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# Incorporating Environmental Uncertainty into Species Management Decisions: Kirtland's Warbler Habitat Management as a Case Study

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**Abstract:** *We present a framework for expressing species management objectives that incorporates the inherent riskiness of species management strategies. This framework identifies two critical parameters in the management objective: the population level that one would like to achieve and the minimum acceptable probability of attaining that population objective with a given management strategy—the safety margin. We then explore the implications of imposing a management objective in this form on habitat management decisions for the Kirtland's Warbler (*Dendroica kirtlandii*). We used a stochastic simulation model to generate probability distributions for Kirtland's Warbler population outcomes under different management strategies. The management parameter we varied was rotation length of commercial logging, and the cost of each rotation length was calculated as the opportunity cost of not operating at the profit-maximizing rotation length. The cost and warbler population distribution associated with each rotation length were then used to derive cost curves for the two critical decision parameters—population level and safety margin. For most of the range of values analyzed, the relationships between cost and both population objective and safety margin are linear. In addition, the rate at which cost rises with population objective increases as the safety margin required for that objective is raised.*

Incorporación de la Incertidumbre Ambiental en Decisiones de Manejo de Especies: El Manejo de Hábitat de *Dendroica kirtlandii* como Caso de Estudio

**Resumen:** *Presentamos una estructura conceptual para expresar los objetivos de un manejo de especies que incorpore los riesgos inherentes a las estrategias de manejo. Esta estructura identifica dos parámetros cruciales en el objetivo del manejo: el nivel de población que uno podría abarcar y la probabilidad mínima aceptable de alcanzar esa población objetivo con una estrategia de manejo dada (margen de seguridad). Posteriormente exploramos las implicaciones de imponer un objetivo de manejo de esta forma en decisiones de manejo para la curruca de Kirtland (*Dendroica kirtlandii*). Utilizamos un modelo de simulación estocástica para generar las distribuciones de probabilidad para la especie bajo diferentes estrategias de manejo. Variamos el parámetro de manejo "longitud de rotación" en la tala comercial. El costo de cada longitud de rotación fue estimado como el costo de oportunidad por la no operación de la longitud de rotación de máxima ganancia. El costo y la distribución de las curruacas asociadas con cada longitud de rotación fueron usados para derivar curvas de costo para los dos parámetros de decisión críticos—nivel de población y margen de seguridad. Para la mayoría del rango de valores analizados, las relaciones entre costo y población objetivo y margen de seguridad fueron lineales. Aunado a esto, la tasa a la cual el costo se incrementa debido a un in-*

crecimiento en la población objetivo, se incrementa cuando el margen de seguridad requerido para ese objetivo también incrementa.

## Introduction

Researchers advocating policy prescriptions for biodiversity loss and other environmental issues, such as the greenhouse effect and ozone depletion, have been challenged by critics who argue that, because so much is unknown about these processes, it is not possible to justify such prescriptions. The presence of uncertainty is one of the most significant characteristics of environmental management decisions; environmental processes result from a complex interaction of factors that are difficult to identify, much less predict, and often occur over very long periods of time. Management decisions will have economic effects that are equally complex and difficult to predict. Yet within this haze of uncertainty, decisions must be made and action taken. Because it is difficult to make and then systematically defend management decisions that treat this uncertainty in an arbitrary manner, one of the most critical tools in a decision maker's repertoire should be a consistent and explicit treatment of this uncertainty.

Various theories have addressed the challenge of explicitly expressing how uncertainty fits into the decision-making process (Loomes & Sugden 1982; Faucheux & Froger 1995); the expected utility theories of Von Neumann and Morgenstern (1947) are perhaps most familiar. Many of these research paths draw a distinction between "risk" and "uncertainty." A risky decision is one for which decision makers can identify for each management strategy all possible outcomes, along with the probabilities that each outcome will be achieved; this scenario is also referred to as "statistical uncertainty." True uncertainty, on the other hand, refers to those situations in which there is not enough information to identify outcomes and their probabilities; the decision maker is fundamentally unsure of the possible repercussions associated with a decision.

Although many environmental management decisions fall along a continuum between the two extremes, most of these theoretical approaches are concerned with decisions that fit into or can be converted into the risky decision framework. Such theories focus on determining how decisions are made among alternative "lotteries," or distributions of outcomes. The decision maker is assumed to optimize some sort of function, such as "expected utility," and this function can therefore be used to rank the desirability of alternative distributions. Are such approaches applicable in the context of environmental management?

In many cases of environmental management, such as those involving health issues or endangered species, the management objective is to ensure that minimum safety standards are met or that a particular population remains viable; such objectives do not seem easily incorporated into the prevailing optimization framework. Recent efforts to explicitly include an element of risk in applied research suggest that one source of this apparent inconsistency may be the specification of the original management objective, which fails to take into account the probabilistic nature of environmental management outcomes (Beavis & Walker 1983; Lichtenberg & Zilberman 1988; Lichtenberg et al. 1989).

