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Conservation and Management for Multiple Species: Integrating Field Research and Modeling into Management Decisions

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ABSTRACT / Multiple-species reserves aim at supporting viable populations of selected species. Population viability analysis (PVA) is a group of methods for predicting such measures as extinction risk based on species-specific data. These methods include models that simulate the dynamics of a population or a metapopulation. A PVA model for the California gnatcatcher in Orange County was developed with landscape (GIS) data on the habitat characteristics and requirements and demographic data on population dynamics of the species. The potential applications of this model include sensitivity analysis that provides guidance for planning fieldwork, designing reserves, evaluating management options, and assessing human impact. The method can be extended to multiple species by combining habitat suitability maps for selected species with weights based on the threat faced by each species, and the contribution of habitat patches to the persistence of each species. These applications and extensions, together with the ability of the model to combine habitat and demographic data, make PVA a powerful tool for the design, conservation, and management of multiple species reserves.

Multiple-species reserves aim at conserving the biodiversity of a region by ensuring that a representative set of native species are protected. These species are selected based on various criteria, which may include their ecological or economic importance, taxonomic uniqueness, status as threatened or endangered species, or sensitivity to environmental impacts. Multiple-species reserves aim at supporting viable populations of these species. Viability of a species is often expressed with such variables as risk of decline, chance of recovery, or expected time to extinction (Burgman and others 1993, Akçakaya and others 1999). Population viability analysis (PVA) is a group of methods for predicting such measures as extinction risk based on species-specific data (Boyce 1992). These methods often include models that simulate the dynamics of a population or a metapopulation.

This paper describes a PVA model that combines demographic data (such as censuses, mark-recapture studies, surveys, and observations of reproduction and dispersal events) and geographic data (such as habitat maps from a GIS). This approach has been implemented as the program RAMAS GIS (Akçakaya 1998), and it has been applied to several species,[1] including the northern spotted owl (Akçakaya and Raphael 1998), the marbled murrelet, the red-cockaded woodpecker, the helmeted honeyeater (Akçakaya and others 1995), and the Florida scrub-jay (Root 1998).

The approach of combining demographic and geographic data has recently been used to model the metapopulations of California gnatcatcher (*Polioptila c. californica*) and cactus wren (*Campylorhynchus brunneicapillus*) in central and coastal Orange County, California. These two species were selected as target species for the conservation of the coastal sage scrub community under the State of California's Natural Community Conservation Planning (NCCP) program by the NCCP coastal sage scrub Scientific Review Panel.

In this paper, the California gnatcatcher model is summarized, and the potential applications of the model to the design, conservation, and management of multiple species reserves are discussed.

Model of California Gnatcatcher in Orange County

In a recent study, Akçakaya and Atwood (1997) developed a metapopulation model of California gnatcatcher (*P. c. californica*) in Orange County. The study started with a compilation of habitat data on vegetation and topography, and demographic data on survival, reproduction and dispersal of this species. The habitat

KEY WORDS: Population viability analysis; Geographic information systems; Extinction risk

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[1] Summaries of these case studies can be found at www.ramas.com with a list of publications and detailed reports.

Table 1 Variables used by Akçakaya and Atwood (1997) in logistic regression for determining the habitat suitability function for the California gnatcatcher

Map name	Symbol	Units and description
Elevation	**ELV**	m above sea level
Slope	**SLP**	percent (i.e., 0 for flat areas; 100 for a 45° incline)
Aspect	**ASP**	degrees from north (e.g., 180 for south, 90 for east and west, 0 for north)
Coastal sage scrub	**CSS**	m^2 (per 1-ha cell)
Distance from trees	**DTR**	m (distance to the nearest cell with at least 10% cover of trees or other woody vegetation)
Distance from grassland	**DGR**	m (distance to the nearest cell of grassland)
Distance from water	**DWT**	m (distance to the nearest cell of wetland or riparian vegetation)

data included raster maps of habitat variables (see Table 1). These data were organized by a geographic information system (GIS) and combined with locations where gnatcatchers were observed.

