest-planning research or may not place high importance on its use in forest management. In the literature, the countries or continents where most of the published forest planning problems are geographically situated (Figure 8) are: USA (68 papers), Canada (34 papers), and Europe (48 papers). However, researchers and practitioners have also solved some spatial forest planning problems in Oceania (6 papers), South America (7 papers), Asia [54, 241], and Africa [181].

3.6 Spatial Concerns As we noted earlier, spatial forest planning is used to examine patterns and trends in the spatial development of landscapes, and focuses on forestry and natural resource management activities

Table 6: Related papers for constraint categories for forest-level planning peer-reviewed articles.

Constraint categories	Literature
Net present value	.51
Revenue	48, 138, 166, 168, 174, 175, 181, 202, 208, 238
Budget	55, 68, 82, 117, 133, 141, 164, 179, 181
Wood flow	2, 5, 6, 8, 15, 18, 20, 21, 24, 26, 27, 31, 40-49, 52, 53, 60-65, 67, 68, 70, 73, 75-77, 79-82, 84, 90, 96, 98, 99, 103-106, 108, 109, 113, 115, 116, 133-135, 137, 138, 141, 142, 148, 153, 157-162, 164, 166, 168, 169, 171, 173-178, 181, 183, 186,187, 189, 190, 196, 198, 199, 201, 205, 206, 209, 211, 215, 218-220, 222, 223, 226, 229-231, 233, 236, 238, 241, 243, 245
Stream sediment	27, 31, 151, 220, 231, 233, 238
Stream temperature	27, 31
Water yield	35, 133, 151, 205, 220
Forest structure or inventory	5-7, 17-19, 21, 28, 39, 46, 51, 52, 57, 59, 62, 64, 65, 68, 76, 77, 80, 83, 95, 104-106, 109, 110, 116, 117, 120, 138, 156-158, 160-162, 171, 173, 175, 176, 182, 185, 186, 188, 189, 196, 198, 200, 202, 205, 208, 209, 216, 227, 229, 230, 241
Adjacency	7, 9, 10, 15, 17, 24, 26, 32, 36-38, 41-45, 52, 53, 60, 61, 63-67, 76, 81-88, 90, 94, 100, 107, 108, 111, 117-119, 134, 139, 144, 146, 148, 149, 151, 154, 156-159, 166-170, 174-177, 184, 185, 190, 198, 200, 201, 208-213, 215, 216, 218-220, 222, 223, 226, 227, 230, 239, 241, 243
Road-related	2, 10, 60, 66, 74, 82, 104, 105, 134, 142, 166, 174, 177, 189, 201, 231, 233, 238
Wildlife	25, 30, 33, 34, 42, 49, 50, 62, 87, 89, 94, 100, 101, 103, 106, 133, 147, 151, 161, 172, 180, 181, 200, 202-204, 220, 224, 227, 240
Minimum or maximum harvest age	8, 19, 24-26, 28, 30, 34, 42-44, 51, 65, 67, 77, 83-88, 95, 98, 102, 103, 109, 111, 148, 159, 161, 171, 176-178, 182, 212, 216, 227, 243, 244
Fire	199
Entomology	97, 162
Biodiversity	19, 133, 146
Carbon	135
Optimal bucking	73, 141
Processing capacity or materials	6, 48, 80

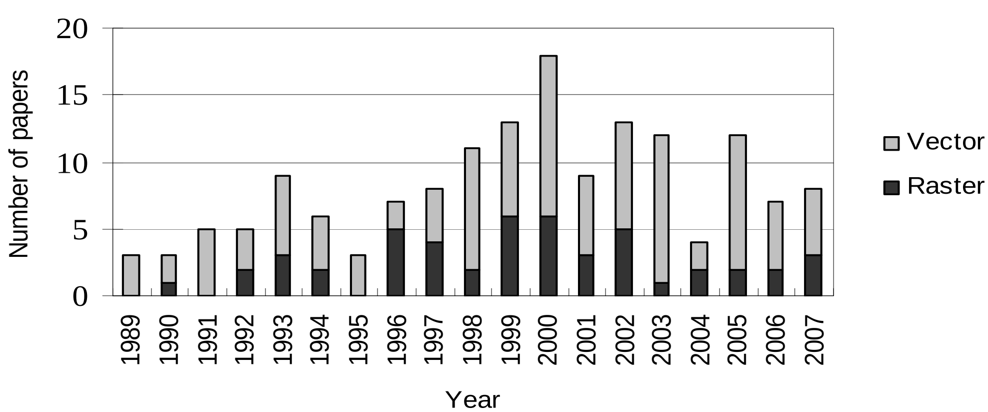

Figure 5: Vector and Raster data in the spatial forest planning literature, by year.