Beavis and Walker (1983) argue that because levels and composition of discharge are stochastic, environmental quality standards and constraints must be expressed in probabilistic terms. There are therefore two essential parameters that must be considered when environmental policy decisions are made under risk: the "standard" that one would like to achieve, and the minimum acceptable probability that such a standard will be attained. They go on to explore how such probabilistic expressions complicate calculation of efficient discharge levels. Subsequently, researchers have expanded upon the stochastic framework in studies of efficient policy approaches to environmental contaminants that pose a health risk but for which the health risk estimates are subject to a great deal of variation (Lichtenberg & Zilberman 1988; Lichtenberg et al. 1989). This approach relies on the ability to express outcomes in probabilistic terms, and its application is therefore limited to risky rather than uncertain decisions.

Risk analysis has long been incorporated into conservation planning, as evidenced by the variety of methods used for estimating a species' risk of extinction (Simberloff 1988; Boyce 1992). Extinction risk has been used as a metric to categorize the endangerment of different species (Mace & Lande 1991), to identify major population risk factors affecting a species (Haig et al. 1993), and to evaluate alternative conservation plans (Haig et al. 1993; Ralls & Starfield 1995). More recently, risk considerations have been integrated into economic analyses of species management as well. Montgomery et al. (1994) performed a marginal cost analysis of preservation of the Northern Spotted Owl (*Strix occidentalis caurina*) based on the tradeoffs between costs of preservation programs and marginal improvements in the species' probability of survival.

The probabilistic objective approach to environmental decision making can be applied naturally to wildlife

management issues. Haight (1995) used a hypothetical forest species and the premise that outcomes of species management efforts will be probabilistic to construct a decision model that explicitly incorporates this risk into an analysis of forest management options. A simulation model was created to translate the information available on the species' natural history into a distribution of population outcomes, thereby converting an uncertain decision into one for which it is possible to assign probabilities to management outcomes. This is the approach we used in this study.

According to this approach, a fully specified wildlife management objective should take the form of

$$\text{Prob}\{N < S\} \leq \alpha,$$

where  $N$  represents the population size at the end of the management period,  $S$  represents the population size standard that the manager would like to achieve, and  $\alpha$  represents the maximum acceptable risk that the standard will not be achieved. The quantity  $(1 - \alpha)$  is the minimum acceptable probability of attaining the standard. Haight (1995) calls this quantity the "margin of safety."

Given an objective of this form, the manager's optimal management strategy is the one that satisfies the optimization problem of minimizing management costs subject to  $\text{Prob}\{N < S\} \leq \alpha$ . We explore some economic implications of this decision framework by evaluating the tradeoffs that exist among alternative management strategies between cost and the two elements of the species management objective,  $S$  and  $\alpha$ . The framework is then used to analyze alternative management strategies for the endangered Kirtland's Warbler (*Dendroica kirtlandii*).

To illustrate the tradeoffs for this particular species management problem, we develop a stochastic simulation model to translate warbler natural history and management parameters into a distribution of possible population sizes at the end of the management period. We vary the management parameter—timber cutting age—to calculate the effect of different management strategies on the probability of achieving a warbler population size objective, and then we estimate the tradeoffs between the probability of attaining the target and the economic costs of doing so. These tradeoffs are expressed as cost curves for both the management standard ( $S$ ) and the safety margin selected.

## The Kirtland's Warbler

The Kirtland's Warbler is one of the rarest birds in North America. The 1951 and 1961 official censuses of the entire warbler's population estimated that there were 432 and 502 singing males, respectively (Mayfield 1953; Walkinshaw 1983; Nelson 1992). The estimated population then plummeted to only 201 singing males for the

next census in 1971 and fluctuated only slightly around this level between 1971 and 1989 (Walkinshaw 1983). In 1990, however, census results indicated a precipitous increase in the number of warblers, and by 1995 the population had reached 765 pairs (Michigan Department of Natural Resources, personal communication).

The known nesting area of the Kirtland's Warbler is restricted to a single watershed in the jack pine (*Pinus banksiana*) plains of Michigan's northern lower peninsula. Currently, most of its breeding area is located on the Huron-Manistee National Forest and in surrounding state forests (Radtke et al. 1989).

The warbler migrates each fall to wintering grounds in the Bahamas and the nearby Caicos Island and Dominican Republic (Nelson 1992) and returns in the spring to its summer breeding range in Michigan. The nesting habits of the Kirtland's Warbler are extremely habitat-specific: the species nests only in young jack pine stands such as those that occur naturally after forest fires. Kirtland's Warblers are a ground-nesting species and nest only on poor-quality Grayling sands, a soil that is loose and well drained and therefore minimizes the risk of nest flooding during rains (Mayfield 1960; Nelson 1992). Generally jack pine stands are occupied only when they are 7–21 years old. After this time the thinning lower branches of the trees do not offer adequate protection for the nests and the stand is no longer recolonized (Probst 1988).

Once a stand is colonized, the population in the colony tends to increase for 3–5 years, remain steady for 5–7 years, and then decline for 3–5 years (Probst 1988). The highest density of birds is supported during the middle occupation stage, suggesting that habitat at this age is optimal for breeding and that the younger and older stages, although suitable, are of marginal quality for breeding (Probst & Hayes 1987; Probst & Weinrich 1989).

