INTRODUCTION

A number of mathematical programming techniques have been used by forestry organisations over the past fifty years in their effort to support decision-making processes related to forest management activities. Many of the techniques have been illustrated by academics and practitioners through peer-reviewed journal articles. The creation or illustration of new techniques has generally been reflective of the environment within which forest planning must operate, thus forest planning decision processes have become increasingly complex as information and communication technologies change (Weintraub and Bare 1996), and as the decision environment has evolved. Both public and private forestland managers in North America have been faced with a shifting management emphasis over the last decade, from commodity production or economic goals to ecological or social goals (Weintraub and Bare 1996), thus the types of goals that are perceived to be important in planning processes have changed. In this survey, we illustrate the evolution of mathematical programming techniques in North America as expressed by the publication of forest-level planning processes in peer-reviewed journals. Insight into the trends that seem evident in the use of programming techniques, and into the types of goals and objectives modelled, is presented. This review of the literature will provide 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.

METHODS

In order to assess the trends in the development of operations research science within the field of forest planning, seven major North American forestry journals were surveyed for peer-reviewed papers, which had an emphasis on forest-level management planning. The time period considered included the years 1950 to 2001. Bounds on the type of forest-level planning approaches were developed to include those articles that demonstrated or described the forest planning process and algorithm utilised, while also presenting a case study of an application of the process. Essentially, the journals included in this analysis describe a process and demonstrate an application of planning methodology to the scheduling of activities to two or more stands or stratas that describe a forest. The types of techniques that fell outside of these bounds included stand-level optimisation techniques (i.e. an emphasis on planning within a single stand) and regional...
or global supply or demand models. In addition, purely theoretical papers, those that did not provide an application of the technique, were excluded, as were papers that described some portion of a planning process (e.g. the scheduling of adjacent activities, or the simultaneous scheduling of nearby activities) without providing a forest-level planning example.

The type of information recorded about each article included the publication date, the journal, the type of technique(s) described or demonstrated, and the emphasis of the planning problem (either portrayed through the objective function or major constraints). In addition, we noted whether the approach described considered spatial restrictions on the scheduling of forest management activities. The journals considered included the following: Canadian Journal of Forest Research, Forest Science, Journal of Forestry, Northern Journal of Applied Forestry, Southern Journal of Applied Forestry, The Forestry Chronicle, and Western Journal of Applied Forestry. We grouped the mathematical programming techniques into the following categories: linear programming and derivatives (linear programming, goal programming, probabilistic linear programming, non-linear programming, mixed integer programming, and integer programming), simulation, heuristics (heuristic, Monte Carlo integer programming, simulated annealing, tabu search, and genetic algorithms), dynamic programming, and other (binary search, capital budgeting, optimal control, decision analysis, economic optimisation, area control, and other timber cutting rules). Areas of emphasis included the following groups: economic analysis (net present value, economics, optimal stand rotation ages), wood production (wood production, wood supply, harvest scheduling, sustained yield, allowable cut, allowable cut effect, area control), wildlife and other biotic resources (wildlife, aquatic resources, range, and insects), fire (fire damage, fuel breaks), adjacency restrictions (green-up requirements), and other (multiple use, recreation, wilderness, resource allocation, non-market goods, environmental quality, natural disturbances, biological diversity, transportation, reserve networks, old-growth, welfare, and reforestation).

The results are summarised in a chronological manner, with emphases on the journal within which the papers have been published, the types of objectives and constraints illustrated, the type of mathematical programming technique used, and whether or not spatial goals are recognised.

