# Population Viability Analysis

To evaluate the viability of the Florida panther population and to complement the habitat suitability analysis, we reviewed previous population viability analyses (PVA) published in the scientific literature, and we developed a new spatially explicit metapopulation model for the Florida panther in South Florida. Given the vulnerability of this species and the need to make predictions about the population dynamics of the single remaining population in South Florida, a number of approaches have been used to assess the viability of the panther.

## PVA and its Assumptions

How much habitat is enough? Population Viability Analysis (PVA) is a process that attempts to provide an answer to this and other questions (Gilpin and Soule 1986, Soule 1987). One element of PVA, minimum viable population (MVP) analysis, attempts to estimate the minimum number of individuals for a particular species that is needed for a viable population (Shaffer 1981, Boyce 1992). As originally defined by Shaffer (1981, p.132), "a minimum viable population for any given species in any given habitat is the smallest isolated population having a 99 percent chance of remaining extant for 1,000 years despite the foreseeable effects of demographic, environmental and genetic stochasticity and natural catastrophes." Shaffer suggested that these guidelines were flexible and both the survival probability and time frame could be adjusted. The critical aspect is that the MVP provides an estimate of the number of individuals needed to preserve a species (Menges 1991). In practice a goal of 95 percent probability of persistence for 100 years is often used in management strategies and conservation planning, particularly for situations where it is difficult to accurately predict long-term effects.

From a genetic standpoint, Franklin (1980) recommended minimum viable population sizes of around 50 organisms to prevent serious inbreeding or other deleterious genetic effects. His estimate assumes an "effective population size" of 50; the effective population size is the number of breeders and may differ significantly from the total population size. To maintain long-term fitness of a species as well as the potential to evolve, however, Soule (1980) recommended populations substantially larger than 50 individuals. More recent

research by Lande (1995), using *Drosophila melanogaster* as a model, suggests that an effective population size of about 5,000 is necessary to maintain normal levels of genetic adaptation and avoid negative genetic effects. Even larger populations, 10,000 to 100,000, may be required for maintenance of some particular traits, *e.g*. single-locus disease resistance factors (Lande and Barrowclough 1987, Lande 1988). There are no clear guidelines that seem appropriate for all species under all circumstances; instead, choosing a set of criteria becomes part of the PVA itself.

The use of models greatly facilitates the study of how such factors as habitat loss, or environmental and demographic stochasticity affect population viability, allowing estimation of the risk of extinction or the 'quasiextinction' risk, *i.e*., the chance of crossing a specified low population threshold (Gilpin and Soule 1986; Burgman *et al.* 1993). Many types of models have been utilized:

- Simple birth-and-death models examine the effects of demographic and/or environmental stochasticity on the birth and death rates of a population (Boyce 1992, Burgman *et al*. 1993).
- Using extrapolations based on current demographic rates, demographic projections model future trends in population growth, usually as some form of exponential growth (Lande and Orzack 1988, Boyce 1992, Burgman *et al.* 1993).
- Structured models (stage- or age-based) incorporate different demographic characteristics for each age or developmental stage class while assessing risk of extinction (Burgman *et al.* 1993).
- The effects of habitat patch quality, size, and distribution on the risk of extinction are examined using spatial or patch models (Caswell 1989, Boyce 1992, Burgman *et al.* 1993).
- Metapopulation models, which may be spatially explicit, treat the population as a collection of interacting subpopulations each occupying separate patches of suitable habitat (Levins 1969, Burgman *et al.* 1993).

Because of the complexity of the models that incorporate all of the important factors potentially influencing extinction risks, many PVAs are utilizing computer simulation

modeling (Boyce 1992). The methods to be used depend on the specific case at hand. Simulation models are often constructed to assess the long-term viability of a population or metapopulation. These models, in general, utilize the available demographic data and project these values into the future based on a few assumptions or rules.

