

Revised Population Viability Analysis III for the Alabama Beach Mouse

Peromyscus polionotus ammobates



Report to the U.S. Fish and Wildlife Service

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David H. Reed, Ph.D. and Kathy Traylor-Holzer, Ph.D.
IUCN Conservation Breeding Specialist Group

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Executive Summary

Introduction

The Alabama beach mouse (*Peromyscus polionotus ammobates*) is one of several endangered subspecies of oldfield mice known as beach mice. Beach mice inhabit the coastal dune habitats of the southeastern U.S. and prefer sand slopes with patches of sea oats and other native coastal vegetation. They are primarily nocturnal, spending the day in burrows in the sand and emerging at night to feed on seeds and insects. Endemic to the coastal dunes of Alabama, the Alabama beach mouse (ABM) is the most western beach mouse subspecies along the Gulf of Mexico. The distribution of this subspecies is restricted to the western tip of the Fort Morgan Peninsula eastward to Perdido Pass in Baldwin County. The historical range of this subspecies also included Ono Island; however no ABM are currently believed to exist there. ABM habitat consists of public lands (Fort Morgan and Perdue Units of the Bon Secour National Wildlife Refuge as well as Gulf State Park) and privately owned lands. Some level of connectivity is suspected across this range, although ABM are believed to avoid areas of human disturbance or habitation.

Coastal Baldwin County is an area of increasing recreational and residential development. Development on privately owned lands includes single family and duplex dwellings, condominiums, hotels and restaurants. Increased commercial and residential development has the potential to negatively impact beach mice populations through habitat loss and fragmentation, increased mortality, and increased vulnerability to the impacts of hurricanes. As a step in assessing the effects of development and other factors on the viability of ABM populations, in 2004 the U.S. Fish and Wildlife Service (FWS) initiated a Cumulative Impact Assessment (CIA) for this subspecies and began development of a population viability analysis model, which has been subsequently refined. These evaluation tools provide a better understanding of the population dynamics of the species and the expected impact of future development scenarios and management options.

PHVA Workshop and Model Results

The Conservation Breeding Specialist Group (CBSG) of the IUCN – World Conservation Union was invited to conduct a Population and Habitat Viability Assessment (PHVA) workshop for the Alabama beach mouse to assist in the development of viability projections for the species. The PHVA workshop, sponsored by FWS, was held June 8-11, 2004, in Point Clear, Alabama, and included 31 participants from 13 agencies and organizations. At the PHVA, Alabama beach mouse population data were examined and discussed in detail. A computer population simulation model (*Vortex*) was used to evaluate current and future risk of population decline or extinction with no further actions or destruction of habitat and under alternative development and management scenarios. Participants developed detailed reports outlining these discussions and justification for those values chosen for the model. The main goal of this PHVA workshop was to develop an ABM population model and use this model to assess the current status of ABM habitat and populations and projections for continued existence.

Working group and plenary discussions during and following the PHVA led to the estimation of model input values for the ABM model based on the best expert opinion available. This included

estimation of population structure, habitat carrying capacity, demographic rates, hurricane effects, the impact of development, and the testing of various management scenarios. Although accurate estimates of most of these parameters are not currently available, the PHVA workshop participants used all available published and unpublished data and expertise to provide the best estimates possible for use in developing the *Vortex* model. It was agreed that the development of an ABM model is a dynamic process, and that this model is likely to be revised as new data and modeling techniques become available.

The results of the 2004 PHVA baseline model suggested that the ABM metapopulation has an 18% to 21% probability of extinction over 100 years, depending on assumptions of how fast the habitat recovers following hurricanes (Traylor-Holzer *et al.* 2005). Sensitivity tests of alternative values for uncertain model parameters yielded probabilities of ABM extinction ranging from 13% to 36%, with the strongest impacts observed when habitat carrying capacity, juvenile survival, or adult survival was varied. The Perdue and Multi-Family model units appear to be the stabilizing portion of the overall metapopulation. These relatively large areas contain high elevation habitat that is less affected by hurricanes, and are centrally located relative to the linear array of subpopulation model units along the coast. Areas in the eastern part of ABM range (Gulf State Park and Orange Beach) suffer local extinctions, typically within 5 to 10 years. ABM subpopulations in these units have a high probability of extinction when hurricanes occur, particularly with more severe storms, and are not naturally recolonized due to isolation from other ABM populations. Subpopulations at the Fort Morgan, Single Family, and West Beach model units also frequently do not survive hurricanes (with median times to extirpation of 11 to 23 years), but they are often recolonized from adjacent units.

As expected, hurricanes are a major influence on the population dynamics of this subspecies. Additional potential threats include habitat loss due to the spread of cogongrass (an exotic invasive species) and high mortality due to predation by domestic cats, each of which have the potential to drive the ABM population to extinction (see the *Alabama Beach Mouse PHVA Final Report* for a complete description of the model results). Several future development scenarios were also modeled, both with and without management to minimize impacts upon ABM subpopulations. Some development options projected only minor impacts on the probability of overall ABM extinction (but may lead to local extinctions), while others caused significant reductions in projected metapopulation size and probability of persistence.

Revised PVA II Model and Results

Several events occurred in the months following the June 2004 PHVA workshop that had implications for the ABM. The FWS approved several Incidental Take Permits to allow additional development in the Single Family model unit (resulting in a loss of 0.4% of ABM habitat in that model unit). A more significant event was the impact of Hurricane Ivan, a Category 3 hurricane whose eye passed over the Fort Morgan Peninsula on September 16, 2004, resulting in a major loss of primary and secondary dunes throughout ABM habitat. Finally, as work with ABM and the CIA continued, new data and ideas arose for refinement and expansion of the ABM *Vortex* model. At the invitation of the FWS, CBSG met with FWS staff from local and regional offices in December 13-14, 2004 to discuss building upon the PHVA model to develop a PVA II for ABM. This discussion included developing a set of development scenarios that more closely matched those outlined in the CIA.

