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Integrating harvest scheduling and reserve design to improve biodiversity conservation

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ABSTRACT

Reserve establishment and strategic harvest planning are two longstanding but often separate approaches to conserving biodiversity in working landscapes. Our paper unites these fields and explores how ecological characteristics of landscapes influence conservation outcomes, with a particular consideration of tropical forests. We used an integer programming model to compare the performance of different management designs on simulated landscapes with different species diversity values and degrees of conspecific spatial aggregation. We explored three classes of reserve and harvest plans: optimal, random, and fixed-pattern (the last of which is most common in tropical forest management). Optimal designs (and performance criteria) were rooted in the *Optimized Floating Refugia* strategy, a new approach to landscape-level forest management that assumes local extinctions will occur and seeks to facilitate recolonization for as many species as possible via strategic spatiotemporal planning. We found several interesting interactions between harvest planning and reserve establishment. On landscapes with ecological characteristics resembling those of tropical forests (high species diversity and high conspecific aggregation), strategic harvest plans with no reserves saved more species than fixed-pattern, aggregated harvest plans with over 20 percent of stands set aside as reserves. Our findings also suggest an important rule of thumb: less aggregated harvest plans lead to fewer extinctions than more aggregated harvest plans. Overall, we found that the integration of harvest planning and reserve design led to novel insights, and that the divergence in absolute performance between different management regimes (but not the ordinal ranking) was highly dependent on the ecological characteristics of the landscape.

1. Introduction

Tropical forests, the most species diverse terrestrial ecosystems, are actively managed for a broad range of objectives including watershed protection, carbon sequestration, timber production, and biodiversity conservation. With an ever increasing amount of tropical forest threatened by logging and land conversion, there is growing emphasis among conservation biologists on creating forest management plans that conserve species diversity through data-driven and quantitative methods (Fisher et al., 2011; Boyd et al., 2008; Jørgensen, 2005). Spatial planning has become a key technique that forest planners are utilizing to create optimal, multi-use, ecologically-driven, landscape-level management plans (Hof et al., 1994; Kurttila, 2001; Constantino et al., 2008; Williams et al., 2004). In this paper, we use spatial planning techniques to create comprehensive plans for biodiversity conservation and to identify general rules of thumb for situations in which site-specific data are scarce.

Two well-established spatial management approaches for conserving biodiversity exist: harvest scheduling and reserve network design (Kurttila, 2001; Bettinger et al., 2003; Williams et al., 2005). Biological reserve design has focused on both the ecological rules used to select reserves (Williams et al., 2004) and the computational methods used to find an optimal design. Key findings include: spatial effects, such as proximity of populations and adjacency of available habitats, can have strong effects on species diversity in managed landscapes (Kurttila, 2001; Williams et al., 2004; Kangas et al., 2006); different ecological reserve selection rules often lead to different optimal networks (Önal, 1997; Olschewski and Benítez, 2010); and multi-criteria optimization methods enable compromise between competing ecological, economic, and social objectives by illustrating appropriate trade-offs (Kangas, 1994; Diaz-Balteiro and Romero, 2004; Venema et al., 2005; Wolfslehner

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et al., 2005). Computational methods for finding optimal reserve designs have typically used integer programming with one of two classic formulations (Camm et al., 1996; Önal, 2004): the Set Covering Problem (SCP), which minimizes the number or cost of sites reserved given a baseline species conservation constraint, or the Maximal Coverage Problem (MCP), which maximizes the number of species protected given a constraint on the total number of sites selected (Camm et al., 1996). These studies have structured the MCP with constraints that create thresholds of reserve number, reserve proximity, reserve connectivity, and spatial compactness of reserves (Williams et al., 2005; Nicholson and Possingham, 2006). Extensions of MCPs solved with mixed-integer programming have "protected" species with a range of qualifications, including a threshold reliability rate of species survival (Haight et al., 2000) or focused on decreasing probability of species extinction (Nicholson and Possingham, 2006). These formulations, however, only counter the effects of harvesting through permanent, non-harvested areas, and do not consider the potential for species to be saved through sustainable harvesting methods.

To date, harvest scheduling research has mostly utilized mixed-integer programming to apply general rules of thumb to spatial management plans rather than utilize species-specific considerations. Similar to adjacency specifications in reserve selection, Murray and Church (1996) maximize profit while imposing general adjacency restrictions that prevent simultaneous harvest of neighboring units. Extensions on this mixed integer programming model account for additional general considerations of ecological complexity (Snyder and ReVelle, 1996; McDill et al., 2002).