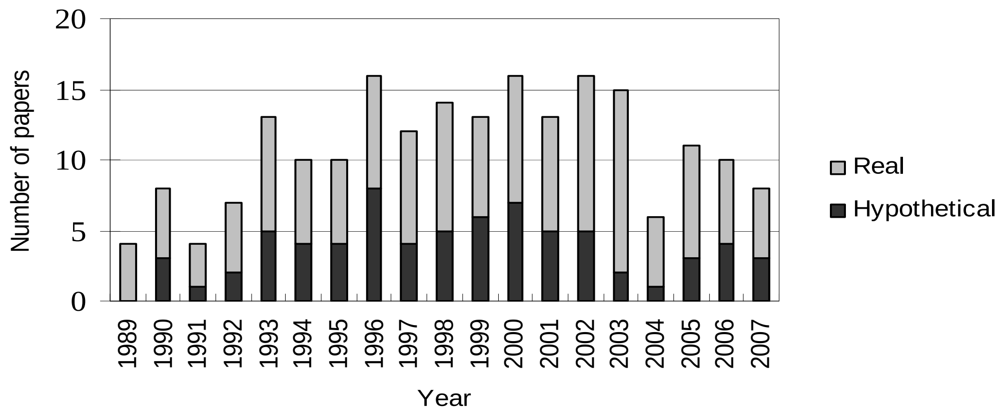

Figure 6: Real and theoretical data in the spatial forest planning literature, by year.

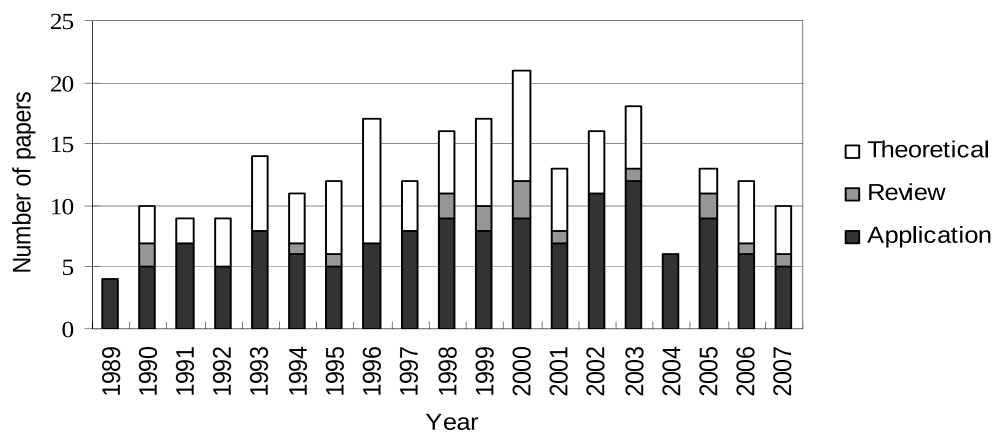

Figure 7: Type of papers in spatial forest planning literature, by year.

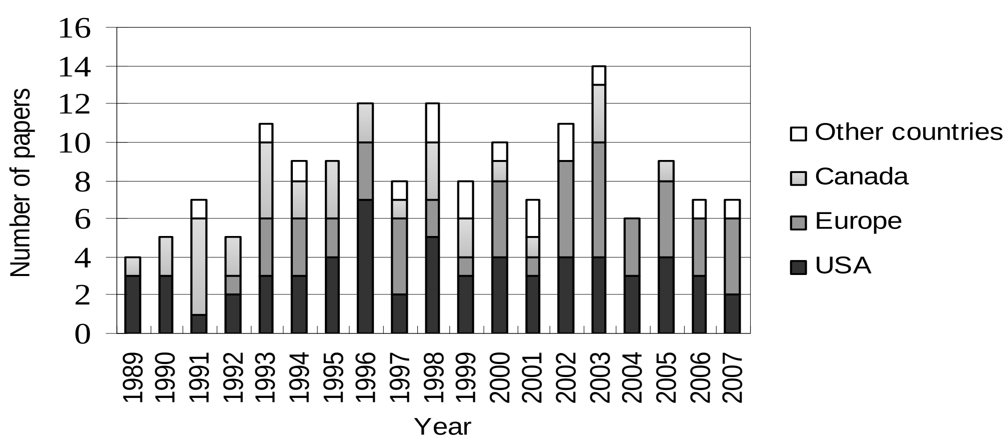

Figure 8: Location of spatial forest planning analyses, by year.