Models are a simplified representation of the real world; as such, they inevitably require assumptions. Some of the common assumptions are: mates are freely available and not limiting; habitat is static, contiguous, homogeneous, and of good quality; catastrophic or epidemic events do not occur; and demographic rates in the past reflect those that will occur in the future. There may also be a number of very specific assumptions. For example, all population models assume that individuals of the same age or stage (*i.e.*, adults) have the same annual survival rate. Density dependence is commonly simplified. Most often limits are placed on a population with a density ceiling or specified carrying capacity. This type of density dependence assumes that the population grows at the same rate regardless of how close it is to saturation, which may or may not be a realistic assumption. Many of these assumptions, though, are vital to produce models that do not require excessive amounts of data and to overcome the limitations of available data.

One of the more difficult decisions in building simulation models is deciding the level of complexity of the model that is appropriate for a given problem. The characteristics of the species under study (*e.g.*, its ecology), what we know of the species (the availability of data), and what we want to know or predict (the questions addressed) will influence the model's complexity. Building a model is a method of combining the existing information into predictions about the persistence of species under different assumptions of environmental conditions and under different management options. The structure of the model and the questions addressed usually determine how the results will be presented. The model will often include random variation (stochasticity), which means that the results must be presented as probabilities of risk.

Risk curves provide a convenient way of presenting results of a simulation. Figure 54 shows an example of a risk curve. The risk of decline in a population is typically displayed as a function of the amount of decline. The right end of the figure (100 percent decline) represents extinction. In this example, there is about a 10 percent probability of extinction. In this example, there is a 28 percent probability that the population will decline by 60 percent or

more in the next 50 years, and the risk that it will decline by 40 percent or more is about 65 percent. Such curves can be compared for a variety of scenarios to examine the influences on the long-term viability of the species of concern.

**Previous Florida Panther PVA Research**

In the first PVA conducted for the Florida panther, Ballou *et al.* (1989) estimated that an initial population of 45 Florida panthers was at high risk of extinction within 25-40 years. The analysis further indicated that unless the population size was increased, genetic heterozygosity would continue to be lost at a rate of about 6 percent per generation.

In 1989 Seal and Lacy developed a simple model in the program Vortex (Lacy *et al.* 1995). Vortex's key strength is its ability to predict the future heterozygosity of a population based on the demographic parameters; details of the input parameters are found in Table 22. This model was based on a small number of individuals and was quite pessimistic. The Seal *et al.* (1989) model predicted that there was a 100 percent chance of the existing panther population (estimated at 30-50 adults) becoming extinct in the next 100 years (Figure 55). It also predicted that the population would have greatly reduced genetic viability. Based on these findings, the recommended course of action was a vigorous program of captive breeding.

The Vortex model was later improved based on a larger sample of panthers (Seal *et al.* 1992); details of the input parameters are found in Table 22. The newer model projected population fates over 25, 50, 100, and 200 years; evaluated three levels of inbreeding depression (*i.e.*, 0, 1, and 3 recessive lethals per individual); utilized initial population sizes of 30 and 50; assumed that carrying capacity remained constant, decreased at 1 percent per year for 25 years, or decreased at 2 percent per year for 25 years; and assessed results when first breeding was set to occur at 2 or 3 years of age. The results of this model also suggested that the panther had reduced genetic viability and a significant chance of extinction in 100 years (Figure 55).

The most optimistic scenario assumed an initial population of 50 adults, no change in carrying capacity, first reproduction at 2 years of age, and 20 percent juvenile mortality. Under this set of conditions Seal *et al.* (1992) estimated that the probability of extinction

within 100 years was zero. However, even under this optimistic scenario, populations were nearly always driven to extinction due to the interacting effects of demographic variability and inbreeding when inbreeding effects on juvenile mortality were similar to those seen in other mammals (Ralls *et al.* 1988). Most of the modeled scenarios that assumed changes in carrying capacity (*i.e.*, habitat loss) and 50 percent mortality of juveniles predicted high probability of extinction within 100 years (Seal *et al.* 1992). The recommendation was to introduce genetic material from another population.

Cox *et al.* (1994) and Kautz and Cox (2001) performed PVAs for 11 species of wildlife including the Florida panther. A computer program based on the work of Shaffer (1987) was modified to include catastrophic events. The model followed females only and simulated year-to-year changes in fecundity and survival over 200 years. Due to variability in input parameters, a range of fecundity and survival values was modeled to represent "favorable" (*i.e.*, high fecundity and survival), "moderate," and "harsh" (*i.e.*, low fecundity and survival) environmental conditions. The smallest populations of Florida panthers estimated to have a 90 percent chance of persistence over 200 years were 63 panthers under favorable conditions, 76 panthers under moderate conditions, and 84 panthers under harsh conditions.

