Quantitative Tools for the Monitoring of Threatened Species: A Marbled Murrelet Case Study

John G. Boulanger
Integrated Ecological Research
924 Innes Street, Nelson, BC, VIL 5T2, Canada
boulange@ecological.bc.ca

ABSTRACT

Recent developments in quantitative methods can potentially improve the statistical rigor of monitoring programs. Matrix modelling and power analysis are valuable tools in the design of monitoring programs even for species in which sparse data exist. Newer distance and mark-recapture methods can improve the quality of estimates when compared with count-based methods. This paper presents a case study of the marbled murrelet (*Brachyramphus marmoratus*) to illustrate the application of these methods. Two possible murrelet life history scenarios that represent the extremes of plausible murrelet parameter values, given the limitations of current knowledge, are examined to illustrate matrix modelling and power analysis. Sensitivity analysis suggests that regardless of life history scenario, murrelet populations are more sensitive to changes in adult survival, and less sensitive to juvenile survival and productivity. Power analyses of population trajectories generated by the matrix model suggest that only large reductions in individual population parameters would be detected in 10 years by at-sea census techniques. Results of these analyses have helped to prioritize strategies for monitoring and research of murrelet populations. The results of recent studies are used to illustrate the applicability of mark–recapture and distance methods to marbled murrelet populations. Estimation of survival rates for marbled murrelets in British Columbia using mark–recapture methods is providing new insight into the life history of the murrelet. Distance methods improved power of at-sea surveys of murrelet populations in California. Comprehensive power analysis (MONITOR), mark–recapture (MARK), and distance (DISTANCE) software programs are currently available free from specialized Web sites.

Key words: distance sampling, mark–recapture, matrix models, population monitoring, power analysis, uncertainty.

Population monitoring programs involve the complex task of detecting demographic trends, which are the result of the interaction among species demography, environmental perturbations, and stochastic effects. This paper focuses on how quantitative methods can potentially improve the statistical rigor of monitoring programs.

Matrix modelling and power analysis are valuable tools in the design of monitoring programs even for species in which sparse data exist. Many recent studies have used matrix model methods to evaluate conservation measures and forecast population trends for rare species (Crouse et al. 1987, Caswell 1989). These mathematical studies have mainly been conducted for species in which substantial research efforts have produced precise parameter estimates. However, for many species, not enough data currently exist to allow precise parameter estimates; therefore, little effort has been made to understand the species population dynamics using the rigorous framework of a population model. Sometimes the lack of understanding regarding the effect of specific parameters on overall population dynamics has led to unfocused research and conservation efforts.

A case study of marbled murrelets is used to illustrate the basic steps in the matrix model and power analysis approach to monitoring study design. This paper cannot fully document the modelling process; refer to Boulanger et al. (in press) for a thorough discussion of this case study. Power analysis of monitoring data may reveal a low probability to detect a population change and discussion is provided on alternative methods to boost power.

METHODS

MATRIX MODELS

Various matrix and population viability analysis (PVA) models are available for use in species management and monitoring design. These models vary in complexity from simple matrix models to spatially explicit metapopulation models. This paper focuses on the use of simple matrix models and power analysis to prioritize monitoring objectives. For this

L. M. Darling, editor. 2000. Proceedings of a Conference on the Biology and Management of Species and Habitats at Risk, Kamloops, B.C., 15 - 19 Feb.,1999. Volume One.
B.C. Ministry of Environment, Lands and Parks, Victoria, B.C. and University College of the Cariboo, Kamloops, B.C. 490pp.

paper, matrix models are used to explore monitoring strategies but cannot be used to determine absolute rates of population change given the high uncertainty in model parameters. Readers should consult Beissinger and Westphal (1998) for the advantages and pitfalls of PVA methods.