and the specific tools used to develop, implement, and evaluate forest plans and alternative policies [9]. These are core elements of spatial forest planning. Control of these concerns has been accomplished through the objective function and constraints of the problem formulation (see tables 5 and 6, and sections 3.2 and 3.3). Therefore, given the structure of the model being used and the creativity of the planner, there are a number of ways by which one can acknowledge and accommodate spatial concerns in forest plans. An increase in the spatial restrictions or objectives in forest planning problems is evident by the results (Figure 9). In our classification of objectives, spatial objectives include those related to wildlife habitat (some maximizing acres in habitat are not spatial), forest structure, adjacency, and many others. The spatial constraints include adjacency, aquatics, forest structure or inventory, wildlife, and road management. Only 37 papers among 245 papers we found used non-spatial models. Among these, a few attempt to address hypothetical problems [16, 98, 99, 102, 113, 115, 203, 209] and related these to potential practical application.

3.7 The use of Geographic Information Systems (GIS) Since the introduction of GIS in natural resource management, there has been a logical increase in the application of GIS to forest planning (Figure 10). The role of GIS technology in spatial forest planning has, however changed significantly, from the source of input to the analysis tool of spatial models. One vital function of GIS is the ability to address locational issues, and to manage information in digital form, through an attribute database. GIS has also traditionally been used in forestry to store maps in electronic form and to make calculations, such as areas and distances [14]. However, if the spatial restrictions or objectives were not included in a forest planning problem formulation, and subsequent spatial analysis was necessary, GIS is used to only address these post-plan development issues. More recently, its use has been extended to analyses of potential land uses and other complex problems, which have a spatial context. However, it is not uncommon to see GIS used as an input facilitator rather than as an analysis tool.

4 Discussion

There are still many important areas in quantitative forest planning that need to be further studied. Although we have discussed that MIP methods are limited by problem size and are difficult to use for solving spatial problems, researchers and practitioners still attempt to use innovative formulations of MIP to obtain exact answers. For example, two MIP harvest-scheduling formulations have been developed to solve area-based adjacency problems [59]. Forest planning problems with patch size constraints or objectives that are essential for wildlife habitat concerns have also been addressed with new formulations of MIP [198]. Finding ways to apply exact methods, especially mixed integer programming, to very large problems without running into restrictions of the number of constraints, or without requiring extensive computational time to solve the problems is an area worth further research.

As we know, a large number of new algorithms appear every year in the area of operations research, and applying those algorithms to forest planning practice is an interesting topic. One relevant classification of heuristic methods is to separate heuristics that are based on populations of solutions from heuristics that are based on a single change to a solution (point-based algorithms). A point-based algorithm will only have one unique solution per iteration, and we update the best one with the new obtained solution if it is better than the best we have found before. With a point-based algorithm, we only need to define the current solution and use a metaheuristic to obtain a new solution. With a population-based algorithm, we have to define the current population and new population in each iteration. Additionally, we also need to initiate the population size and define the maximum population size allowed. Other population-based heuristic methods like particle swarm optimization, which has been successfully used in other areas including optimization of artificial neural networks, image processing, and computational biology, could also been applied in forest planning. More discussion of the advantages and disadvantages should follow, and they should be tested against various standard forest planning problems.

No matter what heuristic techniques one adopts to solve spatial forest planning problems, choosing the appropriate parameters seems to require the most attention. This issue is treated lightly in many papers, thus a broader explanation of the parameters for typical forest planning problems is needed in future work. One might ask whether there ways to estimate the parameters based on the type and size of a problem (figure 11), rather than needing to perform a number of trials to locate the acceptable range of parameters. Ultimately we need to find ways to estimate the appropriate parameters rather than have the user try to identify them, taking this process out of their hands.