Kautz and Cox (2001) also incorporated a genetics component into their population viability analyses by using the technique described in Reed *et al.* (1988). The goal was to estimate the size of a census population needed for an effective population size of 50 (*i.e.*, 50 breeding panthers), a minimum suggested size to prevent extinction due to inbreeding depression over the short term. Although they acknowledged that effective populations on the order of 100 to 1,000 times greater than this may be needed to ensure genetic variability over the long term, Kautz and Cox (2001) elected to estimate the smallest population sizes likely to persist in the short term for their conservation planning purposes. They assumed that, if plans can be derived that allow populations to dip no lower than an effective population size of 50, there will be opportunities to achieve larger populations and avoid genetics problems through patch recolonization, translocation of individuals, or removal of environmental constraints on a population through management. Kautz and Cox (2001) estimated that a census population of Florida panthers in the range of 100-200 individuals is needed to achieve an effective population size of 50.

Maehr *et al*. (2002bb) expanded on earlier Vortex models incorporating panther monitoring data (prior to the introduction of female Texas cougars in 1995), a consensus approach for parameter estimation, estimations of habitat loss, and periodic genetic supplementation. The model assumed an inbreeding depression of 3.14 lethal equivalents, reproduction that was not density dependent, juvenile mortality of 20 percent, an initial population size of 60 panthers, a habitat carrying capacity of 70 panthers, no habitat loss, and included augmentation of the population with two females every 10 years. The results of some of these modifications are shown in Figure 56. Under the "consensus model" there was a 99 percent or greater probability of the panther population persisting for the next 100 years, although the final median population size varied depending on the conditions. For example, a 25 percent loss in habitat (over 25 years) did not increase the probability of extinction but the final population size was 46.72 panthers compared to 65.58 panthers without habitat loss. Maehr *et al.'*s (2002b) recommendations were to protect habitat and maintain connections among habitat patches. They also concluded that genetic management might be necessary if the population does not expand.

Maehr *et al.* (2002b) also varied a few of the consensus model input variables to simulate four possible management scenarios. The first variation simulated the population without the addition of two females every 10 years. The model yielded a median final population of 64.16 panthers with 0 percent chance of extinction within 100 years, but it also predicted a 9.1 percent decrease in expected genetic heterozygosity and a 38 percent decrease in number of extant alleles. The second variation simulated the population with the addition of two females every 10 years and a 25 percent reduction in habitat over 100 years. The model produced a median final population of 46.72 panthers with a 100 percent chance of persistence for 100 years, but it predicted a 5.3 percent decrease in expected heterozygosity and a 14 percent decline in number of extant alleles. The third variation simulated the population with no addition of females and with a 25 percent reduction in habitat. The model resulted in a median final population of 45.21 panthers with 99.8 percent chances of persisting for 100 years, but it predicted an 11 percent decrease in expected heterozygosity and a 42 percent decrease in number of extant alleles. The fourth variation simulated no addition of females, a 25 percent loss of habitat, and a removal of two females a year for 3 years to model the impact of removal of animals for a captive breeding program. The model predicted a

median final population of 44.70 panthers with a 99.2 percent chance of persistence for 100 years, but it resulted in a 21 percent decrease in expected heterozygosity and a 52 percent decline in number of extant alleles.

Figure 56 illustrates the population trajectories and risk curves of some of these variants. The "Baseline" represents a model with no habitat loss, no augmentation, and constant carrying capacity. The results of a 25 percent reduction in habitat is shown as "Habitat Loss." "Supplementation" represents the model with an addition of two females from an external population every 10 years over the 100 year simulation. The "Catastrophe" model included a 5 percent chance annually that vital rates (*i.e.*, fecundity and survival) would be reduced 5 percent.