One of the modifications included building the occurrence of a Category 3 hurricane into the first time step of the model to simulate the effects of Hurricane Ivan. Another significant change was the reduction in the estimated impact of hurricanes on ABM habitat, as the original values (based on storm surge estimates according to the National Hurricane Center's SLOSH model) were thought to overestimate habitat loss. This decision was reached following a comparison of SLOSH model estimates of storm surge for a hypothetical Category 3 storm and observed storm surge from Hurricane Ivan (a strong Category 3 storm that made landfall on the Fort Morgan Peninsula in 2004). Restoration efforts were modeled in what is believed to be a more realistic manner. The results of a population viability analysis using this revised model were presented in a report to the FWS in June 2005 (Traylor-Holzer 2005) and are summarized below.

The revised *Vortex* model projected the Alabama beach mouse to have about a 14% risk of extinction over the next 100 years. Much of this extinction risk was due to the impact of hurricanes on ABM populations and habitat, which can result in relatively frequent and severe population declines. Population projections were slightly more optimistic than those from the ABM PHVA model, primarily due to the revision of hurricane impact estimates. Results indicated that land development has the potential to lower ABM viability by reducing habitat, increasing mortality, and exacerbating the effects of hurricanes by reducing high elevation refugia. These negative effects increase with increased levels of development, but none of the development scenarios modeled in this analysis resulted in certain ABM extinction. In the highest level of development modeled (i.e., full build-out of privately owned lands), the risk of metapopulation extinction was 34% over 100 years. Maximum development of the Gulf Highlands/Beach Club West parcels and maximum build-out of all private lands had substantially greater impacts than lower levels of development in these areas. Development led to high risk of local extinction not only in the developed area itself but also in adjacent private and public lands. Fort Morgan and Single Family subpopulations were projected to be most affected by the development of private lands followed by the West Beach subpopulation, while ABM in Multi-Family and Perdue areas were least affected. ABM were projected to be extirpated from Gulf State Park in all scenarios modeled. Habitat restoration following hurricanes may help to reduce overall extinction risk by allowing ABM populations to recover faster; however, restoration as modeled in this analysis is unlikely to substantially reduce or eliminate extinction risk. Restoration may make a small but measurable impact on ABM viability for some development scenarios.

Revised PVA III Model and Results

In the original PHVA for the ABM, it was agreed that the development of an ABM model is a dynamic process and that the original model was likely to be revised as new data and modeling techniques became available. In this spirit, and at the invitation of the FWS, CBSG met with FWS staff from local and regional offices on December 14, 2005, to discuss building upon the PHVA model and revised PVA II model of the previous year. This was prompted by the availability of improved data and by the fact that FWS faces important decisions in 2006 concerning several Incidental Take Permits (ITPs).

The following modifications were made to the ABM model from the previous PVA:

- Addition of freshwater flooding as a catastrophe. Observation of extensive freshwater flooding due to heavy rains was observed in 2005. The model now incorporates freshwater flooding as a potential catastrophe.
- Change in initial conditions to reflect effects of freshwater flooding observed in late March 2005 followed by the impacts of Hurricane Katrina in late August 2005. These environmental conditions occur in the first calendar year of all iterations of the model.
- Revision of habitat carrying capacity estimates for all model units. Removal of maritime forests and wetlands has altered the amount of habitat available for ABM. This is particularly true for the crucial Perdue model unit. Further, in earlier models there were some inconsistencies in the way the available habitat was calculated for the Perdue model unit versus the other model units; these inconsistencies were corrected.
- Hurricane impacts were increased to 100% of the values given in the original storm surge estimates, according to the National Hurricane Center's SLOSH model, for Category 4 and Category 5 storms. This decision was based on observations of record storm surge inundation in coastal Mississippi during Hurricane Katrina (2005).
- Time to full recovery of the habitat following storms was decreased for Category 1-3 hurricanes. This was based on observation of recovery times from Hurricane Ivan.

Vortex can be used to estimate population outcomes and to aid in the decision-making process concerning specific questions posed by the FWS. Alternative management scenarios were developed based upon these revised model conditions and evaluated to address the following questions:

- What is the projected viability of existing ABM populations given habitat corridors among model units (interconnected populations baseline scenario)?
- What is the effect on ABM population viability if existing model units become isolated through loss of habitat corridors, eliminating gene flow (ABM movement) among model units (isolated populations scenario)?
- What is the impact on ABM population viability if all ABM habitat on privately-owned lands is lost, resulting in ABM persistence only on public lands (public lands only scenario)?
- How effective might translocation be as a management tool to improve ABM population viability by re-establishing populations in habitat patches where ABM have disappeared (translocation scenarios)?

Given current ABM population status and habitat availability and using the revised *Vortex* model, the Alabama beach mouse metapopulation is projected to have a $26.8\% \pm 1.0\%$

likelihood of extinction over the next 100 years. Mean size of surviving populations average about 38% of estimated carrying capacity. The remaining gene diversity (expected heterozygosity) in the population, in the absence of mutation, is expected to be only 66% of that currently contained by the population. These population projections are more pessimistic than the approximately 20% probability of metapopulation extinction predicted from the original PHVA and the 14% risk of metapopulation extinction predicted from the revised 2005 PVA II model. The decreased probability of population persistence is due primarily to the reduction in the carrying capacity of the Perdue unit, which is critical to metapopulation survival because of its size and central location along the linear array of model units, and to the increased estimates of storm impacts with the most damaging hurricanes.

Land development can lower ABM viability by reducing habitat and exacerbating the effects of hurricanes by reducing high elevation refugia. Development can also lower viability by reducing connectivity among habitat patches. Modeling the same six model units as contained in the baseline model (Fort Morgan, Single Family, Multifamily, Perdue, West Beach, and Gulf State Park), but without the possibility of ABM movement among the units, increased the risk of extinction of the metapopulation significantly to $41.2\% \pm 1.1\%$ (from 26.8%). A more extreme form of habitat loss potentially facing ABM is the total loss of private lands as suitable habitat, limiting the species to public lands in the Fort Morgan, Perdue, and Gulf State Park model units with no migration possible among these units. This leads to a further significant, but more modest, increase in the probability of metapopulation extinction to $46.8\% \pm 1.1\%$ over 100 years.

