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Optimizing wetland restoration and management for avian communities using a mixed integer programming approach

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ABSTRACT

Conservation planning and management decisions often present trade-offs among habitats and species, generating uncertainty about the composition and configuration of habitat that will best meet management goals. The public acquisition of 5471 ha of salt ponds in San Francisco Bay for tidal-marsh restoration presents just such a challenge. Because the existing ponds support large numbers of waterbirds, restoring the entire area to tidal marsh could cause undesirable local declines for many species. To identify management strategies that simultaneously maximize abundances of marsh- and pond-associated species, we applied an integer programming approach to maximize avian abundance, comparing across two objectives, two models, and five species weightings (20 runs total). For each pond, we asked: should it be restored to a tidal marsh or kept as a managed pond, and with what salinity and depth? We used habitat relationship models as inputs to non-linear integer programs to find optimal or near-optimal solutions. We found that a simple linear objective, based on maximizing a weighted sum of standardized species' abundance, led to homogeneous solutions (all-pond or all-marsh). Maximizing a log-linear objective yielded more heterogeneous configurations that benefit more species. Including landscape terms in the models resulted in slightly greater habitat aggregation, but generally favored pond-associated species. It also led to the placement of certain habitats near the bay's edge. Using the log-linear objective, optimal restoration configurations ranged from 9% to 60% tidal marsh, depending on the species weighting, highlighting the importance of thoughtful a priori consideration of priority species.

1. Introduction

Conservation planning and reserve-design algorithms are well-developed and have been applied widely for large landscapes that encompass multiple habitat types containing different suites of species (Csuti et al., 1997; Margules and Pressey, 2000; Possingham et al., 2000). Measures of species diversity, rarity, endemism, and complementarity (Vane-Wright et al., 1991) have been used to identify conservation configurations with the highest biodiversity conservation potential (Williams et al., 1996; Kerr, 1997; Faith et al., 2004). However, in smaller areas with similar habitat and species composition throughout, conservation potential may depend more upon landscape configuration and habitat management

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strategies than upon the protection of individual sites. This is especially true for urbanized or otherwise transformed landscapes where ecological functions are compromised, disturbance levels are high, and active management may be necessary to maintain biodiversity, often with trade-offs among species. Typically, reserve design and conservation planning research in urban and transformed areas has been focused on small habitat "islands" where species are threatened by isolation, extinction, and changes in predator/prey dynamics (Soulé et al., 1988; Bolger et al., 1991; Crooks and Soulé, 1999). However, opportunities for large-scale (on the order of 10^3–10^4 ha) conservation and restoration also exist within urban and transformed settings, especially for major estuaries such as San Francisco Bay, where large expanses of tidal marsh may be restored passively by breaching levees and restoring tidal action to diked former wetlands (Williams and Faber, 2001). In addition to providing conservation and flood-control benefits, tidal marshes also sequester carbon at high rates (Chmura et al., 2003), providing an additional economic incentive for restoration with the emergence of global carbon markets.

1.1. Optimization algorithms

There are many possible approaches available for conservation planning and reserve-design problems, including simple expert opinion. Quantitative approaches can be generally classified as those that provide guaranteed optimal or near-optimal solutions, such as integer programming (Papadimitriou and Steiglitz, 1982), and heuristic methods that attempt to find good solutions, but provide no guarantee on their solution quality, such as simulated annealing (Possingham et al., 2000). Both have been used in conservation planning and reserve design, but heuristic approaches are more widely used (Bedward et al., 1992; Cabeza and Moilanen, 2003; Leslie et al., 2003). In part, the popularity of heuristic approaches has been facilitated by the development of user-friendly software packages such as Marxan (Possingham et al., 2000), C-Plan (Pressey et al., 2005), and Zonation (Moilanen, 2007). Some researchers have argued that optimal solutions, especially for integer programming, are too computationally expensive or complicated to achieve, and that heuristic algorithms can provide solutions that are equally or nearly as good (Pressey et al., 1996; Moilanen, 2008). Others maintain that heuristic approaches can be problematic and that optimization approaches are well-developed and preferable, yielding solutions that can be measured against performance standards (Underhill, 1994; Camm et al., 1996; Önal, 2004). Despite the computational complexity, optimization approaches have been used in several reserve design (Nevo and Garcia, 1996; Hof and Raphael, 1997; Rodrigues and Gaston, 2002; Önal and Briers, 2003; Williams et al., 2004) and other spatial ecosystem management and land-use planning applications (Hof and Bevers, 2000; Seppelt and Voinov, 2002; Aerts et al., 2003).

1.2. Wetland conservation planning

The restoration and management of major estuaries and associated wetlands present a conservation planning challenge well-suited to optimization approaches. Often, these wetland areas are large (thousands of hectares), fairly homogeneous, and management-dependent, with conflicting habitat requirements among species of management interest (Vickery et al., 1997). We focus here on bird communities of the South San Francisco Bay, where the 2003 public acquisition of 5471 ha of salt ponds provides an unprecedented opportunity to restore large areas of tidally influenced habitat, especially tidal marsh. The conversion of these salt ponds to tidal marsh would result in a doubling of habitat for tidal-marsh-associated bird species, possibly increasing overall viability of species such as the endangered California clapper rail (*Rallus longirostris obsoletus*) (Foin et al., 1997). The existing salt ponds support a high diversity and abundance of waterbirds, however, including 5–13% of the federally threatened Pacific coast population of the snowy plover (*Charadrius alexandrinus*) (Page et al., 1991), which could experience substantial declines with the loss of this habitat (Warnock et al., 2002). The potential for conflict among conservation objectives is clear.

For migratory waterbirds, which have lost a large portion of their historical coastal intertidal stopover and wintering habitat, artificial and managed open-water habitats (including salt ponds) now provide a substantial portion of their foraging and roosting habitat (Davidson and Evans, 1986; Weber and Haig, 1996; Stenzel et al., 2002). Depth, salinity, and configuration of ponds are among the most important factors determining habitat quality and capacity (Erwin, 1996; Elphick and Oring, 1998; Isola et al., 2000). Other wetland species, particularly tidal marsh endemic rails and songbirds, have contrasting habitat requirements, in that they are dependent on tidally-influenced vegetated wetlands (Foin et al., 1997; Spautz et al., 2006). Thus, the issue becomes one of assessing priorities and trade-offs among different species of conservation concern Elphick (2004).

1.3. San Francisco Bay optimization goals

For San Francisco Bay salt ponds, the problem is one of both site selection (which salt ponds to restore to tidal marsh) and optimal management (how to manage remaining ponds). In theory, any pond could be managed in any way, with different effects on different species of conservation interest. Assuming that habitat is a limiting factor for the species of interest and focusing on pond salinity and depth—two variables with significant predictive value for waterbirds (Stralberg et al., 2006)—we developed a model defining the relationships between pond conditions and log-transformed species density. The ability to encapsulate these management considerations and their importance for avian species into linear equations made this problem suitable for the application of linear integer programming techniques. The non-linearity introduced by the use of log-transformed bird densities (as well as other non-linearities to be discussed) complicated the problem, however, resulting in a non-convex, non-linear integer problem (Papadimitriou and Steiglitz, 1982). Such optimization problems are typically limited to heuristic optimization methods, but in our case, because of the special structure of the optimization model, we were able to apply integer programming.