The Michigan Department of Conservation initiated efforts to manage habitat for the Kirtland's Warbler in 1956, and the warbler was placed on the federal endangered species list in 1973. As required under the guidelines of the Endangered Species Act, a Kirtland's Warbler recovery team was assembled in 1975 to design a Kirtland's Warbler recovery plan. The recovery plan has as its primary objective to "reestablish a self-sustaining wild Kirtland's Warbler population throughout its known former range at a minimum level of 1000 pairs." One of the means by which this objective is to be achieved is to maintain and develop 135,000 acres of suitable nesting habitat for the Kirtland's Warbler throughout its former known range. The original Kirtland's Warbler Habitat Management Plan was completed in 1981, then revised and updated in 1995.

The plan designated land that was believed to be appropriate for warbler nesting as "essential habitat" and constructed a framework for managing these essential areas. Essential habitat falls on both state (Michigan De-

partment of Natural Resources) and federal (U.S. Forest Service, U.S. Fish and Wildlife Service) lands, and the agencies cooperate in implementation of the plan. Because modern wildfire suppression policies prevent natural regeneration of warbler habitat, the management strategy calls for regeneration of habitat primarily through commercial logging, prescribed burning, and restocking. On average the habitat is managed based on a 50-year rotation, with 1097 ha developed into nesting habitat each year.

Hypotheses about factors that limited the warbler population between 1971 and 1988 include mortality on the wintering ground and during migration and the availability of suitable breeding habitat (Ryel 1981; Sykes 1989). A number of factors suggested that, since the initiation of a cowbird removal program in 1973, a lack of suitable breeding habitat had been the principal limiting factor for the Kirtland's Warbler population (Probst 1988; Nelson 1992). The recent population increase has corroborated the theory of habitat limitation. The amount of available warbler habitat nearly doubled in the late 1980s as a result of management efforts as well as an unplanned 10,000-ha wildfire in 1980 (the Mack Lake Burn), which by 1989 had provided a substantial amount of additional acreage of suitably stocked habitat for the warbler. It is likely that this sudden increase in carrying capacity is what permitted the warbler population to increase so rapidly. Predictably, occupancy of the Mack Lake Burn peaked in 1994 and began to decline, reflecting the decline in habitat desirability as the area matures. Unless other, more recent wildfire and management areas are able to accommodate the increased population as nesting pairs move off the Mack Lake Burn, the population growth may be stalled or even reversed. Habitat availability therefore will continue to play a critical role in controlling the population of Kirtland's Warbler.

## Objectives and Methods

There is an element of uncertainty in management decisions for the Kirtland's Warbler because at the end of any specified planning period the warbler population will be at a level that is only partially determined by the management strategy implemented. The population will also have responded to a number of factors over which managers have no control. Thus, the projected outcome of any management strategy can be expressed as a distribution of possible population levels, and any particular population level is associated with a level of risk about whether it will be reached.

We used a simulation model with stochastic elements integrated into the warbler's nesting success rate and its mortality rate to capture the effects that exogenous variables such as weather and prey availability will have on

the warbler's population. This model enabled us to generate a distribution of possible population sizes that could result from different management strategies, thereby converting the uncertainty in the management decision into statistical uncertainty—or risk—and assigning different possible outcomes, or population levels, a probability of achievement. The management parameter, which represents the different management strategies, was the rotation length of the commercial logging practices that regenerate the warbler's jack pine habitat. Costs were calculated as the sum of the opportunity cost, in terms of foregone timber revenues, of logging at a rotation length that does not maximize profits and the costs of restocking cut land.

The simulation model was applied to the management of Kirtland's Warbler to derive illustrative cost curves for both elements of the decision process—the population size standard ( $S$ ) and the probability of achieving the standard ( $1 - \alpha$ ). Such cost curves make explicit the tradeoffs that exist between relevant decision parameters such as cost and distinct elements of the management objective.

The model comprises three components: forest dynamics, warbler population dynamics (Table 1), and logging yields and returns. Each run of the model tracks the size of the warbler population as it colonizes, nests, migrates, and then returns to repeat the cycle. Each run has a 100-year horizon and produces at the end of that period an estimate of the warbler population as well as cost information on the management strategy used. To generate a distribution of population sizes, we iterated the simulation 1000 times for each combination of management strategy and natural-history parameters; the changing values of the random variables resulted in a distribution of  $N$ . The use of a simulation model is ideal for this sort of procedure because it would be extremely difficult, if not impossible, to specify an equation to compute expected population size analytically.

## Forest Dynamics

The forestry subsystem illustrates the cycling of the forest through distinct age classes. These age classes are based on differences in occupation rates by the warbler. The five age classes in this model represent the period before occupation (class 1, <8 years old), the growth stage (class 2, 8–11 years), the level stage (class 3, 12–17 years), the decline (class 4, 18–21 years), and the post-occupation stage (class 5, >22 years old). The post-occupation stage lasts until the stand is harvested, restocked, and returned to the pre-occupation stage. The length of this stage depends on the specified length of the rotation cycle.

The total area designated for Kirtland's Warbler management is 51,700 ha (Probst 1988). The total area included in this model was 50,000 ha. To represent an

Table 1. Natural history parameters of Kirtland's Warbler.