Addressing limitations of the search process is also an area requiring more work. As we discussed, it is probably better for GA to swap small amounts of genetic material during each iteration of a spatial forest planning process, because the transfer of large amounts of genetic material during the crossover results in numerous violations of spatial constraints. The same is true in spatial

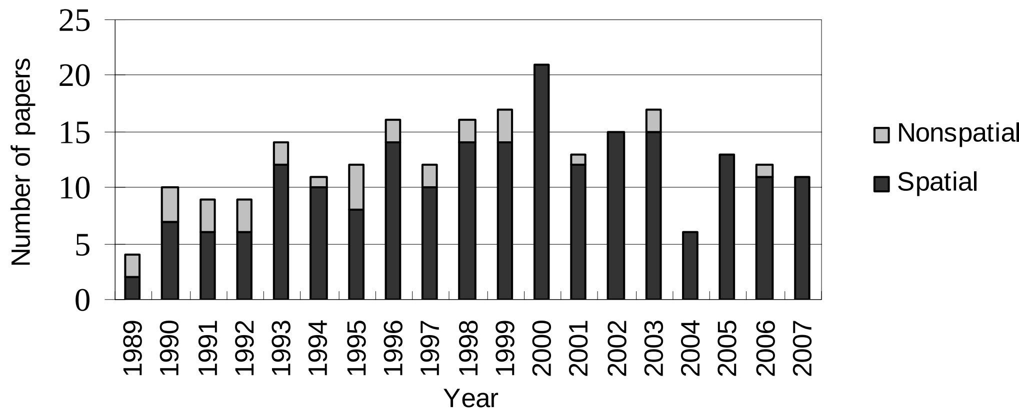

Figure 9: Number of papers that include spatial goals, by year.

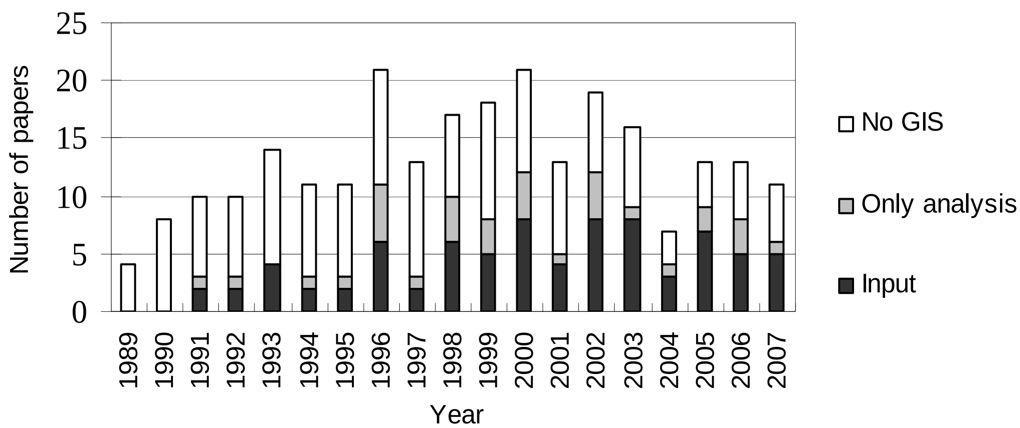

Figure 10: GIS use in spatial forest planning literature, by year.

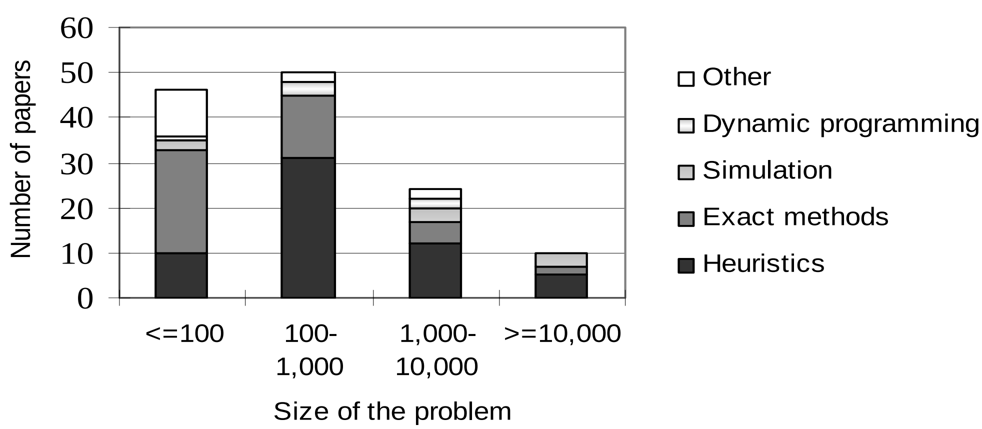

Figure 11: Size of the problem in spatial forest planning literature, by year.

forest planning problems when the mutation rate is high. After addressing these types of limitations, GA and its modifications could be more effectively used for spatial forest planning problems. Recently, an intelligent mechanism of combining standard heuristic methods such as TS, SA, TS, and the raindrop method has been developed by Li (2007). Using such a mechanism to study how to intelligently combine GA with other heuristics is new, and needs additional research to determine the most effective meta heuristic model.