RESULTS

The number of peer-reviewed forest planning papers available through the major North American forestry journals began with an infrequent collection of papers from 1950–1960, transitioned to a stable 1–2 publications per year from 1960 to the late 1970s, then dramatically increased from 1980 to present (Figure 1, Table 1). The Journal of Forestry (JF) was initially the main source of forest-level planning papers, but the Canadian Journal of Forest Research (CJFR) and Forest Science (FS) have, beginning in about 1980, supplanted JF as the leader in the presentation of mathematical forest planning papers (Figure 2). The CJFR and FS maintain a high rate of publication on mathematical programming techniques applied to forest-level planning problems. The more general (JF) and applied journals (Northern Journal of Applied Forestry [NJAF], Southern Journal of Applied Forestry [SJAF], The Forestry Chronicle [TFC], and Western Journal of Applied Forestry [WJAF]) also have aims and scope that allow the publication of forest planning manuscripts, however, the complexity of the methodology within forest management planning papers may direct many researchers to the two journals (CJFR and FS) that are more research-oriented.
The results also show an increase in the recognition of spatial goals or constraints within forest planning systems (Figure 3). Spatial goals, for example, may include recognition of maximum clearcut sizes or recognition of the placement of adjacent harvest activities. Without the explicit incorporation of spatial objectives or constraints into a problem formulation, these goals have been traditionally evaluated in a posterior manner. For example, forest plans were once developed using primarily economic (e.g., net present value) or wood production (e.g., harvest

### TABLE 1
Citations for forest-level planning peer-reviewed articles presented in the major North American forestry journals

<table>
<thead>
<tr>
<th>Year</th>
<th>Citations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1952</td>
<td>Gross (1952), Meyer (1952)</td>
</tr>
<tr>
<td>1958</td>
<td>Grosenbaugh (1958)</td>
</tr>
<tr>
<td>1961</td>
<td>Rock (1961), Stevenson and Schores (1961)</td>
</tr>
<tr>
<td>1962</td>
<td>Curtis (1962)</td>
</tr>
<tr>
<td>1964</td>
<td>Loucks (1964)</td>
</tr>
<tr>
<td>1966</td>
<td>Kidd et al. (1966), Nautiyal (1966)</td>
</tr>
<tr>
<td>1967</td>
<td>Nautiyal and Pearse (1967)</td>
</tr>
<tr>
<td>1968</td>
<td>Teeguarden and Sperber (1968)</td>
</tr>
<tr>
<td>1971</td>
<td>Thompson and Haynes (1971), Ware and Clutter (1971)</td>
</tr>
<tr>
<td>1972</td>
<td>Fortson (1972)</td>
</tr>
<tr>
<td>1973</td>
<td>Field (1973), Madill (1973), Thompson et al. (1973)</td>
</tr>
<tr>
<td>1975</td>
<td>Leuschner et al. (1975)</td>
</tr>
<tr>
<td>1976</td>
<td>Johnson (1976)</td>
</tr>
<tr>
<td>1977</td>
<td>Dane et al. (1977), Schuler et al. (1977)</td>
</tr>
<tr>
<td>1979</td>
<td>Dyer et al. (1979), Kao and Brodie (1979)</td>
</tr>
<tr>
<td>1983</td>
<td>Armstrong et al. (1983), Berck and Bible (1983), Hoganson and Rose (1983)</td>
</tr>
<tr>
<td>1985</td>
<td>Walker (1985)</td>
</tr>
<tr>
<td>1990</td>
<td>Clements et al. (1990), Davis et al. (1990), Jamnick et al. (1990), Jamnick et al. (1990), Nelson and Brodie (1990), Pickens et al. (1990), Roise et al. (1990), Roise et al. (1990), Sherali and Liu (1990)</td>
</tr>
<tr>
<td>1992</td>
<td>Bare and Mendoza (1992), Hof and Joyce (1992), Hof et al. (1992), Jordan and Baskent (1992)</td>
</tr>
</tbody>
</table>
level) objectives and constraints, and any subsequent spatial analysis was performed with geographic information systems (GIS) after plan development. The trend is now to develop the knowledge necessary to account for spatial goals with GIS prior to developing a forest plan, and have this knowledge influence the decisions that are suggested by the resulting forest plans. The development of adjacency constraints is a prime example, where the knowledge of the proximity of each land management unit with respect to its neighbours is used when assessing proposed management activities. Many of the papers that include spatial forest planning considerations have either been published in the CJFR or FS journals (Figure 4).