Source	Adult survival (years)	Juvenile survival (years)	Nesting density <sup>a</sup> (pairs/40 ha)			Nesting success rate (young/pair)	Pairing success <sup>a</sup>		
			young	optimal	old		young	optimal	old
Probst & Hayes 1987	0.75	0.21-0.26 <sup>b</sup>				3.1	0.6	0.95	
Ryel 1981	0.65	0.35				1.5 (with parasitism)			
Walkinshaw & Faust 1974						3.4			
Walkinshaw 1983						3.1			
Mayfield 1989	0.65	0.22 <sup>b</sup>				3.1			
Bergland 1983	0.65-0.70	0.27-0.32 <sup>b</sup>				2.2			
Probst 1988			1.9-2.8 (average)			3.1 <sup>c</sup>			
Probst 1986	0.75	0.23 <sup>b</sup>	1.3-4.8 (3.2 overall)			3.1	0.85 average		
Mayfield 1960		0.36							
Probst & Weinrich 1991			1.9-2.9 (average)						
Kepler 1992 <sup>d</sup>	0.64	0.33							
Value used in this model	0.7	0.35	2.4	3.8	1.6	3.1	0.8	0.95	0.90

<sup>a</sup>Young, optimal, and old refer to the age-based status of jack pine habitat. Probst and Hayes (1987) hypothesize that males in older habitat have lower probability of successfully attracting a mate.

<sup>b</sup>Values inferred from what is necessary to maintain a stable population.

<sup>c</sup>Author hypothesizes that nesting success in marginal habitat is 25-35% that of optimal habitat.

<sup>d</sup>Data included in the Kirtland's Warbler Population and Habitat Viability Assessment, a publication of the Captive Breeding Specialist Group. Species Survival Commission, World Conservation Union, Gland, Switzerland.

equilibrium age distribution, this area was initially divided evenly so there would be an equal amount of forest in each year of growth. For a 50-year harvest cycle, for instance, there were 1000 ha of land in each of 50 years. Harvest rates were designed to maintain this age distribution. For a 50-year harvest cycle, 1000 ha are harvested each year, whereas for a shorter harvest cycle, which would have a larger amount of land in each growth year, a larger area must be harvested annually to maintain the equilibrium distribution.

### Warbler Population Dynamics

The warbler population subsystem calculates each year how many birds settle in each forest age class, how many young are produced in each age class, and how many birds return from the annual migration to settle the following year. This subsystem interacts with the forestry subsystem through the carrying capacity converters, which convert the amount of land in each age class into an appropriate carrying capacity for the warbler. Because only age classes 2 through 4 are suitable nesting habitat, only those classes have a non-zero carrying capacity. These carrying capacities reflect the breeding preferences of the warbler; fewer birds per area are supported in age classes 2 and 4, when the population is increasing or decreasing, and more are supported in age class 3, when the habitat is optimal.

Because there is evidence for differing survival rates between adults and first-year juveniles during the migration, adults and juveniles are tracked separately until they actually return from the migration, at which point

they are grouped together into the adult population and tracked as they recolonize the forest and produce a new flock of young. Juveniles therefore become adults after their first migration and are eligible to breed when they are a year old.

The reoccupation of territories is assumed to proceed systematically, with warblers first filling up the optimal habitat (age class 3), then the marginal-young stands (age class 2), and finally the marginal-old stands (age class 4). Because males establish territories and attract mates, this model tracks only the behavior and population of male warblers. Although no reliable data exist for the Kirtland's Warbler adult sex ratio, many estimates assume it to be 1:1 and calculate the total adult population by doubling the number of males (Radtke et al. 1989). We also followed this guideline.

The literature on warblers suggests that there are differences in nesting success among the age classes. The model reflects this by providing lower estimates of fledglings produced per pair per nest for the marginal age classes 2 and 4 than for the optimal age class 3. Probst and Hayes (1987) suggest that, in marginal habitat, reproductive success may be as low as 25-35% that of optimal habitats. These figures were purely speculative, so we calculated marginal habitat nesting success using a more optimistic estimate of 50% of the nesting success of optimal habitat.

There are two sources of random variation in the model. The first is a normally distributed random variable that affects fledgling production. In optimal habitat, nesting pairs have a 14% coefficient of variation (CV) in mean nesting success. This coefficient was calculated from the actual variation in estimates of number of nest-

lings fledged between 1972 and 1977 (Walkinshaw 1983). The same random draw is converted to its equivalent value from a normal distribution with mean 1 and standard deviation 0.20. This value is then multiplied by the mean nesting success for pairs in marginal habitat—age classes 2 and 4. (*Equivalent* in this sense is used to mean the number that, when selected from a normal (1,0.2) distribution, has the same cumulative probability as the random draw from the distribution with a 14% coefficient of variation.) The assumption was therefore made that nesting success in marginal habitat is not only lower but also more variable than nesting success in optimal habitat. The coefficient of variation for marginal habitat is 20%. A CV estimate of 20% is often used in models of other bird species; it is consistent with the results of a number of studies on year-to-year variation in the reproduction rate of small passerines (Temple & Cary 1988; Thompson 1993).