These data were then used in a stepwise logistic regression, in which the gnatcatcher observations were the dependent variable and values from habitat maps were independent variables. The habitat function predicted by this regression included the variables CSS, ELV, DTR, and DGR, and the interactions CSS × ELV, CSS × DTR, and ELV × DTR (see Table 1 for the symbol for each habitat map). The habitat function that was predicted by the regression was then used to calculate a habitat suitability (HS) value (between 0 and 1) for each cell in a raster map. The value gave the probability of finding a gnatcatcher pair at that location, and thus reflected the suitability of the habitat.

The resulting habitat suitability map was then validated by estimating the regression function from the northern half of the landscape and using this function to predict the habitat suitability for known locations in the southern half. Because the observations used in estimation of the function were not the same as those used in testing it, the result showed the predictive ability, hence validity, of the function, rather than simply its goodness of fit. The validated habitat suitability map was analyzed to calculate the spatial structure of the species' metapopulation (i.e., the number, size, carrying capacity, and location of its subpopulations), based on the distribution and quality of the habitat.

At the population level, the model for the California gnatcatcher incorporated demographic data on survival, reproduction, and environmental variability for each population inhabiting a habitat patch. Demographic data collected by banding studies (Atwood and others 1998) were used to parameterize a stage-structured, stochastic matrix model with two stages (juveniles and adults). The stage matrix, which assumes a "birth-pulse" population and a postreproductive census (see Caswell 1989), is

$$\begin{bmatrix} P_{JB}M & S_aM \\ S_j & S_a \end{bmatrix}$$

where S_a is survival rate of adults; S_j is survival rate of juveniles; P_{JB} is proportion of last year's juveniles that are breeders this year; and M is maternity or fertility (number of fledglings per breeder). Because the demographic data were collected for several years, both average values and temporal variability of the matrix elements could be calculated. The temporal variabilities were used to model environmental stochasticity (random, year-to-year fluctuations in vital rates). In addition, the model included two types of catastrophes: cold/wet winters that affect vital rates and fires that affect carrying capacities.

At the regional (metapopulation) level, the model incorporated data on spatial factors that are important determinants of the risk of decline, including dispersal among patches (based on sightings of banded juveniles), catastrophes (Akçakaya and Baur 1996), and spatial correlation of environmental fluctuations among the patches (LaHaye and others 1994).

The model was used to perform a risk assessment that incorporated the effects of natural variability, as well as the uncertainties in model structure and parameters due to lack of knowledge and measurement errors (see Akçakaya and Atwood 1997).

Currently the model is being updated in two directions. First, new demographic data collected over the two last years (Atwood and others 1999) are used to get better estimates of demographic parameters, such as survival and fecundity. Second, the spatial structure of the metapopulation is recalculated to incorporate the structure of the NCCP reserves (see Fig. 1). This is done by applying a "protected area mask" to the habitat suitability map. This mask corresponds to the "Pro-