The traditional mathematical programming techniques (linear programming and its derivatives) continue to be illustrated for use in developing forest plans within the literature (Figure 5), although it is recognised that they either assist in the development of plans that solve a “relaxed” problem formulation (absent of spatial constraints) or that the size of the problem to be solved may be limited due to the combinational nature of certain constraints. The total number of techniques illustrated is more than the total number of publications due to the presence of more than one technique in some publications. Linear programming is also used increasingly in the literature to develop a relaxed solution to a forest planning problem against which integer problem formulations are compared. The LP solution provides an upper bound on an objective function value to a more constrained planning problem, and the addition of spatial constraints to the formulation provide solution values at levels below the upper bound. The cost of additional constraints can be assessed with this process. Simulation, heuristic, and dynamic programming techniques have shown some promise in the last few years as techniques to handle large forest planning problems with spatial constraints.

Measures of wood production and economics continue to dominate the objectives and constraints of forest plans presented in the literature (Figure 6). Measures of multiple use, however, are increasingly being incorporated directly into forest planning efforts, as demonstrated by the increase in wildlife and other non-timber resource management goals over the past decade into the development process of forest-level planning efforts. Green-up, or adjacency, constraints have been the focus of a number of papers in the last decade, as organisations have adopted either internal standards for scheduling adjacent activities, or have adopted programs such as the American Forest & Paper Association’s Sustainable Forestry Initiative (AF&PA 2002). Researchers and practitioners have obviously responded with journal articles to provide direction to forest planners in the handling of spatial restrictions. The total number of areas of emphasis illustrated is more than the total number of publications due to the presence of more than one area of emphasis in some publications. Over the last 51 years, linear programming and its derivative techniques have been applied to a broad range of forest planning problems (Figure 7). Although heuristic
techniques are relatively recent additions to the set of tools available to forest management planning efforts, their applications have also mainly focused on economic analysis and wood production combined with other management goals and constraints. Some researchers (e.g., Bettinger et al. 1998, 1999) have obviously used heuristic techniques to overcome the problem size limitations related to the recognition of integer variables in LP techniques.

DISCUSSION

Over the past 51 years, the seminal papers on forest planning in North America include the concise introduction and use of linear programming in forest management (Curtis 1962; Loucks 1964; Kidd et al. 1966; Kidd 1969; Thompson and Haynes 1971; Ware and Clutter 1971; Leuschner et al. 1975), along with the introduction and use of other models, such as goal programming (Field 1973; Dyer et al. 1979; Kao and Brodie 1979; Arp and Lavigne 1982; Hotvedt et al. 1982; Walker 1985; Mendoza 1986; Rustagi and Bare 1987), heuristics (Lockwood and Moore 1993; Yoshimoto et al. 1994; Weintraub et al. 1995; Bettinger et al. 1998; Richards and Gunn 1999; Sessions et al. 2000; Falcão and Borges 2001), and simulation (Hall 1981; Van Wagner 1983; Andison and Marshall 1999; Nicholls et al. 1999; Gustafson et al. 2000). The introduction and advancement of mathematical programming notation in forest management planning is also found in several research papers (Loucks 1964; Kidd et al. 1966; Walker 1985; Reed and Errico 1986, 1987; Rustagi and Bare 1987; MacMillan and Fairweather 1988; McKillop and Krumland 1989).

Some of the early contributions regarding economic and commodity production aspects of forest planning include those related to the allowable cut (Gross 1952; Meyer 1952; Grosenbaugh 1958), the allowable cut effect (Binkley 1980; Tedder and Schmidt 1980; Montgomery and Cleaves 1986), even-flow of timber harvest volume (Armstrong et al. 1984; Hof et al. 1986; McKillop and Krumland 1989), area control of harvests (Stevenson and Schores 1961), changes in discount rates (Kidd 1969), and uncertainty (Thompson and Haynes 1971; Hoganson and Rose 1987; Marshall 1988; Gassman 1989; Hof and Pickens 1991; Hof et al. 1995; Weintraub and Abramovich 1995; Boychuk and Martell 1996; Forboseh and Pickens 1996; Pukkala and Kangas 1996). In addition, significant contributions of research include those related to multiple-use management (Madill 1973; Arp and Lavigne 1982; Burroughs and Kurtz 1982; Osteen and Chappelle 1982) and fire (Van Wagner 1983; Reed and Errico 1986; Johnson et al. 1998). Other significant work includes comparisons of planning models (Teeguarden and Sperber 1968; Tedder et al. 1978; Johnson and Tedder 1983; Jamnick 1990; Nelson and Brodie 1990; Boston and Bettinger 1999), and the usefulness of combining planning models (Hotvedt et al. 1982, Mendoza 1986; Borges et al. 1999; Laroze 1999).