The second source of random variation in the model affects migration survival. This variation affects adults and juveniles differently. Each year the adults' stochastic variable is selected from a normal distribution with mean 1 and standard deviation 0.1 and multiplied by the estimate of adult migration survival. The resulting coefficient of variation in survival of adults (10%) is consistent with assumptions made by Thompson (1993) about the variation in annual survival but is lower than the 20% assumed by Temple and Cary (1988). The coefficient of variation of juvenile survival is equal to that of the adult distribution when the stochastic value drawn is greater than 1; when conditions are favorable and result in improved survival, both adults and juveniles are affected equally. When the random number generated is less than 1, however, meaning that conditions result in lower-than-average survival, then the random number selected from a normal (1,0.1) distribution is converted to the equivalent value selected from a normal (1,0.2) distribution and then multiplied by the juvenile survival rate. This conversion has the effect of magnifying the variation in survival rate among juveniles: under these conditions, juveniles are more strongly affected by conditions that decrease survival rate. This construction was suggested by the fact that juvenile members of migrating bird species have often been found to have higher variability in survival than adult members of the same species (Ryel 1981).

### Logging Returns and Yields

The logging subsystem calculates the expected annual value of the wood harvested in the model under different rotation lengths and discounts it back to the present to estimate a present value. Costs of management for the warbler that do not vary with rotation lengths, such as posting of nesting areas, insect and disease control in

the jack pine ecosystem, and predator and parasite control, were not included in the model. The direct costs of harvest were also not explicitly included because the prices of the wood products used were stumpage prices and therefore already incorporated harvest costs. The only actual expenditure included was the cost of management that is expected to vary with rotation lengths, which is the cost of restocking. Although the per-acre cost remains constant, the amount of area restocked each year varies with rotation length, so the total cost incurred each year also varies with rotation length.

The amount and type of wood yielded by a stand depends on both the stand's age and its quality. This model assumes that the distribution of site quality on the 50,000 ha is perfectly representative of the overall distribution of site quality on state and national lands combined in Michigan. Poor-quality land in this study is defined as that with a site index of 40–52, medium quality as that with a site index of 53–65, and high-quality as that with a site index greater than 66. (*Site index* in a jack pine stand refers to the average height attained by 50-year-old jack pine [Gevorkiantz 1947]). Based on these definitions and on U.S. Forest Service estimates of land ownership in Michigan, 74.3% of state and national lands are poor quality, 19.3% are medium quality, and 6.4% are high quality. These proportions are assumed to hold for the model's 50,000 ha as well. The stand's age at harvest depends on the rotation length specified.

The annual value of wood was calculated by first dividing the total area harvested into high-quality, medium-quality, and low-quality stands. For this task we assumed that the harvest is always taken proportionately from the quality available, so that the composition of each harvest reflects perfectly the overall composition of the area (74.3% poor quality, 19.3% medium quality, and 6.4% high quality). The amount of wood yielded from each quality type was calculated based on per-acre estimates of sawtimber yield and pulpwood yield from stands of different ages (Gevorkiantz 1947). The estimates of total pulpwood and sawtimber yield were then multiplied by estimated sawtimber and pulpwood prices to create an overall revenue estimate for that year.

The real prices of sawtimber and pulpwood are assumed to increase at a constant rate of 1.5% for sawtimber and 1% for pulp. According to data provided by the U.S. Forest Service on the rates of nominal price increases for jack pine pulpwood and sawtimber stumpage between 1950 and 1994, pulpwood prices have been increasing at an average of 4.1–6.4%, depending on region, and sawtimber prices have been increasing at an average of 5.4–6.7%. We subtracted an estimated 4% inflation rate to arrive at rates of real price increase. Some U.S. Forest Service estimates have used an estimated real price increase rate of 2% in calculating returns from future yields of jack pine sawtimber, but for this study we used a more conservative intermediate value of 1.5%.

Pulpwood and sawtimber prices have varied enormously from year to year. In 1995 sawtimber prices in some areas almost doubled, while pulpwood prices increased by two-thirds. Because this upsurge may simply represent a temporary peak in prices, we did not use the 1995 prices as the base prices for the initial time period in the model but instead chose the more moderate values of U.S. \$70 per merchantable board foot (sawtimber) and \$17 per cord (pulpwood). These prices were selected arbitrarily, however, and the revenue results produced are not meant to be interpreted as predictions of actual revenue values but rather are meant only to illustrate the types of tradeoffs that could exist at different levels of timber production.

### Model Sensitivity

When there is some question about the true values of the parameters that drive a model, the results of a simulation model reflect two sources of uncertainty: true variation introduced in the model through random elements, and imprecision uncertainty introduced by the modeler's ignorance of the actual parameter values. The former source of uncertainty is built into the model and, as in this study, is often the element of interest in the model. Imprecision uncertainty, however, is an undesirable complication that researchers do their best to eliminate, or at least to quantify.

We used values of warbler population parameters found in the literature. Because for most parameters a range of possible values were found, we also performed a sensitivity analysis to determine which sources of uncertainty were most influential in affecting the model results. We found that the model results were most sensitive to nesting density estimates, followed by migration rate estimates (adult and juvenile), with growth rate estimates a distant fourth. Variation in these parameters, however, did not affect the qualitative nature of the results revealed in the behavior of the relationships illustrated below.

### Results

Deriving cost curves for the two decision parameters—the standard and the safety margin—requires mapping the relationships among population distribution, rotation length, and cost. As explained earlier, cost of rotation length is defined as the opportunity cost of logging at the rotation length chosen for management purposes rather than at the profit-maximizing rotation length. Because the area must be managed for warblers and because warblers must have young trees, the option of not logging at all is not permissible, although this option

may seem attractive if the total costs of logging are not covered by the revenues generated. If this is the case, as it has been in the past, then the base standard of “profit-maximizing” rotation lengths can be expressed instead in terms of “cost-minimizing” rotation lengths. The underlying premise of tradeoffs between rotation lengths and costs remains the same.