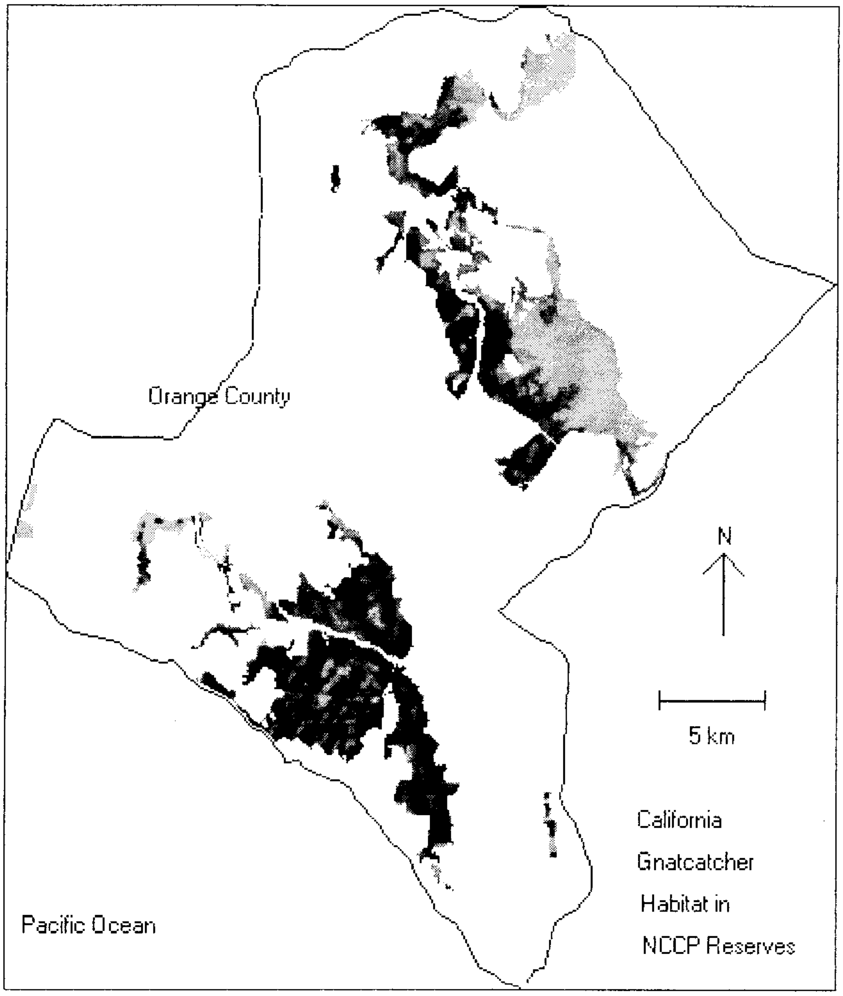


Figure 1. Spatial structure of the California gnatcatcher habitat in the NCCP reserves in central and coastal in Orange County (based on Akçakaya and Atwood 1997). Darker areas indicate higher habitat suitability.

posed Habitat Reserve System Map" (Figure 12 of the *Draft EIR/EIS for Central/Coastal NCCP*). In Fig. 1, the reserve system map is used to mask nonreserve areas while letting the proposed reserve areas to show through.

Future Directions: Potential Applications of the Model to Management

Results of modeling efforts like this one can be used in several different ways. They can be used to prioritize species based on their predicted risk of extinction and/or chance of recovery. They can be used to rank management or conservation options (such as reserve design, translocation, reintroduction, building habitat corridors, etc.) in terms of their effectiveness in increasing viability. They can be used to assess human impact (such as habitat loss or hunting) in terms of their effect in increasing extinction risks. In cases where data are not sufficient to make such assessments, results of sensitivity analyses can be used to determine which factors are most important (and hence which parameters to estimate more precisely). Such results can be used to guide fieldwork, saving time and resources in data collection efforts.

These and other potential applications are discussed below. These applications also indicate future research directions. We believe that the research directions outlined below will lead to a set of practical tools for evaluating options for the management and conservation of the coastal sage scrub community.

Planning Fieldwork and Refining Models with Model-Driven Field Research

Most parameters of a PVA model are known with a certain amount of uncertainty. Further fieldwork may yield data to narrow down these uncertainties and thus make model predictions more accurate and reliable.