Translocation of mice from habitat patches where the population persists to patches where ABM are extinct should help to reduce overall extinction risk of the metapopulation. Translocation, as modeled here, had a relatively small but positive and statistically significant effect on extinction risk. For the baseline Interconnected Populations scenario (where natural migration could occur), the effects of translocation were (not surprisingly) non-significant and the estimated risk of metapopulation extinction was $25.5\% \pm 1.0\%$ (as opposed to 26.8% without translocation). In the Isolated Populations scenario the probability of metapopulation extinction with translocation was $34.9\% \pm 1.1\%$ (as opposed to 41.2% without translocation). In the Public Lands Only scenario the probability of metapopulation extinction with translocation was $40.8\% \pm 1.1\%$ (as opposed to 46.8% without translocation). In both cases where there was no natural connectivity and movement of ABM, the probability of metapopulation extinction was ameliorated by the addition of translocation. However, translocation as modeled here was never as efficient as estimated natural rates of migration in rescuing the metapopulation from extinction.

ABM populations are subject to considerable fluctuations in size due to seasonal variation in breeding and survival, fluctuations in habitat quality across years, and the impacts of hurricanes. The fate of the ABM metapopulation is therefore intrinsically unpredictable, although the *probabilities* of population decimation and the long-term mean numbers of mice can be estimated. These probabilities can be compared among alternative management and development scenarios to evaluate the probable effect on population trends. In addition, the accuracy of model results depends upon the accuracy of the values entered into the model. For many of the ABM model parameters, the best available data allow only approximate estimates of the true values. If these estimates are incorrect, the model results can be misleading regarding the most likely fate of the ABM population.

The ABM *Vortex* model suggests that hurricanes are a driving force for ABM populations, both directly and also indirectly as their impacts interact with other factors such as development of high elevation areas or predation by cats. Habitat corridors among the linear array of ABM habitat patches (model units) that allow the movement of ABM also contributes to the persistence of individual ABM populations by providing demographic and genetic rescue of declining or extinct populations. These corridors can be interrupted by development and by erosion due to human activities as well as frequent, severe storms. These results emphasize the importance of efforts to improve the accuracy of hurricane impact estimates, including loss and recovery of habitat and habitat corridors as well as how ABM use different habitat types before, during and following storms. Better understanding of these processes and more accurate estimation of their frequency and effects would lead to development of an even more useful and valid simulation model for ABM populations.

Revised *Vortex* Model Input Values

***Vortex* Simulation Model**

Computer modeling is a valuable and versatile tool for assessing risk of decline and extinction of wildlife populations. Complex and interacting factors that influence population persistence and health can be explored, including natural and anthropogenic causes. Models can also be used to evaluate the effects of alternative management strategies to identify the most effective conservation actions for a population or species. Such an evaluation of population extinction risk under current and varying conditions is commonly referred to as a population viability analysis (PVA).

Here, the *Vortex* simulation software program was used to examine the viability of the Alabama beach mouse population. *Vortex* is a Monte Carlo simulation of the effects of deterministic forces as well as demographic, environmental, and genetic stochastic events on wild populations. *Vortex* models population dynamics as discrete sequential events that occur according to defined probabilities. The program begins by creating individuals to form the starting population and then stepping through life cycle events (e.g., births, deaths, dispersal, catastrophic events), typically on an annual basis. Events such as breeding success, litter size, sex at birth, and survival are stochastic and determined by random draws from a user-defined probability density function. Consequently, each run (iteration) of the model gives a different result. By running the model hundreds of times, it is possible to examine the probable outcome and range of possibilities (for a more detailed explanation of *Vortex* and its use in population viability analysis, see Lacy 1993, 2000).

Development of the Revised Model

Staff from the USFWS met in Fairhope, AL on December 14, 2005 to discuss and revise the Alabama Beach Mouse (ABM) *Vortex* model based upon new available data and changes that had occurred to ABM habitat and populations since the model was last revised in December 2004. Listed below is a summary of changes made to the revised ABM PVA III model for purposes of this revised analysis (see the ABM PHVA and PVA II reports for model details).

1. Observation of extensive freshwater flooding in some model units during March 2005 led to the addition of freshwater flooding as a catastrophe to the baseline model. Details of the freshwater flooding regime are discussed in detail under *Catastrophes* below.
2. New initial conditions were used that included a freshwater flooding event and a Category 3 hurricane during the first calendar year of the model, simulating events that occurred in 2005.
3. The amount of available habitat (carrying capacity) was revised for all six model units based on more accurate information and using a consistent estimation method. This included a substantial reduction in carrying capacity for the Perdue model unit (see *Carrying Capacity* below for details).
4. The impacts of Category 4 and 5 hurricanes on carrying capacity were increased to the levels originally modeled in the initial PHVA. The effects of Category 1-3 hurricanes remained the same as in ABM PVA II.

5. The function describing the recovery of carrying capacity after a hurricane was revised to create faster recovery for hurricanes of Categories 1-3 (see *Catastrophes* below for details).

These changes resulted in a new baseline model that represents the best available biological and habitat information for ABM and assumes no further development of ABM habitat. The baseline model also assumes permanent, intact habitat corridors between adjacent model units (except for Gulf State Park, which is permanently isolated due to development at Gulf Shores). Some of these habitat corridors have recently been disrupted due to the combined effects of storms and human activities, but are anticipated to recover. Additional scenarios were developed to evaluate the impact of loss of habitat corridors (leading to permanent fragmentation of ABM habitat), the loss of ABM habitat in privately-owned lands (leading to the existence of three isolated ABM populations on public lands), and the effectiveness of translocation of ABM among model units as a management tool to promote population persistence and viability (see *Scenario Descriptions* for further explanation).