Step 1: Conceptualization of Life History Parameters and Formulation of Matrix Model

General life history parameters and scenarios for marbled murrelets were initially determined by discussion between field biologists and quantitative ecologists and review of existing literature. From this process a simple life history model for marbled murrelets was formulated (Fig. 1). Each node in the diagram represents a specific stage, which is controlled by a unique set of life history parameters. In this model the population is censused in the fall after the breeding season. The survival of young of the year for the 2 years is parameterized by juvenile survival (S_j) and after that parameterized by adult survival (S_a). The breeding age birds (assuming an age of first breeding of 2 years) attempt to breed each spring and their success is parameterized by productivity (P). The numerical relationships in the life history diagram can then be easily translated into matrix format.

The projections from the resulting matrix model follow the model of exponential population growth (or decline) as defined by the equation:

$$N_t = N_0 e^{rt}$$

In this equation, N_0 is the initial population number and N_t is the value at a give time t. The dominant eigenvalue of the matrix is symbolized by λ and is equal to e^r. If the population is stable then λ must equal 1. If the population is decreasing, λ is negative, and if the population is increasing, λ is positive. Therefore, by calculating λ from the matrix the future population trajectory for a set of population parameters can be determined (Caswell 1989). Note that the basic matrix calculations can be programmed on an Excel© or similar spreadsheet package whereas more complex matrix calculations require specialized programs such as Matlab© or O-Matrix©.

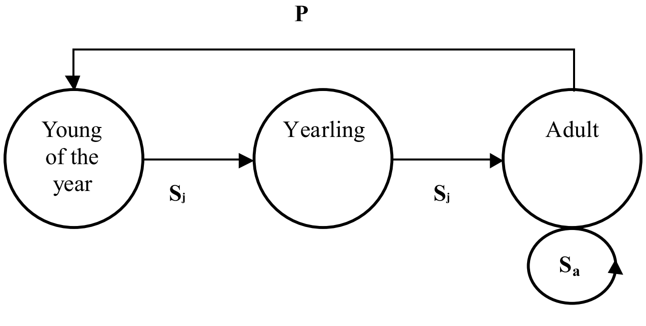

Figure 1. A life cycle diagram for the marbled murrelet for age of first breeding at 2 years. This life history diagram pertains to a population in which a post-breeding census is conducted. P = productivity, S_a = adult survival, S_j = juvenile survival from first fall census to 2 years of age.

Some assumptions apply to this matrix model. First, the model considers that only females are included, breeding age females always find mates, and the population has an even sex ratio. Second, the population is censused in the fall after breeding. Third, the population is at equilibrium and always has a stable age structure. Fourth, the model is linear with no density-dependent effects. Finally, we assume that senescence is solely determined by adult survival values. The matrix model can be easily altered to generate precise predictions which can be used to test these assumptions with field data.

Step 2: Estimation of Life History Parameters and Potential Life History Scenarios

The second step in the modelling process involved assigning likely ranges of life history parameters based on sparse current knowledge of murrelets. Inference from comparison of similar alcid species by Beissinger (1995) gave approximate ranges of survival values for murrelets. Beissinger (1995) estimated that murrelets in their first year of life survive at 70% of adult survival and murrelets in their second year of life survive at 88% of adult survival. To keep the model simple, pre-breeding survival was compressed into 1 parameter by taking the geometric mean of 0.88 and 0.70. Juvenile survival was then calculated by multiplying this value (0.78) by the adult survival for each simulation. Data from observed nests and juvenile adult ratios gave approximate productivity values (Beissinger 1995, Nelson and Hamer 1995, Boulanger et al. in press).

A wide range of life history parameter values were plausible given the uncertainty in the life history of the murrelet. One initial method to formulate likely combinations of life history parameters was to determine which combinations result in a stable population. This was done by iteratively solving the matrix for parameter combinations which resulted in $\lambda = 1$ (Fig. 2).

To account for the large degree of uncertainty in parameter values Boulanger et al. (in press) focused on 2 life history scenarios with parameter values that maintain a stable population (Fig. 2). In the "high productivity" scenario, productivity could possibly be higher than that reflected by juvenile/adult ratios. With this scenario, adult survival falls within the range suggested from allometric comparisons with other alcid species and recent mark–recapture survival rate estimates . The second "high survival" scenario implies that murrelets have higher adult survival than suggested by their body size. This scenario is most plausible if we assume that current juvenile/adult ratios in Beissinger (1995) reflect true productivity.