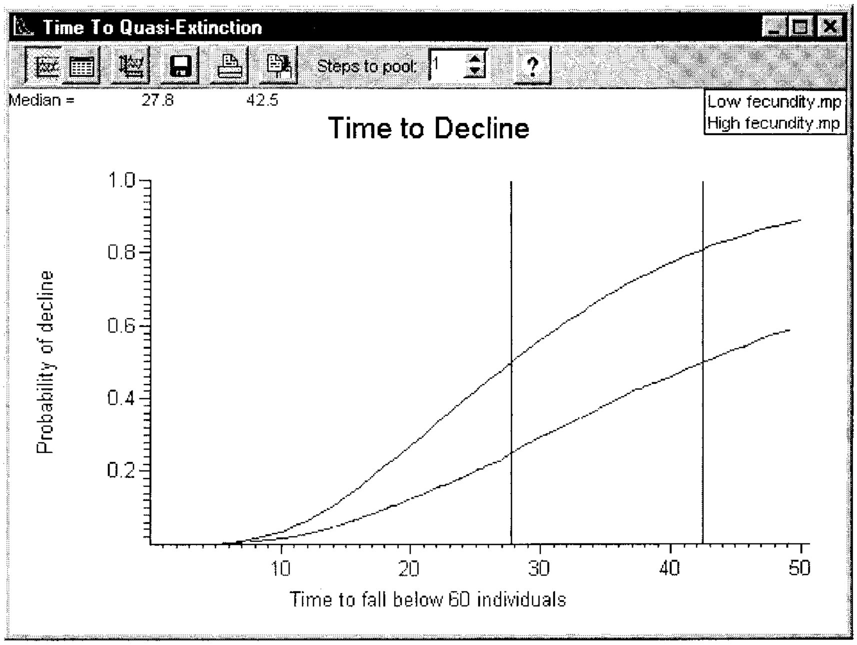


Figure 2. Cumulative probability distribution of time to fall below 60 individuals, under two assumptions (upper curve: low fecundity; lower curve: high fecundity). Each point on a curve gives the probability that the metapopulation will fall below 60 individuals at or before the time step (year) indicated on the *x* axis.

Analysis of the sensitivity of model results to various parameters provides guidance about what kind of data would be most efficient in terms of making the model predictions more reliable. For example, small sample sizes in the gnatcatcher study caused fecundity values to be estimated with substantial confidence intervals. The width of these intervals were used to estimate upper and lower bounds of the fecundity parameter of the model, as a measure of the uncertainty in this parameter. When the model is run with the upper ("high fecundity") and lower ("low fecundity") values, the risk-based results differed (Fig. 2). The difference between the two models gave an indication of the sensitivity of these risk-based results (distribution of time to fall below 60 individuals).

This type of comparison was repeated for each model parameter in a comprehensive sensitivity analysis (Akçakaya and Atwood 1997). The results of this analysis pointed out that the risk of decline of the metapopulation was most sensitive to variation and density dependence in vital rates. These parameters can be estimated more accurately by continued estimation of vital rates in the Orange County populations.

Using a model for management and conservation is an iterative process involving (in an annual cycle) field research, parameter estimation, analysis, and monitoring. Field research provides data for estimating model parameters; analysis of the model provides guidance for further field research as well as for management; monitoring allows independent checks of the model predictions and the evaluation of the effectiveness of management actions. The parameter estimation and analysis (including sensitivity analysis) steps must be carried out at least once a year to incorporate data collected during that year. This will facilitate efficient use of limited time and resources available for fieldwork and management. It will allow more accurate estimation of the most important model parameters, and increase the reliability of the model.

Expanding Geographic Coverage to Southern California

The limits of the study area in central and coastal Orange County are somewhat arbitrary. The coastal sage scrub in this area may be connected to similar habitat in southern Orange county and other counties. Future research should include the populations of the California gnatcatcher and target species in other counties in the metapopulation viability analysis.

The data for central and coastal Orange county is quite detailed, and it may be difficult to find similarly detailed data for other parts of the region. The accuracy of the habitat maps in other parts of the region may be estimated by using the current study area as a standard: after creating the new map with a larger geographic coverage, its habitat suitability predictions in the central and coastal Orange County may be compared with the current map that was based on more detailed data. This comparison will provide a basis for making necessary corrections to the larger map.