Model Input Values

The final values used in the baseline model are summarized below. Detailed explanations of input values and justification for their use can be found in the *Alabama Beach Mouse PHVA Final Report* (Traylor-Holzer *et al.*, 2005).

Number of iterations: 2000 per scenario

Number of years: 100 calendar years

Due to the relatively short generation time for this species, life history events were modeled in four-week time steps rather than 365-day intervals. Therefore, iterations were run for 1300 time steps to project population trends for 100 years.

Extinction definition: Only one sex remaining.

Number of populations: 6

The ABM metapopulation was modeled as six partially connected subpopulations to allow the geographical and management differences across the ABM range to be incorporated and to make it possible to test different future scenarios with respect to these areas. In many cases these areas do not describe biologically separate populations but instead reflect geographical management units, termed *model units*. Model units were defined as discrete ABM habitats having distinct geographic features and/or similar threats. Model units included in the model were Fort Morgan (FM), Single Family (SF), Multi-Family (MF), Perdue (PD), West Beach (WB), and Gulf State Park (GSP).

Inbreeding depression: Yes (1.8 lethal equivalents)

Inbreeding is thought to have deleterious effects on reproduction and survival. Inbreeding depression was included in the model as a reduction in survival of inbred juveniles during their first four weeks. The impact of inbreeding was modeled as 1.8 lethal equivalents, which is the value reported for the Santa Rosa beach mouse (*P. p. leucocephalus*). The inbreeding effect was specified to be due entirely to recessive lethal alleles (100%).

Concordance between environmental variation in reproduction and survival: Yes

It is believed that there is a positive correlation between environmental conditions that affect survival and reproduction for beach mice (i.e., years that are good for survival tend to also be good for reproduction and vice versa).

EV correlation among populations: 0.5

The model includes a moderate correlation between variation in birth and death rates among all model units (populations). A correlation of 0.5 was selected as reasonable given the life history of the species and the extent of the geographic area being modeled.

Dispersal among populations: Yes

Values for dispersal were retained from the PHVA model. The values represent normal dispersal by sub-adults to establish a home range outside of their natal home range, which sometimes causes them to cross an inter-unit boundary. No additional mortality was imposed, as movement across these boundaries is assumed to be no riskier than movement within model units. Inter-unit dispersal rates range from 0 to 2.43% of sub-adult mice. Dispersal was modeled between adjacent model units, with the exception of a barrier to ABM movement between WB and GSP, resulting in the isolation of GSP from the rest of the ABM population (see Figure 1).

Mating system: Long-term polygyny

Although ABM are typically considered to be monogamous, males will also breed with unpaired females. To more accurately represent the consequences of the mating system in the model, mating was modeled as long-term polygyny so that reproduction would not be male-limited.

Age of first reproduction: 3 time steps (84 days)

Vortex defines reproduction onset as the time at which offspring are born, not the age of sexual maturity. The model uses the mean age of first reproduction (parturition) rather than the earliest recorded age of offspring production.

Maximum age of reproduction: 19 time steps (532 days, or approx. 1.5 years)

Vortex assumes that animals can reproduce throughout their adult life. Mice can live and breed beyond 2 years in lab conditions, but few individuals are likely to live beyond one year in the wild. Although the maximum age of reproduction was set at 1.5 years, the mortality rates used in the model result in few mice surviving past one year.

Maximum litter size/litter distribution: 8

Values for litter size were taken from the distribution of litter sizes observed for 413 non-inbred litters of *P.p. leucocephalus*. This distribution was 3.15%, 5.08%, 20.34%, 27.85%, 28.09%, 12.35%, 2.91%, and 0.23% for 1 to 8 pups, respectively, resulting in a mean litter size of 4.23.

Sex ratio at birth: 50% male

Density-dependent reproduction: Yes

Density-dependent reproduction has been observed in several *Peromyscus* species. Density dependence is defined by specifying parameters of a particular functional shape for the relationship between population density and breeding success. The curve that is often used to represent the functional relationship is: % breeding = $[(P_0 - (P_0 - P_K) * (N/K)^B)] * (N/(N+A))$. The specifics of this function were thought to differ in Fort Morgan and Multi-Family model units than in other four model units. The following parameter values were used in the model:

- P_0 Specifies the % of adult females breeding in an average year when population density is very low relative to the food supply and carrying capacity of the habitat. Set at 70% based on data from *Peromyscus* populations (90% for Fort Morgan).
- $P_K=30$ Specifies the breeding rate (% females breeding each year) when the population is at its carrying capacity. Set at 30% based on data from *Peromyscus* populations.
- $A=1$ Defines the Allee effect (difficulty in finding mates at low densities, < 10 mice).
- B Defines the steepness with which breeding decreases as population approaches K. Set at $B = 3$ for most model units; set to a steeper value for Fort Morgan ($B = 0.5$) and Multi-Family ($B = 1$) units.

Environmental variation in breeding rate: 17%

ABM populations have been observed to fluctuate seasonally, with the highest populations observed in the late winter/early spring and the lowest numbers in late summer/early fall. An oscillating sine wave was used to represent seasonal fluctuations in reproduction. In addition, environmental variation was added to the model to account for variation in the percent of females breeding due to variation in environment conditions.

Monopolization of breeding: 95%

There is little evidence for social prevention of mating (e.g., dominance). Most males are believed to have the opportunity to breed; although only about 70% of males examined were reproductively active based on categorization of abdominal vs. scrotal males, abdominal males can quickly come into breeding condition if a female is available.

