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ScienceDirect
Forest Ecology and Management 239 (2007) 45–56
Forest Ecology and Management
www.elsevier.com/locate/foreco

Forest planning using co-evolutionary cellular automata

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Received 4 October 2005; received in revised form 14 November 2006; accepted 14 November 2006

Abstract

The spatial distribution of forest management activities has become increasingly important with, most notably, rising concerns for biodiversity. Addressing both timber production and non-timber goals requires planning tools that support spatially explicit decision-making. The paper examines the capability of a co-evolutionary cellular automata (CA) approach to address forest planning objectives that are both spatial and temporal with global constraints. In this decentralized self-organizing planning framework, each forest stand and its associated management treatment over the planning horizon is represented as a cellular automaton. The landscape management goals are achieved through a co-evolutionary decision process between interdependent stands. A novel, computationally efficient CA algorithm for asynchronous updating of stand states is developed. The specific problem considered in the paper is maximization of cumulative harvest volume and amount of clustered late-seral forest. The global constraints considered are stable harvest flow and minimum amount of late-seral stands in each period of the planning horizon. Applied to a test area from the Northeastern forest region of Ontario, Canada, the model demonstrates short computation time and consistent results from multiple runs. It also compares favorably with outputs from a simulated annealing search. The CA-based algorithm developed in the paper successfully identifies sustainable forest outputs over the planning horizon. It shows sensitivity to both local constraints, strategic goals and strategic constraints and generates spatially explicit forest plans.

Keywords: Cellular automata; Decentralized planning; Evolutionary game; Forest planning; Heuristics; Multiple scales; Late-seral forest; Self-organization; Spatial analysis; Tradeoffs

1. Introduction

Sustainable forest management recognizes and seeks to maintain a wide array of ecological as well as economic and social forest functions, both locally and globally (UNCED, 1992). The challenge in forest management planning is to accommodate timber production with other, non-timber goals such as the protection of biodiversity and ecosystem health. To this end, traditional stand-level cost-benefit-type analyses need to be combined with forest or regional-level analyses in order to adequately select among forest management alternatives. As forest management interacts with ecological processes at multiple spatial and temporal scales, combined analyses can be difficult to conduct (Martell et al., 1998; Nelson, 2003). These issues are usually handled through either top-down or bottom-up planning approaches (Shands et al., 1990).

Top-down planning is the most frequent approach to reconcile processes and goals at different spatial and temporal levels. This approach is often associated with centralized procedures that track the global performance of decision combinations to select the best alternative. Centralized top-down procedures have traditionally been favored in strategic planning with an extensive use of large non-spatial mathematical programming models (Martell et al., 1998). However, an increasing number of location-specific concerns (e.g., environmental buffers, proximity to road network, adjacency, size and distribution of reserve patches) have made necessary the inclusion of spatial considerations in the planning process. For strategic plans to be useful, their spatial implementation must be feasible. Spatial details typically generate a large number of search combinations.

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0378-1127/$ – see front matter
doi:10.1016/j.foreco.2006.11.007

The use of heuristic methods has greatly facilitated solving the resulting computationally difficult planning problems. The most frequently applied heuristics are simulated annealing (Lockwood and Moore, 1993), Monte Carlo search (Clements et al., 1990; Boston and Bettinger, 1999), tabu search (Murray and Church, 1995; Bettinger et al., 1997; Richards and Gunn, 2003), genetic algorithms (Lu and Eriksson, 2000) or combinations of several heuristics (Boston and Bettinger, 2002). Despite the increasing effectiveness of heuristic methods, it remains difficult to formalize spatial objectives such as clustering, connectivity and continuity of set-aside forestland throughout the planning horizon with centralized procedures (Bettinger et al., 2002; Nelson, 2003; Pukkala and Kurttila, 2005). The heuristics used in centralized procedures are based on the evaluation of the global objective values for different management plans. If the global objective value is not satisfactory for a given plan, lower-level decisions are changed until an acceptable objective value is obtained. Another way of finding a satisfactory management plan is to build information from the lower levels (i.e., individual stands).