The larger map may then be used to determine the spatial structure of the metapopulations of the target

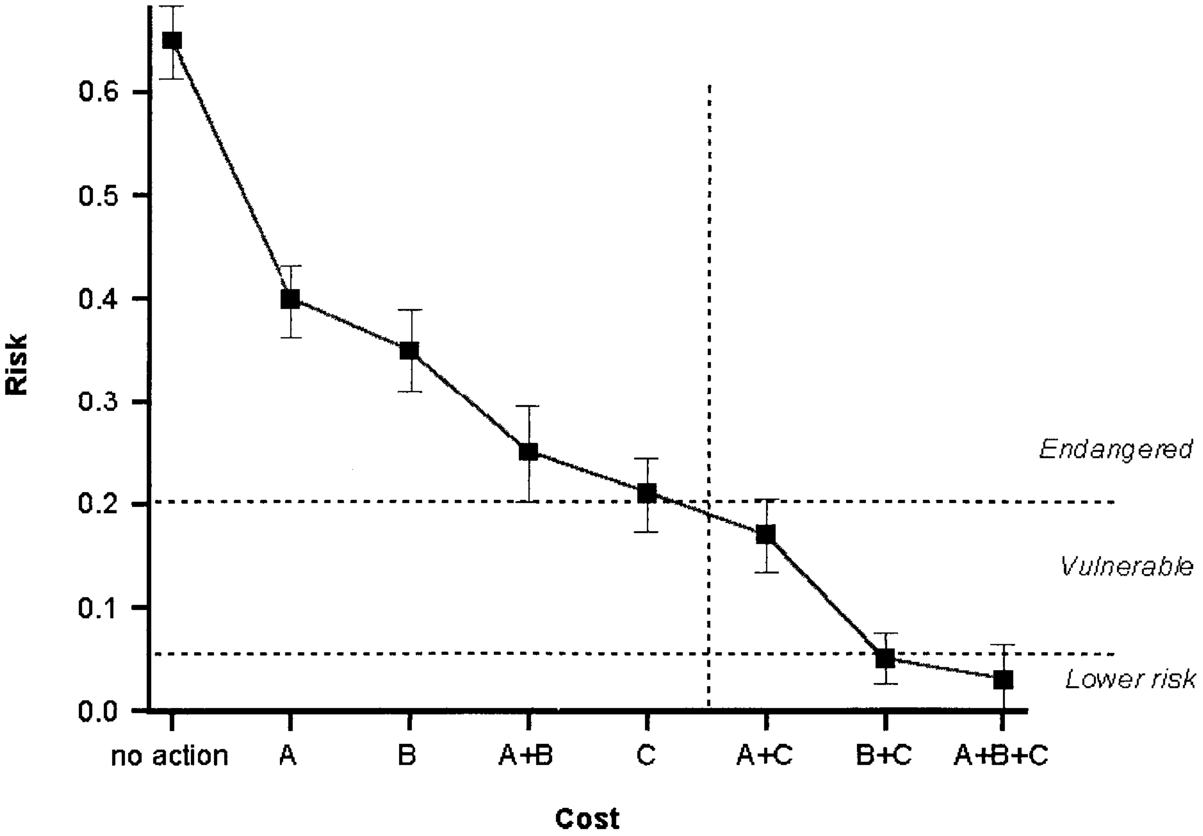


Figure 3. Risk of decline in a hypothetical metapopulation with no protected areas ("no-action" option) and under seven reserve design options. Each option protects one, two, or three of the three habitat patches A, B, and C. The options are in order of increasing cost from left to right (from Akçakaya and others 1999). Error bars represent bounds on extinction risk estimates due to parameter uncertainties in the model.

species in a wide geographic area. This information can be used to expand the current metapopulation models to the whole region. This expansion will allow us to evaluate management options in other parts of the region.

Designing Reserves

Reserve design, especially in a region as crowded as southern California, is determined by a large number of biological, economical, political, and social constraints. These constraints limit the number of feasible reserve configuration options. Metapopulation modeling can help provide scientific guidance to the process of reserve design by showing the environmental managers the ecological consequences of each option. This can be done by calculating the risk of decline for selected species under each reserve design option. Each reserve design option will then be associated with an economic (cost) and an ecological (risk of decline) consequence, as in Fig. 3.