Mortality: See below

Sub-adult and adult mortality rates and environmental variation were calculated from data from ABM populations in Perdue and Fort Morgan units. Mortality was observed to be highest in summer. Juvenile mortality rates were taken from laboratory data and modified to include higher summer mortality, resulting in the following baseline rates used in the model:

<u>Age class</u>	<u>Fall/Winter/Spring</u>		<u>Summer</u>	
	<u>% Mortality</u>	<u>SD (%)</u>	<u>% Mortality</u>	<u>SD (%)</u>
0 – 1 (0-28 days)	36.2	14.4	52.5	14.4
1 – 2 (29-56 days)	21.1	14.4	30.3	14.4
2+ (>56 days)	16.1	10.6	23.7	10.6

Carrying capacity (K): Subpopulation specific

The carrying capacity for each model was based upon estimates of the amount of suitable ABM habitat and ABM density for each model unit, as listed below (see ABM PHVA report for details). No environmental variation was included for carrying capacity, as year-to-year variation in *K* was not considered to be a factor in the absence of hurricane impacts and recovery. No future trend in *K* was added to the baseline model.

Below is the amount of habitat (in acres) for each of the model units from the PHVA and the current PVA. The carrying capacity for each model unit was changed by the same percent as the decrease or increase in available habitat and is also given below.

	Habitat (in acres)		Carrying capacity	
	<u>PHVA</u>	<u>PVA III</u>	<u>PVA III</u>	<u>% Change</u>
Fort Morgan (FM)	173	152	1774	-12.1
Single Family (SF)	677	629	5611	-7.1
Multi-Family (MF)	513	383	2490	- 25.3
Perdue (PD)	1,036	748	7013	-27.8
West Beach (WB)	188	166	1103	-11.7
Gulf State Park (GSP)	111	130	581	+17.1

Initial Population Size (N_0): Subpopulation specific

Initial population sizes were set at carrying capacity. *Vortex* distributes the specified initial population among age-sex classes according to a stable age distribution that is characteristic of the mortality and reproductive schedule described for the model. A freshwater flooding event was then imposed, followed shortly by a Category 3 hurricane to simulate the reduction in ABM and ABM habitat following Spring 2005 flooding and Hurricane Katrina.

Catastrophes: 6 catastrophes of variable effect

Hurricanes and freshwater flooding events were included as catastrophes in the model. Each category of hurricane (1-5) was modeled as a separate type of catastrophe to allow for differences in frequency of occurrence, severity of impacts, and habitat recovery time. Storms were modeled as global catastrophes (i.e., hurricanes hit all model units synchronously) occurring only in August through October. Probability of occurrence was based on site-specific estimates by the National Hurricane Center. Hurricanes affect ABM survival and carrying capacity but not reproduction in the model. These effects differ by model unit, as some units are more resilient to the effects of storms. Impacts on carrying capacity are constant for each storm category and model unit combination, while the effect on ABM survival is variable within a specified range. Recovery of carrying capacity to pre-storm level varies based on the storm category and was modeled using a logistic curve.

Freshwater flooding (FF) was modeled as a global catastrophe, affecting FM, SF, MF and WB model units only. Probability of occurrence was based on the frequency of severe rainfall (≥ 12 inches of rain in a 24-hour period) events recorded on the Fort Morgan Peninsula since 1948. Freshwater flooding reduces the carrying capacity of the environment in the four model units by

variable amounts. Recovery of carrying capacity was modeled using the same logistic curve used for hurricanes.

The frequency of the six different catastrophe categories and the time required for the carrying capacity of the environment to recover fully from each of them is given below. Note that the recovery times for Category 1, 2, and 3 hurricanes were shortened compared to previous ABM models. Also given are the carrying capacities (K) under normal conditions and immediately after the occurrence of a catastrophe.

<u>Category</u>	<u>Frequency</u>	<u>Recovery (in years)</u>
C1	1 in 8 years	2
C2	1 in 16 years	5
C3	1 in 25 years	8
C4	1 in 47 years	25
C5	1 in 100 years	40
FF	1 in 20 years	1*

* Fort Morgan and Single Family model units recover in 5 time steps (140 days).

<u>Model unit</u>	<u>Carrying capacity</u>						
	<u>Baseline</u>	<u>C1</u>	<u>C2</u>	<u>C3</u>	<u>C4</u>	<u>C5</u>	<u>FF</u>
Fort Morgan	1774	852	656	532	153	135	1242
Single Family	5611	4040	1908	1403	168	107	4320
Multi-Family	2490	2415	1843	1021	249	120	1668
Perdue	7013	6775	5253	2504	919	582	7013
West Beach	1103	1037	353	331	132	17	1082
Gulf State Park	581	413	221	134	6	2	581
TOTAL	18572	15531	10233	5924	1627	962	15907

Harvest: None

Trap mortality is negligible. There is no additional harvest in the baseline model. Predation by cats was not included in this model.

Supplementation: None

The addition of individuals to the population from captivity or other sources (via translocation) was not included in the baseline model.

Scenario Descriptions

Interconnected Populations (Baseline model)

The baseline model represents the best estimate of current conditions for the Alabama beach mouse. Six model units are included – FM, SF, MF, PD, WB, GSP. Habitat corridors that allow ABM movement between adjacent model units were assumed, with the exception of a barrier to movement between WB and GSP, resulting in the isolation of GSP from the rest of the ABM population (see Figure 1 for a diagram of model scenarios). Although erosion from storm and human post-storm clean-up activities currently block some of these corridors, these barriers are

anticipated to be temporary. This scenario assumes that these corridors will be restored and maintained.

Isolated Populations (elimination of ABM movement between model units)

Increased erosion from frequent and intense hurricanes, as well as increased residential development and post-storm clean-up activities, threatens the habitat corridors connecting adjacent model units. This could have detrimental genetic and demographic impacts on ABM viability. Erosion is a major factor affecting the health of coastal dune systems. Vegetation and the continuity of the dune system are the beaches only defenses against wind and water. Once the system is interrupted by anthropogenic causes or unusually frequent and severe storms, the dunes can shrink and erode away causing the beach to recede and eventually disappear (Watson 1997, 2003). Continued development on private lands threatens the corridors that allow dispersal among the various model units comprising the ABM metapopulation. For example, barriers to ABM movement have developed between the PD and WB model units as well as between the MF and SF model units, due to Hurricane Katrina. This scenario incorporates the same carrying capacities as the baseline model, but without any movement of mice between model units, and is designed to test the impacts of the potential permanent elimination of these corridors.