This "extreme scenario" approach is a simple way to account for uncertainty in life history parameters. The main rationale behind this approach is that the true life history parameters for murrelets fall somewhere between the 2 extreme values. Modelling the 2 scenarios allows a test of model robustness to uncertainty in life history parameter values.

Step 3: Sensitivity Analysis

Sensitivity analysis was used to investigate the relative importance of each life history parameter in maintaining murrelet population given the range of parameter values previously listed. In each analysis, the change in λ was recorded when each life history parameter was proportionally decreased while the others were held constant (Fig. 3).

Results from the sensitivity analysis suggest that murrelet populations are most sensitive to changes in adult survival, followed by juvenile survival and productivity (Fig. 3). Marbled murrelets may have evolved a life history strategy that tolerates large fluctuations in yearly productivity that has been observed in other seabird species. This strategy would partially explain low model sensitivity to productivity. Given this, Boulanger et al. (in press) recommended that monitoring should emphasize detailing variances in productivity and estimating survival using methods similar to Kuletz and Kendall (1998) and Lougheed et al. (1998).

Step 4: Power Analysis

Power analysis of population trajectories generated by the matrix model allows a testing of how well current monitoring can detect hypothetical changes in population. Boulanger et al. (in press) used the methods of Gerrodette (1987) in which the main input variable for analysis is coefficient of variation, which can be measured from replicated survey data. Coefficients of variation from replicated strip transect surveys conducted by Strong et al. (1995) were used for this analysis. This simplistic power analysis model was useful for approximate power calculations (Link and Hatfield 1990). More sophisticated and robust Monte Carlo simulation-based power analysis models in program MONITOR (Gibbs 1995) are available for free on the World Wide Web (Table 1).

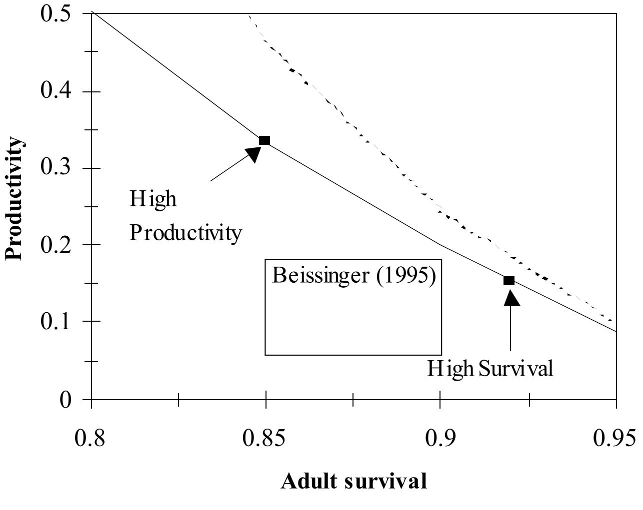

Figure 2. Combinations of adult survival and productivity resulting in a stable population conducted for ages of first breeding of 2 (solid line) and 4 years (dashed line). Labelled points are the parameter values in which the analysis of Boulanger et al. (in press) was conducted. Note that juvenile survival is assumed to be 78% of adult survival in this model and therefore is not shown on axis. The survival and productivity values proposed by Beissinger (1995) for murrelet populations in the Unites States are bounded by the labelled box.

The power analysis of Boulanger et al. (in press) suggests that reductions in population due to adult survival decrease are much more likely to be detected than changes due to juvenile survival or productivity if strip transects methods with precision levels of Strong et al. (1995) are used in surveys (Fig. 4). Murrelet researchers may have to use more direct measures of productivity such as the methods discussed by Kuletz and Kendall (1998). In addition, factors affecting adult survival such as fishing net mortality should be considered when large murrelet declines are detected in short periods of time Boulanger et al. (in press).

ALTERNATIVE MONITORING STRATEGIES

This section discusses alternative monitoring strategies that can increase the statistical power and rigor of monitoring programs.