Maehr *et al.* (2002b) concluded that: (1) the Florida panther population has a high probability of persisting for 100 years; (2) the Florida panther population has an apparent ability for rapid population growth; (3) genetic problems may become severe beyond 100 years; and (4) a population greater than 300 would be needed to retain 90 percent of the population's initial heterozygosity. Maehr *et al.* (2002b) also recommended aggressive landscape management to allow panthers to colonize areas of potential habitat north of the Big Cypress source population, effectively establishing a metapopulation possessing higher chances of persistence and reduced problems with genetics.

Ellis *et al.* (1999) reviewed the results of Ballou *et al.* (1989), Seal *et al.* (1992), and Maehr *et al.* (2002b) and performed additional VORTEX-based PVAs to refine the results of previous modeling efforts. They simulated population sizes and estimated probability of extinction under varying scenarios of juvenile mortality rate, future releases of non-Florida animals, increased carrying capacity, expansion of panthers into newly connected habitat, and habitat loss. Ellis *et al.* (1999) found that the panther population was self-sustaining only if the juvenile mortality rate remained below about 40 percent, a value very close to the current estimate of juvenile mortality rate provided by D. Land (FWS, personal communication, 1999).

While Ellis *et al.* (1999) ran many scenarios, the most important scenario with respect to habitat issues involved expansion of carrying capacity and reduction in available habitat. When juvenile mortality was held at 40 percent and carrying capacity was increased to more than 100 (as would occur if more habitat became available), the simulations predicted final

populations greater than 68 individuals and probabilities of extinction near zero. When juvenile mortality was held at 40 percent, carrying capacity was held at 70, and no habitat loss occured, the population declined from 60 to 37 over the 100 years, probability of extinction was 0.09, and genetic diversity declined. However, under the same scenario but including a 25 percent loss in habitat, the model predicted a final population of 11, a probability of extinction of 0.53, and low genetic diversity. These models indicate that the current population would survive but decline over the next 100 years without any loss of additional habitat. Loss of as much as 25 percent of available habitat would severely affect the ability of the population to persist. Interestingly, 27 percent of the Primary Zone (described in Chapter 3) is in private ownership, and that is the portion most likely to be lost to urbanization. Thus, the model that estimates a 25 percent loss of habitat may provide the best indication of the likely outcome of further development of privately owned habitat within the Primary Zone.

The strength of these Vortex models is that they tracked genetic alleles, providing estimates of heterozygosity. They were, however, not spatially explicit or habitat-based and they incorporated only a simple ceiling type of density dependence. As a complementary approach, the viability issue was revisited using a spatially explicit, stage-based model built in RAMAS GIS (Akçakaya 1998). This stochastic, spatially explicit, stage-based model for the panther population is based on long-term mark-recapture survey data and detailed habitat data. Specifically, the long-term viability of the single South Florida panther population was examined, and the effects of habitat loss and catastrophes were evaluated. Using the model, potential recovery options such as natural dispersal and translocation to increase the number of panther populations were explored.

**Building the Spatially Explicit Metapopulation Model**

RAMAS GIS provides a framework for building more sophisticated metapopulation models with complex spatially explicit structure, although it does not track genetic changes in the population. There are two key differences in the construction of models in RAMAS GIS compared to Vortex: RAMAS GIS models are usually single sex models (rather than two-sex) and they are population-based (rather than individual-based). Table 23 lists the major distinctions between Vortex and RAMAS GIS. RAMAS GIS, though, is well suited for

addressing conservation and management questions for species at risk because of its close integration of demographics with habitat dynamics.

Linking habitat data to metapopulation models requires three key steps:

(1) Identify the species-habitat relationship (HS function). For the Florida panther, the habitat analysis (based on Cox *et al.* 1994, Kautz and Kawula, shown in Figure 57) incorporates the key elements: distance to forest edge, distance to urban, and panther telemetry points. Suitable habitat for the Florida panther is in patches greater than two ha in size, within 200 m of forest and more than 300 m from urban areas.

(2) Locate discrete habitat patches (populations) based on distribution of suitable habitat. Utilizing the habitat suitability map showing the largest suitable contiguous patches developed by Kautz and Kawula, shown in Figure 57, a metapopulation structure was developed that grouped cells that were within normal dispersal distance into the same population. Carrying capacity of each population was based on home range size and patch area (*e.g.*, one panther per 110 $km^2$). The dispersal values were based on the distance among populations and the dispersal patterns documented from telemetry studies.