These results can be used in two ways. First, they can be used to select the least costly reserve design option that still gives a risk of decline no greater than a predetermined level (represented by a horizontal line in the figure). Second, they can be used to select the best reserve design option (with the lowest risk) that costs less than a predetermined amount (represented by a vertical line in the figure).

It is important to note that in this figure the economic cost (e.g., cost of purchasing land for reserves) is represented by the horizontal axis, and the ecological benefits (reduction in extinction risk) is represented by the vertical axis. Thus, ecological and economic variables are kept on different axes. This cost-benefit analysis therefore avoids putting an economic value to the viability of a species, leaving the trade-off between economy and ecology to the environmental manager. What it does provide, however, is a science-based comparison of the reserve design options with respect to their ecological and economic consequences.

This approach can also be used for other aspects of reserve design, for example, designing habitat corridors and other connecting habitat or adding small, "stepping-stone" habitat patches to existing reserves.

Testing Management Options

In principle, all possible management actions can be represented as changes in habitat suitability or demographic parameters once the effect of these management actions are described in terms of model parameters. For example, habitat restoration can be modeled as an increase (or a time-delayed increase) in the carrying capacity of habitat patches; removal of nest parasites (such as cowbirds) can be modeled as an increase in average fecundity; adding habitat corridors can be modeled as increased dispersal rate among existing habitat patches.

The consequences of these changes are estimated by the model in terms of the viability of the species and then used to rank alternative management actions, prioritize conservation measures, and evaluate the relative importance of different parameters.

Scarcity of reliable demographic data (and the resulting model uncertainty) is a common problem for PVAs. However, the model can address questions about management options despite its uncertainties. This is because the model results are much more reliable if interpreted as relative predictions (relative to a no-action scenario or to other management options) than if interpreted as absolute predictions. Results of various sensitivity analyses indicate that even in cases with considerable model uncertainty, the habitat-based risk assessment approach is sensitive to the effects of alternative management actions (e.g., see Akçakaya and Raphael 1998). Thus, it can be used to compare and rank management alternatives in terms of their effect on the viability of the species studied. As an example, the model may not yet be able to accurately predict exactly what the population size of gnatcatchers would be 50 years from now. It may, however, more reliably predict whether fire management or cowbird removal is more likely to increase the viability of the population.

Future research on evaluating management alternatives should start with the identification of management options. The second step is the estimation of the expected effect of each option on the model parameters. This will involve fieldwork that concentrates on the change to be brought about by the management option under consideration. For example, if we are evaluating an option related to habitat improvement, the fieldwork will consist of estimating population parameters affected by habitat (such as carrying capacities and vital rates) at the proposed location of management and at different locations with good-quality habitat. The viability of the target species can then be evaluated by the model with and without each management option and compared among the management options, as well as with a "no-action" alternative.