When considering species-specific sensitivity, harvest scheduling research has generally focused on how extinction probabilities are affected by different combinations of species' traits and harvest schedules (Kurttila, 2001; Costello and Polasky, 2004). Hof et al. (1994), for example, presents a dynamic, spatiotemporal integer programming model to find the harvest schedule that maximizes a species population size for given growth and mortality rates. Computationally, most studies have utilized heuristic processes to find approximate, but not necessarily optimal solutions (Rodrigues and Gaston, 2002; Bettinger et al., 2002; Richards and Gunn, 2003; Moilanen, 2007). This point is reinforced by the fact that, since the initial formulation by Hof et al. (1994), we are aware of only two papers that have used mixed integer programming for landscape-level harvest scheduling with species-specific spatiotemporal considerations (Ramage et al., 2013a,b). These papers explore the *Optimized Floating Refugia* (OFR) strategy, which utilizes integer programming and objectives similar to those used in reserve network design to identify optimal spatiotemporal harvest plans. The OFR strategy anticipates local harvest-induced extinctions and focuses on facilitating recolonization via spatiotemporal management of *floating refugia* (stands remaining unharvested in the current period). The approach is rooted in a very simple assumption: species are less likely to go extinct if the entirety of their range is never synchronously harvested. As such, the basic objective (which can be modified to include adjacency constraints and other considerations) is to minimize the number of species forced to experience range-wide harvest in any single harvest period.

In general, the spatial planning methods described above require detailed knowledge of species-specific traits and/or life histories (although the OFR strategy relies on stand-level presence–absence data only), but these data rarely exist for tropical forests (Jetz et al., 2012). In these incredibly species-rich landscapes, the identification and mapping of individual species is often unrealistic, and the determination of species-specific habitat preferences is even more challenging (Ramage et al., 2013a; Ghazoul and Sheil, 2010). Thus, a more realistic approach for tropical forests may be the use of landscape-level criteria based on general ecological principles (Potts and Vincent, 2007). Despite data limitations, some key basic ecological principles on the structure and diversity of tropical forests have emerged: it is now widely accepted that the majority of species are rare and have highly aggregated spatial distributions, and that there is a high degree of turnover in species composition within landscapes (Fangliang et al., 1997; Condit, 2000; Seidler and Plotkin, 2006).

In this paper, we combine features of harvest scheduling and reserve design to enhance understanding of conservation options for multi-use forest landscapes, and to identify general principles for retaining species diversity in tropical forests. By expanding the OFR strategy to include permanent reserves, we quantify the ability of different harvest plans and reserve networks to conserve species in landscapes with different ecological characteristics. We accomplish this by (1) simulating a series of landscapes with varying species abundance distributions and levels of species spatial aggregation, (2) running fixed-pattern, random, and optimized harvest scheduling in conjunction with different proportional reserve coverages and placement methods (including the OFR strategy with permanent reserves), and (3) determining the number of species conserved under each scenario. Our analyses are novel in that they employ both reserve site selection and strategic spatiotemporal harvesting in a common framework.

2. Methods

We investigated the ability of different harvest plans and reserve networks to conserve species in landscapes with a range of ecological characteristics. Landscapes differed in total species number (i.e., species richness) and the degree of conspecific aggregation. After harvest schedules and reserve networks were determined, we evaluated the effectiveness of all plans according to the criteria underlying the Optimal Floating Refugia (OFR) strategy (Ramage et al., 2013a). Both harvest plans and reserve networks included optimized designs as well as non-optimized designs (random and/or pattern-based). Optimized patterns were found using a Mixed-Integer Program variation of the model developed for the OFR strategy. As such, by definition, optimized plans represent best-case scenarios given these OFR criteria.

2.1. Landscapes

We created landscapes of either 500, 1000 or 2000 species (I) with a fixed total community size (C) of 15,360,000 individuals. Assuming a stem density of 600 adult (>10 cm dbh) trees per hectare (Condit et al., 1996), this equates to a forest area of approximately 25,000 hectares. We used the log series distribution to simulate individual species abundance. We chose to use the log series distribution as it is commonly used to describe plant abundance distributions and has been found to closely resemble data over a broad range of tree communities (Hubbell, 1997; Fangliang et al., 1997). The effect of holding C constant while varying I was to create communities that differed in both the overall species diversity and the commonness or rareness of species. A graph of rank order species abundance is provided in the Supplementary material (Appendix, Fig. A1).

To create landscapes that differed in the degree of species-specific spatial aggregation, we used the HEAP algorithm developed by Harte (2005). The HEAP algorithm randomly selects spatial centers of individual species distributions, and has a single parameter (ϕ) that controls the degree of aggregation assuming that all species have the same spatial aggregation probability. When ϕ is 0, species-specific spatial patterns are entirely random, and when ϕ is 1, species-specific spatial patterns are maximally aggregated (all individuals in one stand). We created landscape with ϕ equal to