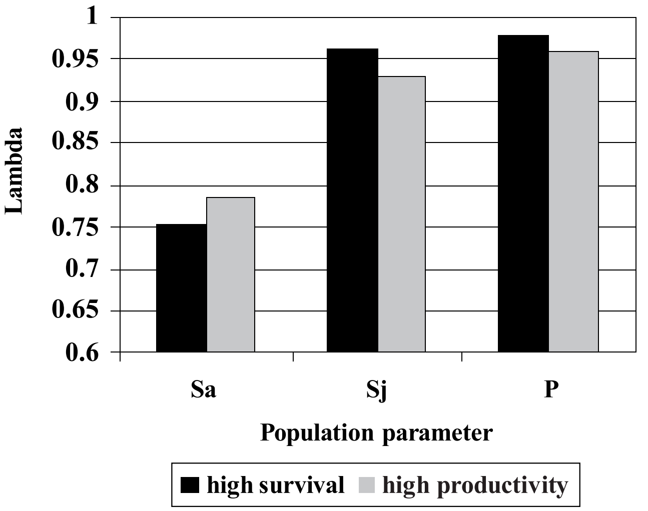

Figure 3. Results of sensitivity analysis (individual parameters reduced by 30%) of high survival and high productivity scenarios. P = productivity, S_a = adult survival, S_j = juvenile survival.

Table 1. Web site addresses for program downloads.

Program	Web address
MARK	<http://www.cnr.colostate.edu/~gwhite/software.html>
DISTANCE	<http://www.ruwpa.st-and.ac.uk/distance/>
MONITOR	<http://www.im.nbs.gov/>
Related programs	<http://www.ecological.bc.ca/links>

DISTANCE METHODS

Often the sampling design for count-based indices is either the point count or strip transect in which all the animals within a specified distance from the survey line or centre are counted. A fundamental assumption of strip transects is that all animals, or a constant proportion of animals, are counted within the survey strip.

When compared with strip transects, the only additional measure needed for the use of distance methods is the distance of individuals (or clusters of individuals) from the survey centre. Data can be measured by distance categories or groupings when it is difficult to get exact distances. Therefore, distance methods can often be used in field situations with little increase in effort (Buckland et al. 1993).

With distance methods, all animals sighted (regardless of distance from the survey centre) are counted and the sightability of animals is estimated, therefore allowing an actual estimate of population density (and associated variance). This method is unlike strip transects which usually underestimate density (due to violation of the assumption of all animals being sighted within the strip) (Burnham and Anderson 1984). In addition, a more robust estimate of survey precision is possible with distance methods. Finally, the seldom tested assumption that index counts and true abundance are linearly related is less likely to be violated with distance methods (Burnham and Anderson 1984, Buckland et al. 1993). All of these attributes may contribute to the increase in power and statistical validity with distance methods.

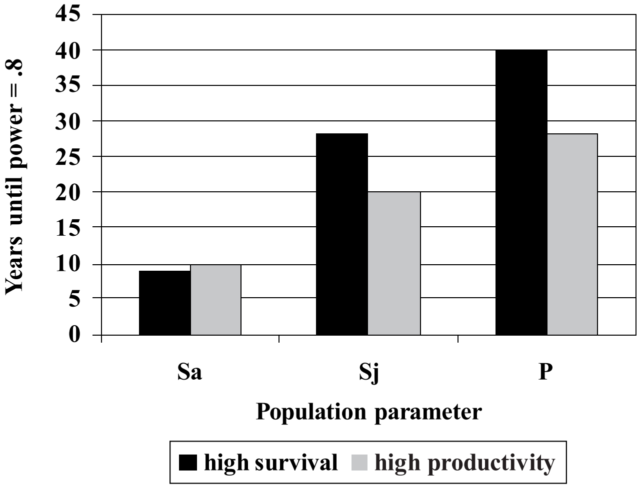

Figure 4. Results of power analysis, based on line transect surveys documented by Strong et al. (1995) for high survival and high productivity scenarios. The *y*-axis represents the number of years it would take to statistically detect a population decrease resulting from a percentage reduction in a given parameter. P = productivity, S_a = adult survival, S_j = juvenile survival.

