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An object-oriented cellular automata model for forest planning problems

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ABSTRACT

Various difficulties are encountered when integrating spatial and temporal goals of forest planning with dynamics of natural processes. Some of these difficulties stem from the difference between the data and models involved in the various processes to be integrated. The focus of this study is the development of a decentralized spatial decision support tool for forest management planning based on cellular automata (CA) modeling. An innovation of this model is that beyond spatially allocating/simulating management activities, the CA rules and state space are modified to allow cells to co-evolve until a plan for all periods of the planning horizon has been achieved. The object-oriented implementation of the CA model in a geographic information system (GIS) is presented as a decentralized bottom-up forest planning approach. Moreover, a sensitivity analysis of the model outcomes to spatial resolution and objective weights is performed. This planning tool effectively addresses local spatial constraints (limitation on the type of management depending on location), global spatial objectives (spatial clustering of old growth conservation areas), global aspatial objectives (timber harvest) and global constraints (stable flow and minimum old growth conservation). The capability of this approach to consider spatial relationships in the strategic planning process is illustrated by a spatially consistent allocation of clustered old growth areas. The object orientation of the implementation permits a fast computation of both local and global limitations on local decision making. This framework allows speedy modification of either local or global requirements and is highly portable to other complex planning problems.

1. Introduction

In contrast with the traditional decision process which primarily focused on the timing of management activities (i.e. scheduling), the rising social, environmental and economic concerns have resulted in an increased interest in the location of management activities. Spatial considerations impact the performance of a management plan with respect to economic, environmental and social goals in a number of ways. Some issues involve specific locations. For instance stream buffers reduce the volume harvested from a block and reserve areas can complicate the access to harvestable land (e.g., Daust

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and Nelson, 1993). Some other issues relate to the spatial arrangement of management activities. This is the case when locating timber activities to minimize the loss of interior forest increases the habitat value for some wildlife (Bettinger et al., 1997; Bevers and Hof, 1999; Hof et al., 1999; Ohman and Lamas, 2005). Another example is that of adjacency constraints and the ensuing dispersal of harvest activities, which can reduce clearcut sizes but limit the potential economies of scales achieved by harvesting larger blocks (e.g., Barrett et al., 1998; Boston and Bettinger, 2001). Given their impacts on management objectives, spatial objectives have been increasingly incorporated in forest decision support systems (Baskent and Keles, 2005; Weintraub and Murray, 2006). A challenging aspect of incorporating spatial objectives is that, in many cases, they cannot be addressed separately or in advance from the decision model (Hof and Bevers, 1998; Kurttila, 2001; Ducheyne et al., 2006): any change to the management schedule of one stand can thus affect the existence and location on the landscape of desirable features such as old growth patches or wildlife corridors (Bevers and Hof, 1999; Loehle, 1999; Ohman, 2000). All these issues raise a need for explicitly incorporating spatial relationships in the planning tool.

In the past decade, a large number of studies have been devoted to solving spatial optimization problems (some comprehensive reviews are provided in Baskent and Keles, 2005; Weintraub and Murray, 2006). The two main techniques to address spatial planning problems are optimization solved with either exact or heuristic methods and simulation models. Spatial planning tools have mainly taken a “top-down” or centralized approach where solutions are assessed according to their contribution to global objectives. With exact techniques or metaheuristics, researchers have devised various ingenious means of addressing management scheduling while directly accounting for spatial considerations such as wildlife corridors (Sessions, 1992), old growth patches (Ohman, 2000), buffers (Van Deusen, 2001) or fragmentation (Loehle, 1999).

The great strength and appeal of optimization approaches is that they directly address the objectives and provide precise solutions. However, these approaches have some drawbacks which are dominated by the large size of planning problems and the non-linearity of spatial relationships (Weintraub and Bare, 1996; Hof and Bevers, 1998; Martell et al., 1998; Murray, 1999; Murray and Snyder, 2000; Bettinger and Sessions, 2003; Nelson, 2003; Baskent and Keles, 2005). Since spatial decision models need to track not only the amount of resource produced by stands over the planning area but also the spatial relationships between these stands, stands need to be treated as individual units and cannot be aggregated into strata. This means that a large amount of information needs to be processed and tracked and that the size of the combinatorial problem becomes very large (Baskent and Keles, 2005; Bettinger et al., 2005; Weintraub and Murray, 2006).

To deal with a large amount of information, most centralized solution techniques tend to simplify one or more aspects of the forest planning problem by either (1) reducing the spatial scale of the problem (Ohman and Eriksson, 2002; Weintraub and Murray, 2006); (2) limiting the number of time periods involved in the problem (Hof and Joyce, 1992; Crowe et al., 2003; Weintraub and Murray, 2006) or (3) simplifying the objectives or decision variables (e.g., no reharvest, homogenous management choice, simplified inventory) (Lockwood and Moore, 1993; Hof and Bevers, 1998; Richards and Gunn, 2000). Another way to address the increasing size and complexity of forest management data and processes is the use of object-oriented programming to provide the solution technique with more flexibility and to store complex spatial and temporal data more efficiently. In forest management planning, Bugg et al. (2002) proposed the use of objects-oriented programming to support forest management and Baskent et al. (2001) presented an object-oriented implementation of a forest-planning model involving a simulated annealing heuristic algorithm. The model successfully solved for a number of priority-sorted objectives including some spatial constraints that take precedence over harvest objectives. However, this top-down model did not address complex spatial objectives such as shapes and size of harvest blocks or reserves.

Unlike the centralized characteristic of most optimization techniques, simulation is essentially a “bottom-up” or decentralized modeling approach where patterns emerge as the consequence of multiple distinct events. Simulations are somehow more holistic in their scope and they permit more detailed modeling of forest growth and management strategies (Martell et al., 1998). Perhaps the biggest advantage of simulations is improved processing efficiency, which is a significant bonus as problems in forest management continue to grow in size and complexity (Gustafson, 1996; Bettinger et al., 2005). The development of simulation models based on the concept of cellular automata (CA) has become particularly popular for use in spatial modeling. CA models have been successfully used to represent spatial and time-dependent processes of complex systems including urban and land use change models (Ward et al., 2000b; White and Engelen, 2000; Almeida et al., 2003; Stevens et al., 2007) and natural ecosystems (Balzter et al., 1998; Favier et al., 2004; Bone et al., 2006; Colasanti et al., 2007).

The key drawback of simulation in general and CA in particular is that it does not address the objectives directly but rather describes the effect of decision alternatives on the overall system objective under various scenarios (Malczewski, 1999). Simulation models have therefore a limited prescriptive ability and are often used to spatially allocate the outputs generated by optimization techniques (e.g., Bettinger et al., 2005). However, if the decisions regarding individual locations can be guided towards meeting global forest management objectives, the “bottom-up” simulation techniques could gain some of the advantages of centralized planning technique while retaining high levels of detail regarding local conditions and processes. Strange et al. (2002) developed a CA-based planning model for a one-time afforestation problem based on the premise that, in spatial planning problem, part of the contribution of stands to management objectives is derived from their spatial relationships to other, stands in close proximity, i.e. decisions regarding two nearby stands can affect each other’s contribution to the global objective more than decisions taken at two distant locations (Hof and Bevers, 1998; Hoganson et al., 1998). It follows that the stand contribution to the global objective for a given management alternative could be calculated by computing the impact of the change on the stand and its neighborhood only.