Under the economic assumptions stated in the description of the economic subsystem, the model yields an inverted parabolic relationship between rotation length and revenue (Fig. 1), with the profit-maximizing rotation length falling at 60 years. Translating cost figures into opportunity cost (by expressing revenues relative to the revenues achievable at the profit-maximizing rotation length) reveals opportunity cost as a monotonically decreasing function of increasing rotation length for the relevant rotation length range of 20–60 years (Fig. 2). The least-cost management strategy will therefore be the longest possible rotation length that achieves the population objective with a given level of certainty. As a result, the manager's objective of minimizing cost subject to a certain probability of achieving a given population size is equivalent to maximizing rotation length subject to the same constraint.

Calculating the tradeoffs between rotation length and the population size at various percentiles of the population's distribution reveals that population sizes at all percentiles are monotonically decreasing functions of rotation length (Fig. 3). The fact that the nesting population increases as rotation length decreases follows intuitively from the nesting habitat preferences of the warbler and from the assumption that the population is habitat-limited. If the entire area is maintained at an even-age distribution, then the shorter the rotation length the more area must be in ages 8 to 21—the stand ages used by the warbler. If more area is at an appropriate age for nesting at any given time, then the nesting capacity of the entire 50,000 ha increases.

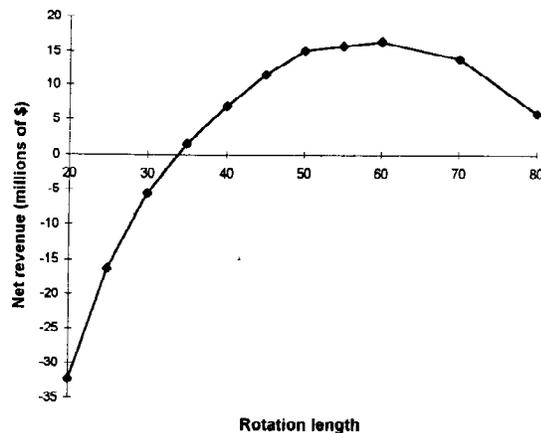


Figure 1. Tradeoff between commercial logging rotation length and logging revenues.

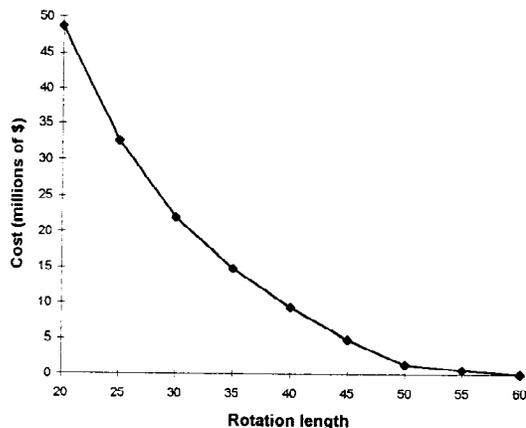


Figure 2. Cost of rotation length as measured by opportunity cost of not logging at the profit-maximizing rotation length of 60 years.

The vertical lines in Fig. 3 indicate graphically the solution to the manager's objective of maximizing rotation length subject to the constraint of achieving 1000 pairs with various safety margins. To produce enough habitat to support a maximum number of 1000 nesting pairs, the rotation length must be at least 44 years. To be 90% certain of achieving 1000 nesting pairs ( $\alpha = 0.10$ ), the rotation length must be shortened by only 1 year, to 43 years. This result is a consequence of the assumptions used to create the model and the population distribution truncation caused by the carrying capacity. Due to the assumption of strong habitat dependence, the population reaches the carrying capacity in approximately 86% of the simulation runs. To achieve 95% certainty ( $\alpha = 0.05$ ) and 99% certainty ( $\alpha = 0.01$ ) requires 39- and 35-year rotation lengths, respectively.

Because the various levels of certainty require different rotation lengths, there will be costs associated with

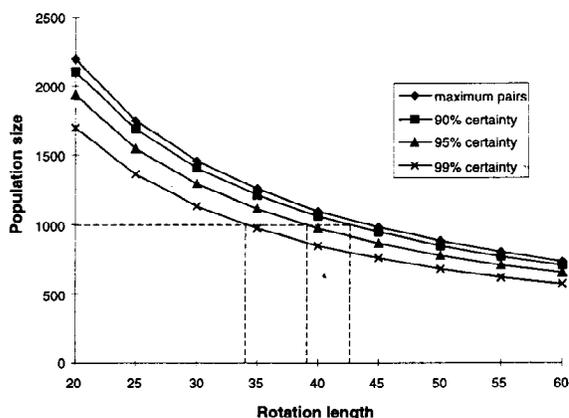


Figure 3. The expected number of resident Kirtland's Warbler pairs at different levels of certainty and at commercial logging rotation lengths of 20-60 years.

changing the level of certainty specified in the management objective ( $\alpha$ ; Fig. 4). As the safety margin ( $1 - \alpha$ ) is increased, the cost of the management strategy necessary (which in this case is decreasing rotation length) rises at an increasing rate. Given that the management objective is 1000 pairs of resident birds, any investment in certainty of less than \$5.8 million does not improve the probability of achieving the objective. This represents the case in which rotation length is set to somewhere between 60 (the profit-maximizing rotation length) and 44 (the maximum rotation length that supports 1000 pairs of nesting birds).