Assessing Human Impact

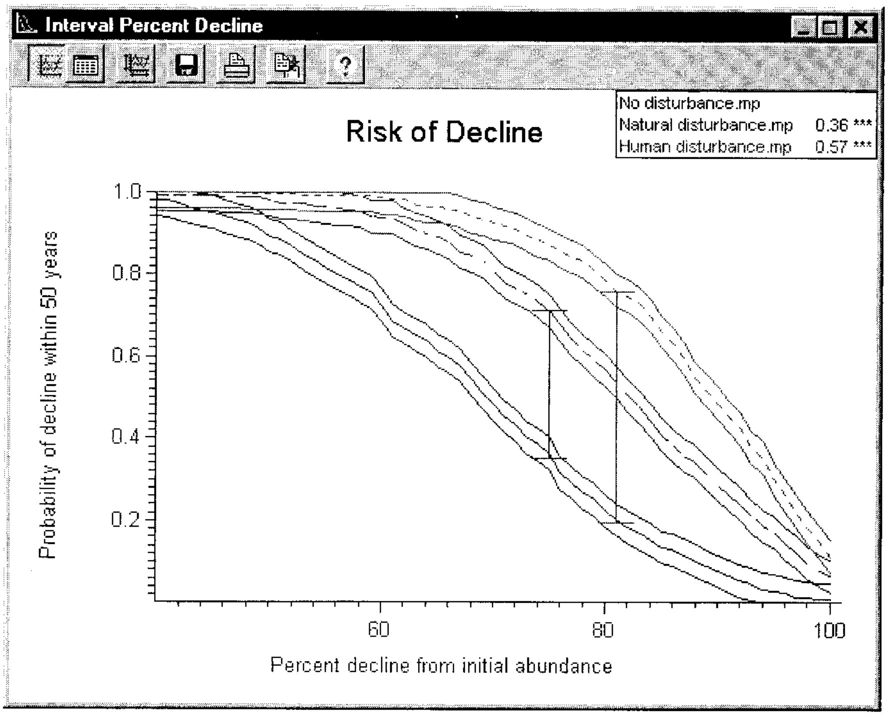
Assessment of human impact can be done in a way similar to the evaluation of management options. Each impact affects the population in a specific way. These effects can be quantified as changes in model parameters or structure. For example, habitat loss may decrease the carrying capacities of affected habitat patches; fragmentation can change the spatial structure of the metapopulation; pollution and widespread degradation of habitat quality may affect vital rates, such as survival and fecundity; geographic barriers may lead to both fragmentation and a decrease in connectivity (dispersal rates among patches).

As in the case of evaluation of management options, an important step is the quantification of these changes in model parameters. Once this is done, the impact or the disturbance can be characterized in terms of its effect on the viability of selected species (see, for example, Fig. 4). Each impact can be compared to a "no-impact" scenario to assess its ecological consequences.

Multiple Species Reserves: Reserve Design and Management from a Multispecies Perspective

The habitat-based metapopulation modeling approach described above is applied to a list of selected (e.g., "indicator," threatened, or sensitive) species. This results in habitat suitability maps, and metapopulation models for all species in the list. The results of the model simulations are used to estimate the risk of extinction or decline of the species in the whole region, as well as the importance of each location for the viability (persistence) of the species.

Each of the individual habitat suitability maps can then be combined into a single aggregate map (a "multispecies conservation value" map) that expresses the worth, in conservation terms, of the locations. The habitat suitability maps can be combined mathematically by using a weighted average of all of the maps. Weighting of the values can be based on the habitat suitability and the risk of extinction of each species. The multispecies habitat suitability will be calculated for each location j (e.g., each cell in a raster map) in the region with the formula



No disturbance.mp
Natural disturbance.mp 0.36 ***
Human disturbance.mp 0.57 ***

Figure 4. A hypothetical example demonstrating the use of risk curves for impact assessment. The three sets of curves show the risk of decline in total abundance as a function of the amount of decline under three disturbance regimes (top: human disturbance; middle: natural disturbance; bottom: no disturbance; in each set, the upper and lower curves indicate bounds due to uncertainty). Each point on a curve gives the probability that the population will decline within the next 50 years by the percent amount indicated on the *x* axis. The vertical bars indicate the maximum difference between the results of two disturbance regimes. For example, in this hypothetical example, the risk of an 80% decline (from the initial abundance) is only 0.2 with no disturbance but over 0.75 under human disturbances.

$$\frac{\sum_{i=1}^{n}(HS_{ij}\cdot P_i\cdot C_{ji})}{\sum_{i=1}^{n}P_i}$$

where n is the number of species, HS_{ij} is the habitat suitability value for species i at location j, P_i is the probability of extinction or decline of species i, and C_{ji} is the contribution of the location j to the viability of species i.