A common reason for not attempting to use distance methods is sample size constraints. Buckland et al (1993) state that most distance models need at least 60 observations to ensure adequate precision. However, if the sightability of animals is high and factors affecting detection rate are not complex (due to proper sampling design), adequate results can be obtained with less than 60 observations (pers. comm., S. Buckland, Mathematical Institute, Univ. of St Andrews, Scotland). Recently, a comprehensive, Windows®-based distance calculation (DISTANCE) has become available and can be downloaded free from the World Wide Web (Table 1).

The increase in power with distance methods with marbled murrelet monitoring is exemplified by the results of Becker et al. (1997) in which the power of strip transects and distance methods (line transects) was compared for marbled murrelet populations off the coast of California. In short, Becker et al. (1997) showed 2.3 times increase (0.24–0.57) in power between line and strip transects. The line transect method always resulted in higher counts of murrelets which most likely contributed to increase in statistical power.

MARK–RECAPTURE METHODS

Mark–recapture methods are similar to distance methods in that the capture probability of animals is estimated which allows a more statistically rigorous estimate of population trend. Historically, mark–recapture methods such as the Jolly-Seber model displayed marginal precision due to the large potential number of parameters being estimated as part of survival rate estimates. Recently, constrained versions of the Jolly-Seber model, and advanced models that include survey covariates (such as effort, weather factors, and biological attributes), have allowed estimates with increased precision and reduced bias (Labreton 1992, White 1998).

The choice of whether to use mark–recapture models is often determined by the viability of obtaining adequate samples of animals in the field given costs and other logistical constraints. In addition, the use of Jolly-Seber models requires a commitment of at least 3 years to obtain survival rate estimates. However, obtaining a viable population trend arguably requires at least 3 years of data and therefore the constraint of time commitment is universal to all monitoring methods (Gibbs 1995). Simulation modules incorporated in newer mark–recapture programs such as MARK (White 1998) and POPAN (Arnason et al. 1998) allow calculation of sample sizes from preliminary survey data (Table 1).

Capture–recapture techniques with marbled murrelets are exemplified by a study in Desolation Sound that uses newly developed mist net and dip net capture techniques. An adult survival rate was estimated at 0.845 (95% confidence limits 0.47 to 0.94) (Lougheed et al. 1998). This estimate is based on 4 sampling sessions (conducted yearly from 1994 to 1997); therefore, precision is low due to low numbers of recaptured birds. Future estimates from this project should provide critical information regarding life history parameter values of marbled murrelets as the sample size of marked birds and corresponding precision of estimates increase (Lougheed et al. 1998).

USE POWER ANALYSIS FOR COUNT INDICES

If counts methods are used then the survey effort should be fine-tuned using specialized power analysis packages. For example, program MONITOR allows the user to vary the number of surveys per year and other survey parameters to determine the optimal survey effort (Gibbs 1995). Note that the user inputs hypothetical rates of population change, and MONITOR does not require knowledge of life history parameters or the use of matrix models. This program is available for free on the World Wide Web (Table 1).

When possible, monitoring efforts should be targeted towards life history stages as determined by the results of matrix model sensitivity analysis. For example, productivity indices of (Kuletz and Kendall 1998) can provide valuable information regarding annual variation in productivity. Becker et al. (1997) provide a good example of the use of program MONITOR in formulating optimal sampling strategies.

CONCLUSION

This paper introduces a general method to evaluate the uncertainty in life history assumptions and formulate monitoring priorities for species at risk. In addition, this method allows evaluation of how the uncertainty in life history parameters relates to field monitoring through power analysis. If data are unavailable for the use of matrix models, researchers must still use power analysis to evaluate monitoring programs. In addition, consider improved monitoring methods such as distance methods, which involve fewer assumptions and many times exhibit higher statistical power than count-based indices. Monitoring populations is a complex, costly, and challenging task. The use of quantitative tools is inexpensive compared with field efforts; these tools can supply valuable inference towards optimal monitoring design as well as more statistically robust results.