The management objective standard of 1000 pairs has been selected because this population size satisfies a particular definition of a viable population. If improved information or some environmental change resulted in a determination that a smaller population size may be viable according to that definition, what economic returns could be realized by lowering the objective standard?

For uncertainty levels between 90% and 99%, the management objective of 1000 birds requires a rotation length of 43-35 years, but at those same uncertainty levels smaller numbers of birds can be attained with longer rotation lengths and less cost. This relationship can be used to calculate the tradeoffs between costs and management objectives for given levels of uncertainty. For most of its range, this relationship is linear for both uncertainty levels; above a specific number of nesting pairs, the costs associated with the management objectives at both levels of certainty increase at approximately a constant rate, though the costs at  $\alpha = 0.01$  increase slightly faster than those at  $\alpha = 0.05$  (Fig. 5).

All of these results have been derived from running the model under specific assumptions about the life-history parameters of the bird and the suitability of the breeding habitat. Different results would be obtained if these assumptions were altered. If the density of breed-

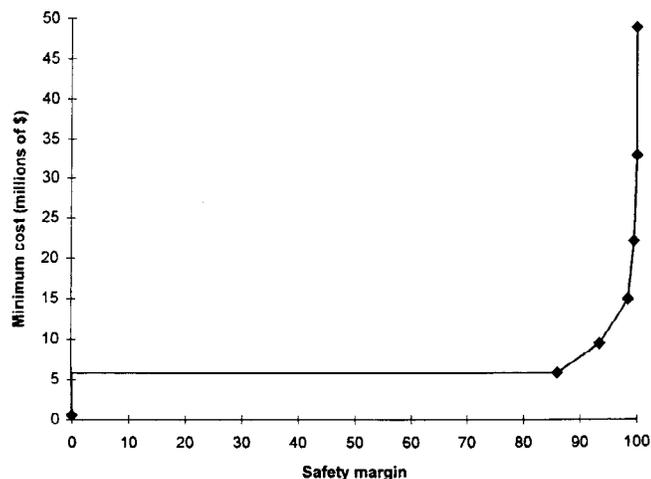


Figure 4. The cost of certainty in achieving an objective of 1000 nesting warbler pairs.

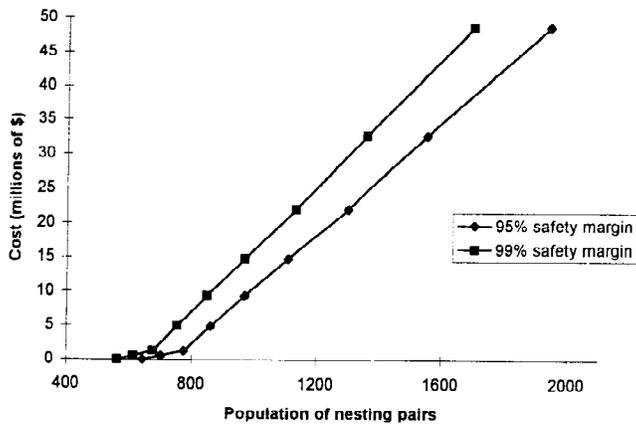


Figure 5. The cost of establishing different management objectives with a 95% and a 99% safety margin.

ing pairs could be returned to historical high levels, for instance, the resulting tradeoff between rotation length and expected number of resident pairs would shift, and larger populations could be supported at longer, more profitable rotation lengths. Analyses such as these can be used to gain insight into which additional management tools may be effective (and cost-effective) in managing the warbler population.

### Model Limitations

This model is based on several simplifying assumptions that may limit the accuracy of its predictions about cost-population tradeoffs. With respect to carrying capacity and population dynamics, the fact that the model is not spatially explicit imposes the assumption that spatial dynamics are not significant in determining nesting capacity and population growth. In truth, there is evidence that the configuration of available habitat, rather than its sheer magnitude, affects parameters such as nesting density. Nevertheless, the model was calibrated against existing data on historical warbler population and performs well in replicating those population levels.

This model is also based on several arbitrary assumptions regarding revenue generation that will affect the accuracy of the predicted revenues. Because the purpose of this study was to illustrate the process of explicitly analyzing the tradeoffs between management costs and the management decision parameters of objective and safety margin, we did not focus on the accuracy of revenue results; the results received and portrayed in the cost curves are merely illustrative.

This model is also not constructed to generate the types of catastrophic shocks to the warbler population that might be expected as a result of fire or hurricanes on the wintering grounds. Because there are two sources of random variation in the model, however, we

are more likely to see larger shocks to the population that result when two unfavorable shocks coincide—a bad summer followed by a bad winter, for instance. The assumption of strong habitat constraints can help justify the omission as well: unless the catastrophic shock permanently eliminates habitat or drives the species all the way to extinction, there is a good chance that the species can recover over a period of 100 years.