The contribution of location j to the viability of species i (C_{ji}) is calculated as follows. The extinction risk of species i is estimated with two metapopulation models. One model includes all locations, the other model excludes location j. The difference between these two estimates of the extinction risk of species i is a measure of the importance of location j for the viability of species i.

The ecological value of a parcel is calculated by summing the conservation values of all the locations (pixels, cells) within that parcel. This formulation incorporates the following:

- Species facing a higher threat of extinction contribute more to the conservation value of their area of occupancy
- Species that are restricted to a small area contribute more to the conservation value of those areas
- Areas used by endangered species have higher value than areas used by the same number of nonthreatened species
- Areas used by species with restricted distributions have higher value than those used by the same number of widespread species
- Areas used by more species have higher value than those used by fewer species

The multispecies habitat suitability for each location will combine the suitability of that location for all species, reflecting the priority for species with higher risk of extinction, and the contribution of each location to the viability of species. The contribution will be calculated as the increase in risk of extinction of a species when that location is excluded from the metapopulation model. Such a map can then be used in several ways:

- It can be used to design reserves based on the multispecies conservation value, or to assess the ecological value of different parcels, based on ownership.

- It can be used to assess the community-level effect of a human impact or a natural disturbance in different places (e.g., in different parcels). This will allow ecological impact assessments to consider the potential harm to the ecosystem and the ecological importance of the areas that may be potentially impacted.
- It can be used to identify ecological "hot spots," i.e., areas of high conservation value. This can be done by identifying areas that are suitable for the collection of the species included in the analysis and using a patch-recognition algorithm to identify contiguous patches of high habitat suitability.
- It can be calculated for the current conditions as well as for the predicted conditions following the implementation of management options. The comparison of the current multispecies map with maps that incorporate effects of management will provide another tool for prioritizing management and conservation measures.

Discussion

Habitat conservation plans, as well as plans for the management and design of multiple species reserves, will work only if they are based on sound science. One of the most powerful scientific tools that land managers and decision makers can use is PVA of selected species. Recent advances in modeling, described in this paper and by others, expand the scope and utility of PVA models in several directions that are directly relevant to reserve design and management:

First, PVA with metapopulation models allow simultaneously considering multiple populations of the same species in the same model. There are various types of metapopulation models, differing in the detail they incorporate, their assumptions, and their data requirements. For reviews, see Hanski and Gilpin (1991), Gilpin (1996), and Breininger and others (2000).

Second, metapopulation models take into account spatial structure, i.e., the geographic distribution (location), size, and shape of habitat patches in which subpopulations of a metapopulation occur. This is done either in the form of spatially explicit individual-based models (Pulliam and others, 1992, DeAngelis and Gross 1992, Dunning and others 1995) or in the form of spatially structured metapopulation models (LaHaye and others 1994, Akçakaya and Baur 1996).

Third, metapopulation models have been developed that explicitly use habitat information in determining the spatial structure of the model (e.g., Lamberson and others 1994, Akçakaya and Atwood 1997).

Fourth, they incorporate uncertainties and use sensitivity analyses (Ferson and Burgman 1995, McCarthy and others 1995, Akçakaya and Raphael 1998). Analysis of the sensitivity of model results to uncertainties in each model parameter provides guidance about what kind of data to collect to make the model more reliable. For example, the difference between the two risk curves in Fig. 2 is a result of the uncertainty in fecundity values of the gnatcatcher model and is a measure of the sensitivity of the model result to this parameter.

In addition to these, an approach outlined in this paper allows combining the results for calculating a multispecies conservation value. These methods can be used to aid various types of decisions in the design and management of multispecies reserves. They can be used to guide fieldwork to use resources in the most efficient way. They can support reserve design decisions with a science-based comparison of the design options with respect to their ecological and economic consequences. They can be used to evaluate management options and impacts in terms of their effect on the viability of selected native species. Finally, they can be used to identify ecological "hot spots," i.e., areas of high conservation value from a multiple species perspective.

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