Public Lands Only (loss of privately owned lands)

Another potential scenario that ABM could face is the development of all privately held lands to the point where those model units no longer provide any suitable ABM habitat. This scenario resembles the above Isolated Populations scenario, in that there is no ABM movement between model units, but with ABM occupying only the FM, PD, and GSP model units (public lands).

Translocation Scenarios

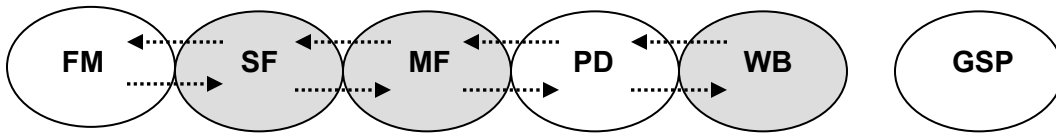
Three translocation scenarios were developed to examine the efficacy of translocation as a management tool in ameliorating the risk of metapopulation extinction. Translocation of individuals from extant populations to model units where the population has gone extinct was added to each of the scenarios above (Interconnected Populations, Isolated Populations, and Public Lands Only) to test the ability of translocation to improve the persistence of the ABM metapopulation.

Translocation was modeled in a similar manner in all scenarios, and occurred when:

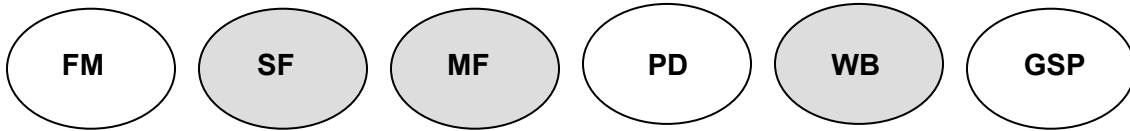
- a model unit (recipient population) had gone extinct;
- the carrying capacity of the empty model unit had recovered to a certain point ($K \geq 0.8 K_{\max}$; $K \geq 0.5 K_{\max}$; and $K \geq 0.2 K_{\max}$ were tested as thresholds in carrying capacity that would trigger translocation, when $K_{\max}$ = full carrying capacity);
- the donor population contained at least 500 ABM (to ensure that translocation did not jeopardize a small donor population);.

Translocation events consisted of 25 pairs (25 females and 25 males) of subadult mice. Perdue served as the donor population, and ABM were translocated to FM, SF, MF, and GSP when those model units went extinct. No translocations were made to WB. [Note: In the *Public Lands Only scenario*, SF and MF model units were not included and, therefore, could not receive mice.] If the Perdue model unit went extinct, it received ABM from the Fort Morgan model unit.

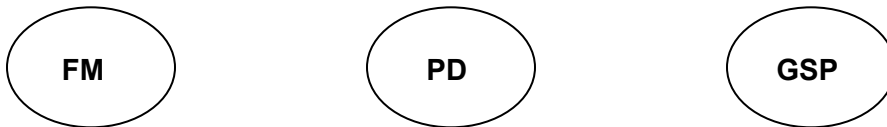
INTERCONNECTED POPULATIONS SCENARIO (BASELINE)



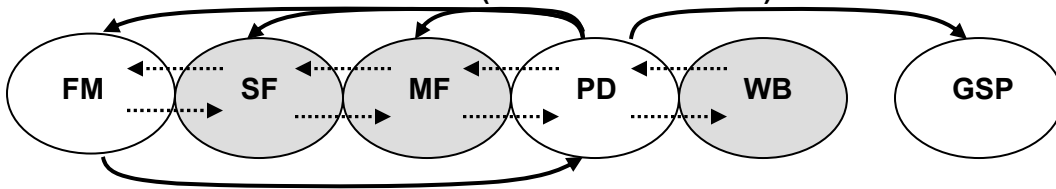
ISOLATED POPULATIONS SCENARIO



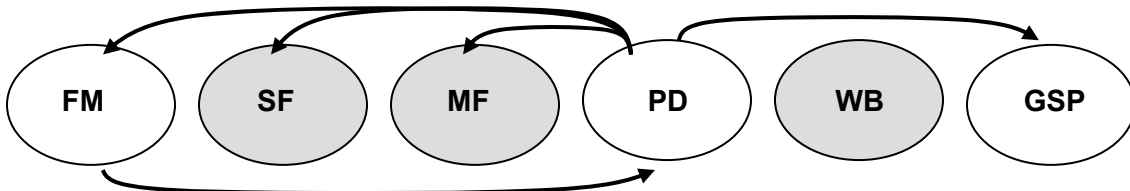
PUBLIC LANDS ONLY SCENARIO



TRANSLOCATION SCENARIO (INTERCONNECTED)



TRANSLOCATION SCENARIO (ISOLATED)



TRANSLOCATION SCENARIO (PUBLIC LANDS ONLY)

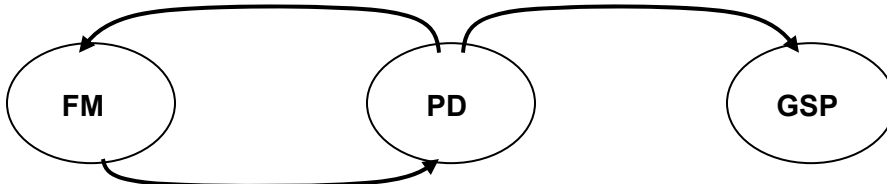


Figure 1. Diagrams depicting six model scenarios (gray shading indicates privately-owned lands; dashed arrows indicate natural ABM movement via corridors; curved solid arrows indicate translocation).