LITERATURE CITED

Arnason, A. N., C. J. Schwarz, and G. Boyer. 1998. POPAN 5: A data maintenance and analysis system for mark-recapture data. Univ. Manitoba, Dep. Comput. Sci., Winnipeg, MB, Canada.

Becker, B. H., S. R. Beissinger, and H. R. Carter. 1997. At sea density monitoring of marbled murrelets in Central California: Methodological considerations. Condor 99:743–745.

Beissinger, S. R. 1995. Population trends of the marbled murrelet projected from demographic analyses. Pp. 385–393 *in* C. J. Ralph, G. L. Hunt, Jr., M. G. Raphael, and J. F. Piatt, eds. Ecology and conservation of the marbled murrelet. U.S. Dep. Agric., For. Serv., Gen. Tech. Rep. PSW-152.

_____, and M. I. Westphal. 1998. On the use of demographic models of population viability in endangered species management. J. Wildl. Manage. 62:821–841.

Boulanger, J., K. Martin, G. Kaiser, and A. E. Derocher. In press. Evaluating uncertainty in estimating population trends for research and conservation of marbled murrelets. Soc. Can. Ornithol., Spec. Publ. No. 2, Biology and conservation of forest birds.

Buckland, S. T., D. R. Anderson, K. P. Burnham, and J. L. Laake. 1993. Distance sampling: Estimating abundance of biological populations. Chapman & Hall, London, U.K.

Burnham, K. P., and D. R. Anderson. 1984. The need for distance data in transect counts. J. Wildl. Manage. 48:1248–1254.

Caswell, H. 1989. Matrix population models. Sinauer, Sunderland, MA.

Crouse, D. T., L. B. Crowder, and H. Caswell. 1987. A stage based population model for loggerhead sea turtles and implications for conservation. Ecology 68:1412–1423.

Gerrodette, T. 1987. A power analysis for detecting trends. Ecology 68:1364–1372.

Gibbs, J. P. 1995. Monitor 4: Software for estimating the power of population monitoring programs to detect trends in plant and animal abundance [computer program]. National Biological Survey, Syracuse, NY. Available on: www.im.nbs.gov/powcase/powcase.html.

Kuletz, K. J., and S. J. Kendall. 1998. A productivity index for marbled murrelets in Alaska based on surveys at sea. J. Wildl. Manage 62:446–460.

Lebreton, J. D., K. P. Burnham, J. Clobert, and D. R. Anderson. 1992. Modelling survival and testing biological hypotheses using marked animals: a unified approach with case studies. Ecol. Monogr. 62:67–118.

Link, W. A., and J. S. Hatfield. 1990. Power calculations and model selection for trend analysis: comment. Ecology 71:1217–1221.

Lougheed, L. W., C. Lougheed, B. A. Vanderkist, S. Webster, R. Bradley, M. Drever, I. A. Manley, G. W. Kaiser, and F. Cooke. 1998. Demography and ecology of marbled murrelets in

Desolation Sound, British Columbia: (1997). Simon Fraser Univ., Burnaby, BC. CWS/NSERC Wildl. Ecol. Chair Tech. Rep. No. 3.

Nelson, S. K., and T. E. Hamer. 1995. Nest success and the effects of predation on marbled murrelets. Pp. 57–68 *in* C. J. Ralph, G. L. Hunt, Jr., M. G. Raphael, and J. F. Piatt, eds. Ecology and conservation of the marbled murrelet. U.S. Dep. Agric., For. Serv., Gen. Tech. Rep. PSW-152.

Strong, C. S., B. S. Keitt, W. R. McIver, C. J. Palmer, and I. Gaffney. 1995. Distribution and population estimates of marbled murrelets at sea in Oregon during the summer of 1992 and 1993. Pp. 339–352 *in* C. J. Ralph, G. L. Hunt, Jr., M. G. Raphael, and J. F. Piatt, eds. Ecology and conservation of the marbled murrelet. U.S. Dep. Agric., For. Serv., Gen. Tech. Rep. PSW-152.

White, G. C. (1998). Program Mark, vol. 1998 [computer program]. Available on:
www.cnr.colostate.edu/~gwhite/mark/mark.htm.