When the research papers are examined by decade, several distinct areas of concentration are noteworthy. During the 1950s, the research concentrated on determining the potential allowable cut from a forest (Gross 1952; Meyer 1952; Grosenbaugh 1958). The 1960s saw the introduction of linear programming as a planning tool in forestry (Curtis 1962; Loucks 1964; Kidd et al. 1966; Kidd 1969), and an emphasis was placed on determining rates of harvest (Nautiyal 1966; Nautiyal and Pearse 1967). Advances in linear programming (Ware and Clutter 1971; Thompson and Haynes 1971; Leuschner et al. 1975) and the introduction of goal programming (Field 1973; Dane et al. 1977; Schuler et al. 1977; Dyer et al. 1979; Kao and Brodie 1979) were presented in the 1970s, along with an emphasis placed on multiple-use forest planning (Madill 1973; Leuschner et al. 1975). During the 1980s, the allowable cut effect was examined (Binkley 1980; Tedder and Schmidt 1980), and advances were made in the use of goal programming (Hotvedt et al. 1982; Rustagi and Bare...
Finally, although the trend indicates that forest-level publishing efforts on the more general or applied journals (FS and CJFR). As examinations of alternative problem formulation increases, researchers will likely goals. As the complexity of the planning technique or to allow the recognition of complex non-timber resource recognise spatial goals within mixed-integer programming (Clements et al. 1990; Lockwood and Moore 1993; Weintraub and Gunn 2000; Falcão and Borges 2001) and the allocation of strata-based harvest schedules to land areas (Nelson et al. 1991; Daust and Nelson 1993; Davis and Martell 1993; Howard and Nelson 1993; Jannick and Walters 1993). In addition, headway was made in the areas of spatial harvest scheduling (Clements et al. 1990; Nelson and Brodie 1990; Roise 1990; Jones et al. 1991; Nelson and Finn 1991, Nelson and Howard 1991; Lockwood and Moore 1993; Nelson and Errico 1993; Weintraub et al. 1994; Yoshimoto and Brodie 1994a, 1994b; Murray and Church 1995, 1996; Snyder and ReVelle 1996a, 1997; McDill and Braze 2001; Walters and Cox 2001), spatial optimisation of wildlife habitat (Hof and Joyce 1992, 1993; Hof and Raphael 1993; Hof et al. 1994; Van Deusen 1996; Haight and Travis 1997; Bevers and Hof 1999), and adjacency formulations (Jones et al. 1991; Weintraub et al. 1994; Yoshimoto and Brodie 1994a; Murray and Church 1995, 1996; Snyder and ReVelle 1997; Hoganson and Borges 2000; McDill and Braze 2000, 2001) One of the earliest papers introducing adjacency restrictions, however, was Thompson and Haynes (1971).

What techniques will dominate the mathematical programming aspect of forest-level planning? Strategic forest plans, those that attempt to develop broad strategies related to harvest levels, habitat levels, and economic expectations, will most likely continue to utilise LP and other non-spatial management planning techniques because the ability of LP to find an exact solution to a given formulated problem of a reasonable size is attractive to many researchers. Tactical forest plans, those that are used to determine where activities will be placed on a landscape, and may require integer decision variables, are those where the selection of the appropriate scheduling technique is more difficult to discern. Researchers and practitioners are addressing combinational problems related to the development of tactical forest plans from two fronts: (1) by developing methodology to efficiently recognise spatial goals within mixed-integer programming formulations, and (2) by developing heuristic techniques to allow the recognition of complex non-timber resource goals. As the complexity of the planning technique or problem formulation increases, researchers will likely attempt to publish their findings in the research-oriented journals (FS and CJFR). As examinations of alternative policies are developed (e.g. a focus on variations in greenup or adjacency rules), researchers may focus their publishing efforts on the more general or applied journals. Finally, although the trend indicates that forest-level planning publications have increased in the journals examined over the past fifty years, the number of publications has seemed to have stabilised in the last few years. Thus it is difficult to determine whether the number of publications will change in the near future.