Since heuristics cannot guarantee optimality, the development of a measure of quality is necessary. What we usually do in validations heuristic results is to assess the solution value, solution running time, complexity of programming codes, and various statistics including maximum value, minimum value, mean, standard deviation, and the estimated global optimum. These are often compared against results generated by other heuristic techniques, or ideally against an exact solution generated by traditional mathematical programming techniques. However, if the exact solution is elusive, a comparison against other heuristics only provides relative validation. One might logically ask about the quality of solutions generated by the other heuristics, and whether this comparison sheds light on overall solution quality. As a result, one gap in the literature is the development of a solution quality index. This opens an area of research for professional statisticians to apply new statistics to validate heuristic results.

Another fertile area of research involves integrating the theories and technologies of heuristics with relationships developed in other areas. For example, we could develop effective partnerships between landscape ecology and forest planning. Landscape ecologists have made significant contributions to the subject the conservation biology. Since forestry entails the alteration of landscapes, the theory and tools of landscape ecology could be integrated into a forest planning process. As the field of landscape ecology grows, its concepts and tools (e.g. remote sensing, GIS, spatial statistics, spatially explicit modeling) are increasingly being used in ecological disciplines including forestry [78]. As we know, modeling ecological processes across scales, including scaling up and scaling down, is essential in landscape ecology. In forest planning, we divide the planning into strategic, tactical and operational levels. We will also face the scaling up and scaling down problem. We could work together with landscape ecologists to integrate these problems. For example the objective function with respect to maximizing acres in wildlife habitat, Bettinger et al. (2002) mentioned that could be divided to strata-based goals, minimum-patch-size goals, and complementary-patch goals, to illustrate that the range of factors one can consider.

At this time, we have not considered the publications from the conference proceedings, graduate-level dissertations and public agencies and advances have been reported in these gray literature, so we leave this job for other researchers. In addition, although we have found theoretical papers in our review that do not specifically relate to spatial forest planning, we did not study the relationship between these and any related applied paper. This should be a time-consuming, but interesting job, because we may eventually infer the kinds of theory in that may have successful application in forest planning.

5 Conclusions

We investigated the difference between the early period (1995 and prior) and recent period (2000 and after) with respect to spatial forest planning research (Figure 12). The results illustrate that researchers and practitioners have relied more on heuristic techniques in the latter period than the early period. At the same time, we find that researchers and practitioners still attempt to use traditional, exact methods no matter what the period is being considered. Due to the increase in the complexity of the planning environment, the type of objective function has shifted slightly from commodity production to other concerns. When the constraint components in the papers are considered, we find that reliance on wildlife, aquatics, and biodiversity constraints have not changed much as time has passed. However, less emphasis has been placed on economics or commodity production in the latter period than the early period, and more emphasis has been placed on other constraints in the latter period.

The type of spatial forest planning problems being solved has evolved over the past 20 years. The trends suggest that forest-level planning publications have increased in the journals examined over the past fifty years, however the number of publications seem to have stabilized in the last few years [23], and perhaps has been decreasing since 2002. While we found the rate of publication easing in the last few years, the reason for this is not clear. For example, one could argue that the science has matured significantly, and that novel approaches to illustrating solutions to complex management problems are becoming moot. In fact many approaches to spatial forest planning have been proposed. Perhaps the questions now lie with determining efficient methods for designing constraint sets, or with designing adaptive heuristics that leave parameterization to the algorithm rather than the user. The rate has not eased due to a reduction in available journals. In fact it is arguable that the aims and scope of many international journals leave open the opportunity to publish spatial forest planning research. In addition, a number