Vortex Model Results

Each model scenarios was run for 2,000 iterations and the results are summarized below. A complete data table of model outputs for the metapopulation and individual model units can be found in the end of this section.

Populations of Alabama beach mice, both in nature and in the computer simulations, are subject to large, unpredictable fluctuations – due to the combination of seasonal changes in survival and breeding, large fluctuations in population performance due to random environmental variation over time, and periodic decimation of numbers of mice and habitat by hurricanes. This can be seen in the sample iteration below (Fig. 2). Note the population crash at the beginning of the simulation, simulating the effects of Hurricane Katrina. In most instances the ABM population is able to grow following crashes as the habitat (carrying capacity) recovers, but the population is particularly vulnerable to extinction when at low numbers. Note the metapopulation extinction around time step 1170 in this example.

Although this fluctuating pattern of population size is typical for each individual iteration, the years in which hurricanes occur vary across simulations, resulting in a mean population size that appears much less dynamic and is intermediate between these population peaks and valleys. These results compiled across iterations project the general population trends that can be compared across alternative connectivity and management scenarios.

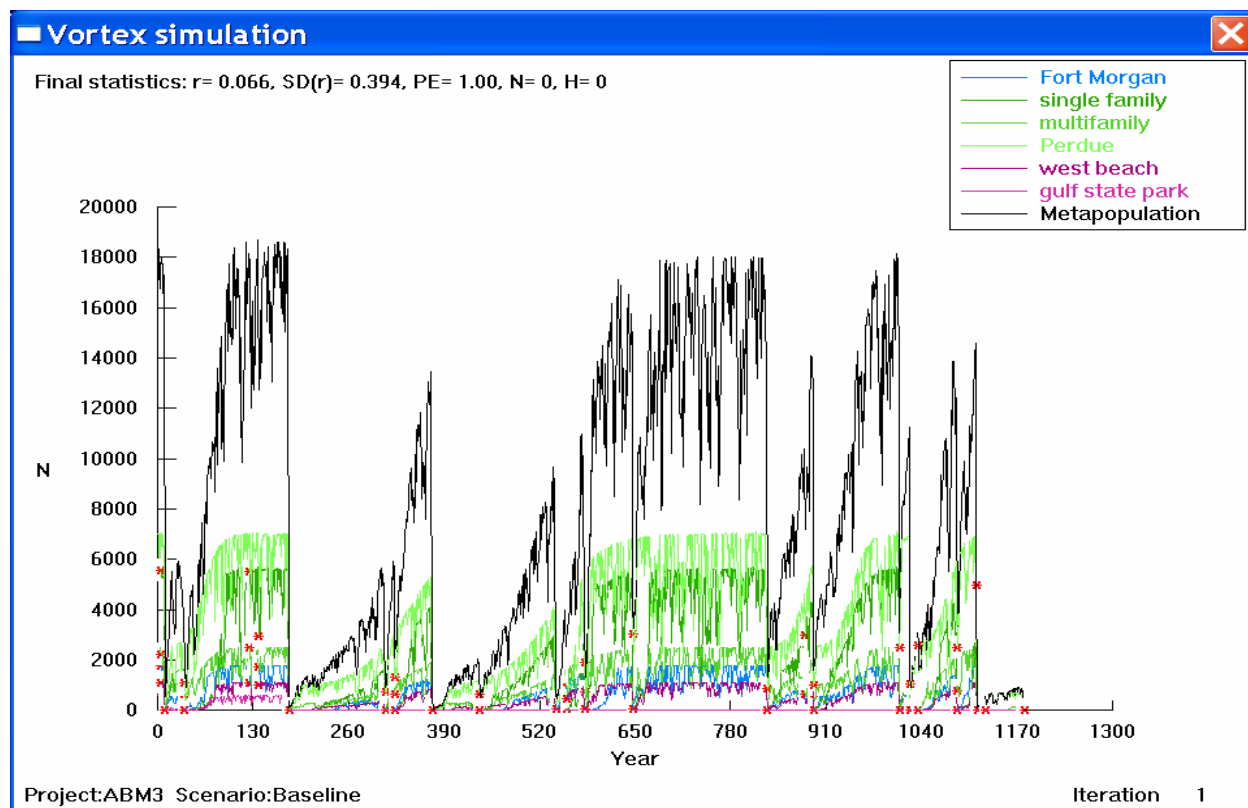


Figure 2. Single sample iteration of the ABM PVA III model over a 100-year period.

Interconnected Populations (baseline model)

Probability of Extinction

The revised ABM model represents the best estimates available as of December 2005 regarding population and habitat status, demographic rates, and hurricane impacts for the Alabama beach mouse. If no further development or other loss of habitat occurs (and given the caveats provided later), the estimated risk of extinction for the entire ABM metapopulation is $26.8\% \pm 1.0\%$. The probability of local extinction in individual model units is higher; almost certain extinction is projected for the smallest and most isolated model unit at Gulf State Park. The importance of the Perdue unit can be seen by observing how closely the probability of metapopulation extinction matches the probability of extinction of the Perdue unit (Table 1). The probability of metapopulation extinction increases in a relatively linear fashion over time (Fig. 3).

Table 1. Probability of extinction over 100 years for each of the six model units individually and the metapopulation as a whole for interconnected, isolated, and public lands only scenarios.