The emphasis placed on economic, ecological, and social goals will likely continue to change, as evidenced by the recent published research, as policy makers suggest goals that are important for inclusion in forest plans, and as researchers suggest ways to integrate complex quantitative models into forest planning processes. For example, recent papers have illustrated how to include stream sediment (Hof and Bevers 2000a), stream temperature (Bettinger et al. 1998), and wildlife models (Hof and Joyce 1993) into forest plans, each with complex spatial analysis components. The emphasis on economic or wood production goals will likely continue, however, as they allow a common standard for manager to evaluate the differences in plans that provide, for example, various levels of wildlife habitat. The continued inclusion of commodity production goals also allow a demonstration of the integration of alternative measures of economic, ecological, and social goals.

A number of high quality publications related to forest-level planning were not included in this analysis, such as those related to the theory behind modelling adjacency constraints (e.g. Murray 1999). Our effort was not to diminish the importance of this research, yet in the process some seminal work in forest planning was bypassed. In addition, the exclusion of publications generated by public agencies (e.g. USDA Forest Service research papers, State- or Province-level reports), conference proceedings, and graduate-level dissertations likely leads to a misrepresentation of the extent to which forest-level planning has been studied in North America. An expanded examination of these publications, however, would require an extensive and time-consuming process, which we leave for other researchers. The development of an Internet-based clearing house for the voluntary contribution of forest-level planning research would contribute to a more thorough compilation of research. Expansion to internationally recognised journals (e.g. Silva Fennica, Ecological Modelling, Scandinavian Journal of Forest Research, and Journal of Forest Planning) would further enhance an understanding of the history, and the state-of-the-art in forest-level planning.

A number of important subject areas were also not included in this analysis, including publications related to stand-level optimisation, transportation and network optimisation, and regional or forest sector optimisation. In addition, papers lacking an example of the use of forest-level planning, and those lacking a mathematical description of the problem formulation or a detailed qualitative description of the planning process were bypassed, since either of which would not allow one to determine how a problem was formulated and solved. Expansion of the discussion to the full range of forest-level planning literature would provide a well-rounded
background into the use of operations research techniques in forest-level planning efforts.

Some of the research summarised in this paper was motivated by research agendas, while other by applied management needs. We did not attempt to discern the intentions of the researchers during our literature review. However, forestry, in general, has been more of an adapter of mathematical programming technology than a developer of such technology. For example, while many of the applications of mathematical programming methods are quite unique to the field of forestry (e.g. the placement of harvests, or the location of wildlife habitat), the techniques were first proposed by other operations research professionals. Heuristics are an obvious example of a set of techniques adapted for use in forest planning, but developed by others (e.g. tabu search by Glover 1989, 1990).

This review of the literature supports the notions brought forward by Weintraub and Bare (1996), that the operations research community associated with the field of forestry have responded to land management planning challenges by adapting or developing models that address the cumulative effects of management activities across broad land areas, that address the concerns of ecosystem management, and that integrate models to account for resources related to issues other than economics or wood productivity. While each land management organisation may have a distinct set of objectives and constraints associated with their management strategy, influenced either by regulations or organisational policies, an attempt has been made by researchers and practitioners to provide direction to the development of increasingly complex problem formulations.

CONCLUSIONS

The use of mathematical programming techniques for forest-level management planning, as expressed by publication of papers in peer-reviewed North American forestry journals, has increased dramatically over the past 51 years. The development of new solution techniques in the field of operations research has prompted an examination of their usefulness to forest planning efforts, as evidenced by the shift in techniques presented in the literature from linear programming to heuristics. Wood production and economic goals dominated the themes of journal articles until about 1990, as the importance of other resource goals in land management planning increased. Spatial components within forest planning processes have also increased dramatically in the last decade, since some resource goals require an explicit recognition of the juxtaposition of activities. Finally, two journals, the Canadian Journal of Forest Research and Forest Science, have become the predominant sources of forest-level planning literature that focuses on forest planning problem formulations and examples of use of mathematical programming techniques in forest-level planning.

REFERENCES