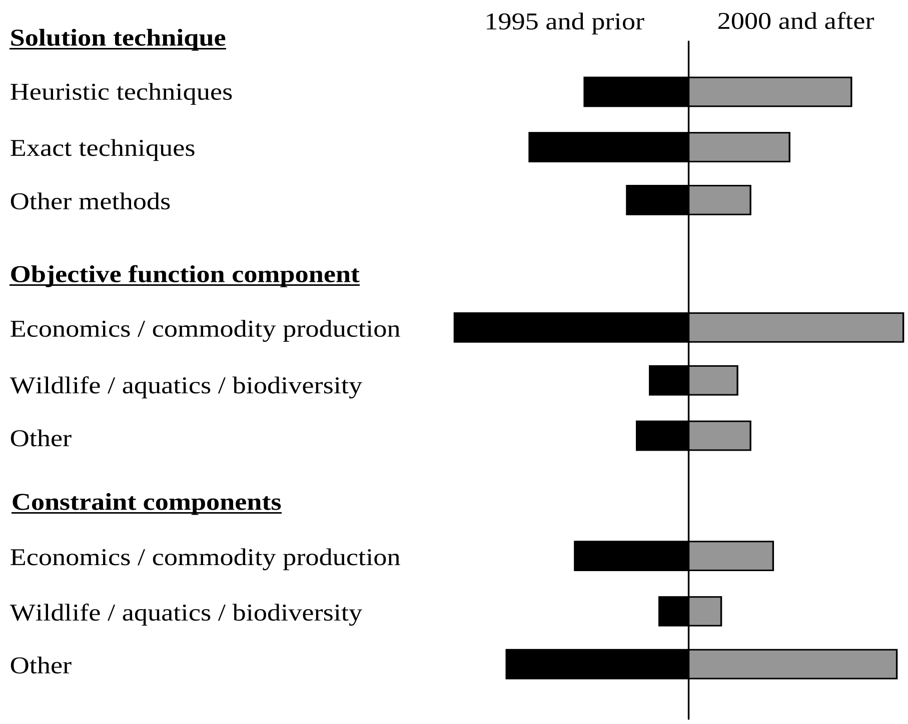

Figure 12: Differences between the early period and recent period.

of new online journals have appeared in the last decade, providing more outlets for research results. One aspect concurrent with the maturing of the science relates to the validation of results. Perhaps higher standards in this area have influenced the quality of peer-reviewed literature, although we did not test this hypothesis here.

It is difficult to predict which methods will dominate quantitative forest planning in the future. The two comprehensive reviews we located both discussed the possibility that the hierarchal structure could be divided into strategic, tactical and operational planning. Strategic forest plans attempt to develop broad strategies related to harvest levels, habitat levels, and economic expectations. Tactical forest plans determine where activities will be placed on a landscape and may require integer decision variables [23]. The operational level involves the determination of a land use plan for an area of the forest, and forest operations problems that represent short-term issues, such as harvesting, production, hauling, planting, pest control, fire management, and road building and maintenance [166]. Since exact methods have the advantage of ensuring that the solution one finds is optimal, the use of these seems valuable for all three levels of planning. However, most planning problems we now face are either tactical or operational, and involve complex problems with discrete integer variables, thus researchers and practitioners have embarked upon solving these problems using heuristic methods.

From this extensive and world-wide forest planning review, we are convinced that the past 20 years represents the seminal period for the development of the spatial forest planning methods. The literature review results convince us that methods used in spatial forest planning have shifted from exact algorithms to heuristic techniques. At the same time, researchers and practitioners have attempted to adopt various other methods to solve forest planning problems. In addition to the economic and commodity production objectives, an increase in ecological and social objectives has been noted. Besides economic and commodity production constraints, adjacency and green-up relationships are now also considered important constraints for industrial and managers in North America. Compared with raster data, vector data are more often used in the planning process. Hypothetical data are used by researchers to introduce new methods or compare various methods. To the extent that forest planning is of concern to forest policy makers, hypothetical examples are of as much value as specific real-life examples, although it was not unexpected to find that 35% of the papers failed to address a real-life problem. The geographic extent of the papers we located is world-wide, however not evenly spread across the world: the United States, Canada, and Europe provide most of the work in this area. Spatial restrictions or objectives in the process are the trend for the forest planning problems. GIS technology is a widely-used tool in forestry and natural resource management, yet thus far has had limited application (generally used as an input tool) in the forest planning process. More research should be conducted to continue to integrate GIS with forest planning algorithms. The gaps in knowledge that we have identified leave room for further investigation into mixed integer methods, applications of new heuristics to spatial problems, exploration of appropriate heuristic parameters, development of a solution quality index, integration with other fields utilizing spatial relationships, and a broader examination of the non-peer-reviewed literature.

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