(3) Estimate population- and metapopulation-level parameters (*i.e.*, survival, fecundity, abundance, density dependence, *etc.*). Using the same data as Maehr *et al.* (2002b) a stage-based model for female panthers was created. This model had a juvenile and adult stage, reproduction at 2 or 3 years of age, a 50:50 sex ratio and populations based on the metapopulation structure found in Figure 58. For models that focused only on the existing panther populations, only populations south of the Caloosahatchee River were considered.

Three general single-sex models were constructed, shown in Table 22. One, labeled Conservative is based on the Seal *et al.* (1989) model except that juvenile mortality was 38 percent instead of 50 percent (based on the latest data, D. Land, FWC, personal communication, 1999). Note this scenario assumes a later age at first reproduction but a larger litter size than the other models. The second model, labeled Moderate, is based on the 1992 Optimistic model (Maehr *et al.* 2002b; see Table 22) parameters except that juvenile

mortality was 38 percent instead of 20 percent. A third model, labeled Optimistic, is based on the 1999 Consensus model (Maehr *et al*. 2002b; see Table 22) parameters except that juvenile mortality was 38 percent instead of 20 percent. All models assumed a 50:50 sex ratio and 50 percent of females breeding in any year.

The basic version of each model had no catastrophes or epidemics, no change in habitat quality or amount and a ceiling type of density dependence. Variants of these models had different density dependence or none, various levels of habitat loss, intermittent catastrophes or epidemics, or scheduled translocations or reintroductions. Models assumed that the existing South Florida panther population consisted of two populations south of the Caloosahatchee River (populations 9 and 10 in Figure 58) and that the populations north of the river were "empty" or unpopulated at the start of the simulations, unless specifically mentioned. Each simulation was run with 10,000 replications for 100 years.

**Minimum Viable Population Size**

What is the minimum number of panthers required to guarantee a 95 percent probability of persisting for the next 100 years? This question is an interesting one but the answer completely depends on the assumptions that are made. This issue was examined using the four original models and several alternatives (Table 22) under the assumptions of no catastrophes, no habitat loss, no inbreeding and no habitat limitations. A series of simulations were run where the initial abundance was increased until the probability of extinction at 100 years was no greater than 5 percent.

**Assumptions**

As in any model of metapopulation dynamics, the model of the Florida panther makes a number of assumptions. These assumptions were necessary largely because of data limitations, but also to keep the model simple enough to be reasonably functional. Below is a list of the major assumptions of the model:

(1) Either two (existing panther populations only) or 10 (existing plus potential populations)

populations functioned as discrete populations loosely connected through migration, forming a metapopulation.

(2) The vital rates of the past (as measured through telemetry data) reflect the values in the future. This assumes that monitoring the population has had no effect on the survival or fecundity rates.

(3) The initial abundance was based on an estimate of 41 females (D. Land, FWC, personal communication, 2001).

(4) The density within a population was assumed uniform throughout the entire area encompassed and only suitable habitat (based on the GIS analysis) for the panther was included in estimations of population area, density and carrying capacity.

(5) The model assumes (except in the scenarios where carrying capacity was changed) that the habitat remains in exactly the same shape and condition that it was at the time of the habitat suitability analysis. In other words, there was no change in the amount or quality or configuration of the habitat of the 100 years of the simulation unless explicitly specified in the scenario.

(6) Habitat within a population was assumed to be contiguous and readily accessible.

(7) Reproduction began at age 2 and, on average, 50 percent of the adult females were breeding in a given year.

(8) Fecundities were the product of the probability of breeding (*i.e.*, 50 percent), number of daughters per female, and the survival of offspring to one year.

(9) Dispersal was considered as permanent movement of a proportion of individuals from one population to another in a single year. This was dependent on the distance among the populations, although travel across the Caloosahatchee River was very infrequent.

(10) A 50:50 sex ratio was assumed in the model; only females were included in the model.

(11) For the purposes of reproduction, mates were assumed readily available and non-limiting.

(12) The density ceiling only applies to adults to simulate territoriality.