Bottom-up planning offers the advantage of directly addressing local spatial goals and constraints. In order to achieve an acceptable level of the global objective, some coordination of lower-level decisions is required. In spatial systems decisions taken at nearby locations can affect each other's contribution to the global objective more than decisions taken at distant locations (Strange et al., 2001; Hoganson and Borges, 1998; Hoganson et al., 1998). This implies that the solution space could be explored in parallel by evaluating local decisions and taking into account their interactions. Given the increasing complexity of forest systems, a decentralized approach based on local-level decisions is a natural way to address strategic forest planning. A decentralized bottom-up framework may address the spatial goals of forest management computationally more efficiently than a centralized framework.

Cellular automata (CA) modeling is a decentralized framework capable of representing discrete dynamical systems whose behavior is specified in terms of local relations (Toffoli and Margolus, 1987). This modeling tool has been almost exclusively used for process simulation and for the exploration of complex systems in physics, geography and biology. If CA models are to be used for planning purposes, the incorporation of guiding rules is needed to ensure that not only local (stand-level) objectives, but also global (landscape-level) goals are met. Strange et al. (2001) developed a planning tool centered on a CA-based evolutionary optimization algorithm, which solves spatial problems involving one-time afforestation decisions (Strange et al., 2002). Mathey et al. (2005) extended the work on using CA for planning by designing an evolutionary CA algorithm to address inter-temporal aspects of forest planning in addition to spatial issues. The newly developed co-evolutionary optimization algorithm was applied to solving spatial multi-period planning problems. The current paper addresses global constraints within this decentralized optimization framework and proposes a modification of both the transition rules and updating method that is capable of guiding the decentralized optimization process toward meeting global objectives while also satisfying landscape scale (global) constraints.

This study describes the co-evolutionary algorithm for both an unconstrained and a constrained forest planning problems and compares its performance with a simulated annealing algorithm. The specific forest planning problem considered is the maximization of a weighted combination of the cumulative harvest volume and a measure of the clustering of old forest stands, while keeping stable harvest flow over time and maintaining a minimum amount of the forested area in late-seral stage. Volume maximization and stable harvest flow reflect timber-related objectives of forest planning. Ecological objectives of forest management are expressed by both maintaining a minimum amount of late-seral forest stands and at the same time promoting the clustering of these late-seral stands. Maintaining clusters of late-seral forest is important for several reasons. First, late-seral forests are most severely impacted by timber management, both through direct degradation and through fragmentation (Harris, 1984). Second, late-seral forests constitute a specific habitat that a number of plant and animal species depend on, partially or entirely. Preserving habitat for these species requires continuity of areas of stands of old forests over the planning horizon (Seymour and Hunter, 1999; Ohman, 2000). Both forest ecologists and managers acknowledge the importance of conserving clusters of old forests (Spies and Franklin, 1996) even if the question of their location, size and distribution is still in contentions (Shafer, 2001; Schwartz, 1999).

The following section describes how cellular automata can be used in forest planning. We detail the co-evolutionary CA algorithm of Mathey et al. (2005) for an unconstrained forest planning problem after which, we present the solution approach to constrained forest planning problems. The model and solution approaches are then illustrated by an empirical study using a forest in northeast Ontario. The tradeoffs in the model are analyzed and a comparison with a simulated annealing search algorithm is proposed.

2. Application of cellular automata in forest planning

CA models are generally constructed as a collection of cells that form a lattice (Toffoli and Margolus, 1987; Wolfram, 1994). Each cell is characterized as being in a particular state. Transition rules applied to a cell are used to compute the cell's state for the next iteration. The transition rules are a function of the cell's own state and the states of its neighbors. CA models progress by discrete steps (a time interval or iteration) during which transition functions are applied to all or a subset of the lattice's cells.

Two properties of CA are particularly relevant to forest planning: scale-integration and self-organization. The integration of processes and objectives from different spatial and temporal scales is a long-standing issue in forest planning: some of the management concerns are local or stand-level (e.g., timber yield, stand structure) while others are tied to the surrounding environment (e.g., landscape patterns, economics and aesthetics). Self-organization in dynamic systems refers to