This model also does not address issues of density dependence, although in reality many of the parameters that drive the model may exhibit some density dependence. Because we did not address the issue of extinction risk and instead dealt with population numbers when the possibility of extinction was quite small (by definition of  $S$ ), we also did not feel it was necessary to incorporate details about small population dynamics such as inbreeding depression or risk of total population loss to catastrophic disturbance. In a model in which the focus is on extinction risk, such considerations would be critical.

### Conclusions and Further Research

There are two components to any regulatory standard or objective that involves a probabilistic management outcome: the first is a specification of the desired outcome and the second is establishment of an acceptable amount of risk in the achievement of that outcome. Specifications of both  $\alpha$  and  $S$  will affect the type of management strategy required and the cost involved.

Regulatory efforts to address phenomena that are irreversible must be particularly sensitive to the issue of uncertainty and to selection of a safety margin. With most outcome probability distributions, bypassing the uncertainty issue altogether by demanding that the standard be achieved 100% of the time (which is equivalent to setting  $\alpha$  to 0) would be infeasible, if not impossible; even safety margins near 100% may require extreme and expensive management strategies. On the other hand, specifying smaller safety margins in the presence of irreversibility means running a greater risk of failing to meet the standard and losing everything already invested in management. When the goal of management is to avoid species extinction, for instance, investing a sum of money in a management strategy that offers only a 50% safety margin means there is a 50% chance that the investor will lose both the sum invested and the species. Any rational investor should be willing to consider the possibility of investing in a more expensive management strategy with a higher probability of success. This tradeoff between cost and uncertainty is a critical element of environmental decision making, yet one that is not often explicitly described or measured.

This study illustrates a probabilistic approach to making habitat management decisions for the Kirtland's

Warbler and explores the tradeoffs that exist between cost and both elements of the management standard. Our results corroborate what one would expect: management costs increase as the objective standard is raised and the acceptable amount of uncertainty in the achievement of the standard is lowered. Selection of a standard is based on a determination of which population size can be considered "viable"; the viability element of the management standard is an objective measure that is based on ecological rather than economic criteria. (Such a characterization of the selection process for the management standard is unique to the construction of this particular management question;  $S$  represents a viable population size, which by definition is an ecological concept.)

Selection of an appropriate safety margin is a subjective bureaucratic decision, however, and it would be interesting to explore in more detail how such selections are made. Lichtenberg and Zilberman (1988) argue that selection of a margin of safety should be noncontroversial; because a safety margin is analogous to a confidence interval, decision makers can simply choose from the levels that are traditionally used in scientific research (i.e., 95% or 99%). Unlike statistical confidence levels, however, which are associated with theoretical risks of making different types of errors in hypothesis testing, different levels of safety margins are associated with very tangible costs. Haight (1995) found that, at certain extinction risk standards, going from a 95% to a 99% safety margin could double or even triple the costs of management, depending on the structure of the management problem.

Such considerations raise the issues of societal risk aversion and how that aversion may be affected by the nature or magnitude of possible losses. When the result of failing to meet the objective involves an irreversible process such as extinction, there may be an inclination to lean toward higher safety margins. Even in the absence of exact information on risk attitudes, however, an approach such as the one used in this study may facilitate selection of a safety margin by explicitly illustrating tradeoffs between uncertainty and cost. The graphs produced may suggest points at which the costs accelerate rapidly while increases in certainty stall, for instance. The results of the application to the Kirtland's Warbler suggest that, for the given management objective of 1000 pairs and over a limited range of safety margins, as the level of certainty is raised the costs increase at a constant rate; there are no obvious discontinuities or anomalies (Fig. 6). In his application to a hypothetical forest species, however, Haight (1995) was able to create scenarios resulting in discontinuous or disjointed cost increases. Such anomalies can suggest a safety margin that would satisfy multiple levels of risk aversion.

The additional information attained by explicitly calculating tradeoffs between costs and the safety margin

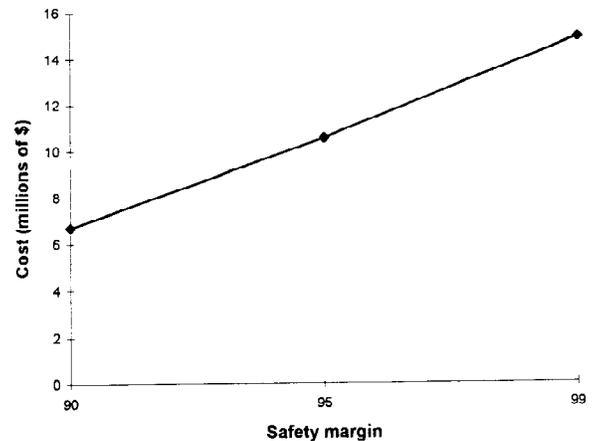


Figure 6. The cost of achieving 1000 nesting warbler pairs at different safety margins.

may help in the estimation of an appropriate safety margin, and it will certainly make the strategy selection process less haphazard and more easily defensible. In the case of the Kirtland's Warbler, for example, although several rotation lengths allow for the possibility of arriving at a population of 1000 nesting pairs, only a 39-year rotation would satisfy a manager's objective of minimizing costs while ensuring a 95% probability of reaching 1000 pairs. A fully specified management objective, or any environmental regulation governing processes with probabilistic outcomes, must therefore include both elements.

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