**Spatially Explicit Metapopulation Model Results**

The results of the model suggest that the long-term survival of the South Florida panther population requires maintenance of the current habitat configuration and condition indefinitely. Establishing additional populations decreases the overall risk of extinction for the species if sufficient habitat is available and there is adequate dispersal. Additional habitat loss or catastrophes would significantly increase the risk of extinction for this species and certainly lead to a decrease in abundance.

A comparison of the results of the basic Vortex models and the RAMAS GIS models with no habitat loss, supplementation, or catastrophes is shown in Table 24. For the Conservative model, the probability of extinction was 78.5 percent in 100 years with a mean final abundance of 3.48 females. Also, the probability of a large decline in abundance (50 percent) was 94.1 percent. (For this reason, no additional results for the Conservative model will be discussed.) Under this model any perturbation such as habitat loss or catastrophes greatly increased the probability of extinction and resulted in mean final abundances near zero. The Optimistic model, on the other hand, resulted in a 1.6 percent probability of extinction and mean final abundance of 51.15 females in 100 years. The probability of panther abundance declining by half the initial amount was only 9.1 percent in 100 years under the Optimistic model.

**Effects of Additional Populations**

The probability of extinction for the existing panther populations in South Florida (SF only in Figure 59) is quite low under either the Optimistic or Moderate scenarios: approximately 2

percent under the Optimistic parameters and 5 percent under the Moderate parameters. However, the probability that the population size will decline is much greater, Figure 59b. For example, there is a 9 percent probability and a 20 percent probability that the number of panthers will decline by half for the Optimistic and Moderate scenarios, respectively. The mean final abundance of females, shown in Figure 59a, is 42.27 females and 51.15 females for the Moderate and Optimistic scenarios, respectively. When we include all of the potential populations north of the Caloosahatchee River (assuming these potential populations are unpopulated at the beginning of the simulation) and allowed infrequent dispersal among all of the populations, the probability of extinction was reduced (1-2 percent); the probability of a 50 percent decline was reduced (5-9 percent); and the mean final abundance is much larger (111-220 percent) as shown in Figure 59.

**Effects of Habitat Loss**

If 25 percent of the habitat is lost over the first 25 years of the simulation (*i.e.*, 1 percent lost per year), the probability of extinction is increased approximately 1 percent (Figure 60b). The mean final abundance with habitat loss, though, is reduced by 26 percent to 37.9 and 31.2 females for the Optimistic and Moderate scenarios, respectively (Figure 60a). Similarly, the probability of extinction is only slightly increased when all potential populations are included, if the habitat loss is restricted to the two southern populations. Even with the additional populations, though, the mean final abundance with habitat loss is reduced by 19-24 percent compared to the same scenarios without the habitat loss.

**Effects of Corridors or Reintroduction**

Suppose a corridor exists across the Caloosahatchee River and one female adult crosses northward each year. Under this scenario the mean final number of females increases substantially from the initial two southern populations (Figure 61a) and the probability of extinction decreases (Figure 61b) with the Optimistic set of parameters. With the corridor, the number of females increases as the northern populations are filled, increasing by 66 additional panthers. It is interesting to note that the increase in the mean final abundance is not present at the end of the 100 years with the Moderate set of parameters and the probability of extinction actually increases slightly.

In contrast if the additional female adult, added to the population north of the Caloosahatchee River, is introduced from a population external to existing populations, such as from a captive Florida panther population, the reintroduction reduces the probability of extinction to zero with either the Moderate or the Optimistic parameters. Reintroduction increases the number of females at the end of the 100 years by 78-87 (Figure 61a).

**Minimum Viable Number**

The minimum number required for panther persistence varies widely depending on which model you choose. As a reference point, estimates based on mark-recapture studies suggest that there are approximately 78 known adult and subadult panthers living in South Florida; of these, 41 are known female panthers. Based on the fecundity and survival values from the 1989 Workshop (Seal *et al.* 1989) model there is no feasible number of panthers that will produce persistence probabilities greater than 75 percent, even if the initial abundance is more than 1,000 females (or 2,000 total panthers, assuming a sex ratio of 1:1). If the more optimistic models with finite growth rates ($\lambda$) much greater than 1.05 are used, 25 females (50 total panthers) provides a 95 percent probability of persistence for the next 100 years. The population models with finite growth rates near 1.05 provide estimates in between these two extremes of 51 females (102 total panthers). A more conservative model that has a finite growth rate less than 1.03 requires a minimum population size of at least 120 females (240 total panthers) for long-term viability.

**Discussion**

Small populations, in general, are susceptible to a number of problems such as inbreeding depression, genetic drift, Allee effects, population bottlenecks, and catastrophic effects. Loss of genetic variability may reduce a species' ability to adapt to its environment. Gilpin and Soule (1986) coined the term "extinction vortex" to describe the tendency of small populations to decline toward extinction. Therefore it is important in a population viability analysis to focus not just on the probability of extinction but also on possible genetic effects, such as loss of heterozygosity and the probability of large declines in abundance.

The results of the panther metapopulation model suggest that the long-term survival of the South Florida panther population requires maintenance of the current habitat configuration and condition indefinitely. Establishing additional populations decreases the overall risk of extinction for the species if sufficient habitat is available and there is adequate dispersal under most scenarios. Additional habitat loss or catastrophes would significantly increase the risk of extinction for this species and certainly lead to a decrease in abundance. In particular, the metapopulation model suggests that reducing habitat by 25 percent slowly (1 percent per year) will substantially reduce the number of panthers that persist for the next 100 years. At low panther abundance, the Vortex simulations indicate that there will be detectable loss of genetic heterozygosity. The loss of about 25 percent of the habitat would be equivalent to losing all of the remaining privately owned land in the proposed Primary Zone. Therefore, while the panther population would probably persist, it would be at reduced levels susceptible to demographic (*e.g.* Allee effects) and genetic (*e.g.* inbreeding depression) degradation.

The probability of a large decline is likely for the Florida panther population unless the population increases substantially in size or its growth rate is increased. The Optimistic model, which had an annual growth rate of approximately 7.7 percent, has the lowest probability of extinction and the largest mean final abundance. The model was also quite sensitive to assumptions about density dependence. If the carrying capacity was increased, the probability of extinction also decreased. Therefore, restoration of habitat or habitat improvement to make it more suitable for panthers would increase the chances of long-term panther viability.

Based on these modeling results and those of the past, there are a number of important management strategies that are recommended. Establishing additional populations, all other things being equal, reduces the overall risk of a decline. Expansion to the north of the Caloosahatchee River should improve the probability of long-term viability and sustainability; a corridor would increase the rate of expansion. The key point, though, is that it is important that there are sufficient “excess” individuals in the existing populations for dispersal or the probability of large declines increases substantially. Under the Moderate model, a simple corridor, with one adult female moving annually, actually increases the risk of extinction and lowers the mean final abundance. The current panther population in South Florida may not be large enough or growing fast enough to compensate for the loss of panthers regularly moving

north over the Caloosahatchee River, which highlights the need to protect and enhance the existing populations of Florida panthers first.

Habitat loss greatly increases the risk of a decline or extinction even under the most optimistic assumption. These models clearly indicate that unless we are able to safeguard the current condition, amount, and configuration of the existing panther habitat, the long-term viability of the Florida panther is not secure. While Florida panthers may continue to persist as habitat is lost, without management interventions the populations will become more vulnerable to problems of small populations, *e.g.*, inbreeding and Allee effects, as the number of individuals dwindles. It cannot be overemphasized that these models assume that there will be no loss of habitat (unless specifically mentioned), no degradation in quality, no difficulties in finding mates, no additional human-induced mortality, and no intermittent catastrophic events.

The exploration of the minimum viable number for panthers is an interesting exercise in that it highlights some of the important issues. It appears that the current number of panthers is sufficient for persistence but not long-term viability or sustainability. This minimum viable population size can only provide a starting point for examining the minimum amount of habitat that will need to be maintained in the current condition, be it agriculture, forest or other. A good reserve design will include a buffer to allow for changes, environmental or human-induced. This minimum number provides a static population. If recovery goals are to expand the population of panthers, more habitat will be needed to allow for population expansion and subsequent dispersal.