Population	Scenario		
	Interconnected	Isolated	Public Only
FM	0.418	0.998	0.995
SF	0.339	0.996	--
MF	0.276	0.819	--
PD	0.274	0.465	0.470
WB	0.339	1.000	--
GSP	0.999	1.000	1.000
Metapopulation	0.268	0.412	0.468

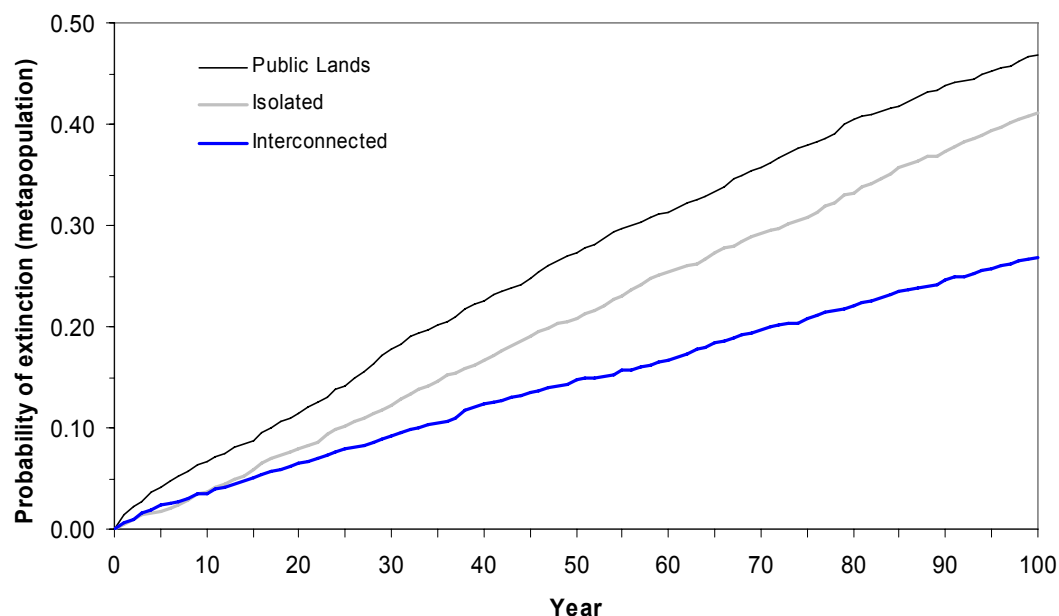


Figure 2. Probability of metapopulation extinction over time, for Interconnected, Isolated and Public Lands populations.

Mean Population Size and Gene Diversity

The mean size of surviving ABM metapopulations averaged around 7,000-7,500 individuals, with the largest populations in the core of ABM range in the Perdue, Multi-Family and Single Family model units. As expected with decreases in mean population size and large temporal variations in size, heterozygosity also declines across the metapopulation, averaging only 66.2% of that initially contained by the metapopulation (Table 2).

Table 2. Mean size and gene diversity retained for *extant* populations at the end of 100 years for Interconnected, Isolated, and Public Lands scenarios.

Population	Mean Pop Size			Gene Diversity Retained		
	Interconn.	Isolated	Public	Interconn.	Isolated	Public
FM	662	674	721	0.57	0.24	0.15
SF	2089	2401	--	0.61	0.29	--
MF	1062	1099	--	0.65	0.37	--
PD	3212	3230	3230	0.65	0.64	0.65
WB	441	92	--	0.61	0.39	--
GSP	491	0	0	0	0	0
Metapopulation	7053	3297	3218	0.66	0.62	0.65

Loss of Habitat Corridors (isolated populations)

The movement of individuals from one habitat patch (subpopulation) to another is expected to have dramatic effects on the viability of a metapopulation (Brown and Kodrick-Brown 1977; Richards 2000; Reed 2004). The two most general ways that migration (and gene flow) affect metapopulation persistence is by recolonizing habitat patches where the local population has gone extinct and by the introduction of novel genetic material that can prevent the erosion of fitness due to genetic drift and increase the evolutionary potential of the population. These phenomena have been termed demographic and genetic rescue, respectively.

In accordance with population biology theory and most experimental manipulations, eliminating ABM movement between adjacent model units led to an increase in the probability of extinction that grows more significant over time (Fig. 3). The estimated probability of extinction for the entire metapopulation increased from 26.8% to 41.2%. Extinction probabilities in each of the individual model units increased dramatically as well (except for GSP, which already had a nearly 100% risk of extinction) (Table 1). The increase in the probability of extinction for the individual model units reflects the loss of demographic and genetic rescue in these subpopulations. Perdue was least affected by the lack of connectivity, because it most often serves as a donor rather than a recipient for recolonization. Yet, it is obvious that the movement of ABM into Perdue is also crucial to metapopulation stability and viability.

Trends in metapopulation size (Table 2) tell a similar story. Though individual population sizes in the model units do not change appreciably when isolated, these numbers are misleading, as they represent the mean population size of *extant* populations (iterations in which the population did not go extinct). The decrease in metapopulation size accurately reflects the increased

probability of extinction and shows that effects of the extinction ratchet, where the extinction of a subpopulation leads to the irreversible loss of carrying capacity in the metapopulation.

Likewise, most of the individual populations show a much greater loss of gene diversity when isolated, indicating the importance of gene flow between adjacent populations. Perdue, and the metapopulation as a whole, show a much smaller but still significant decline in gene diversity when isolated (Table 2). Taken together, these results suggest that connectivity may play an important role in the demographic rescue of Perdue, thus decreasing the risk of extinction for Perdue and for the metapopulation. In addition, connectivity provides genetic and demographic rescue to the smaller populations in Fort Morgan, Single Family, Multi-Family and West Beach.

Loss of Privately Held Land (public lands only)

The Isolated Populations scenario was modified by eliminating privately held lands (SF, MF, and WB) as potential habitat for the ABM to create the Public Lands Only scenario. This scenario led to a significant, but more moderate, increase in the probability of metapopulation extinction from 41.2% to 46.8%. Predictably, the individual probabilities of extinction and mean population sizes for each of the model units remained very similar to that of the Isolated Populations scenario. If all ABM habitat in privately owned lands were lost, it is likely that ABM populations would not persist long-term in Fort Morgan and Gulf State Park, and that any surviving ABM population that might persist would occur only in the Perdue model unit.

Impact of Translocation

In the absence of habitat connectivity and natural movement of ABM across the peninsula, managers may consider translocation of individuals from one population to another. Manipulating gene flow among populations this way can increase the genetic health of individuals and create or restore populations where stochastic extinction has occurred.

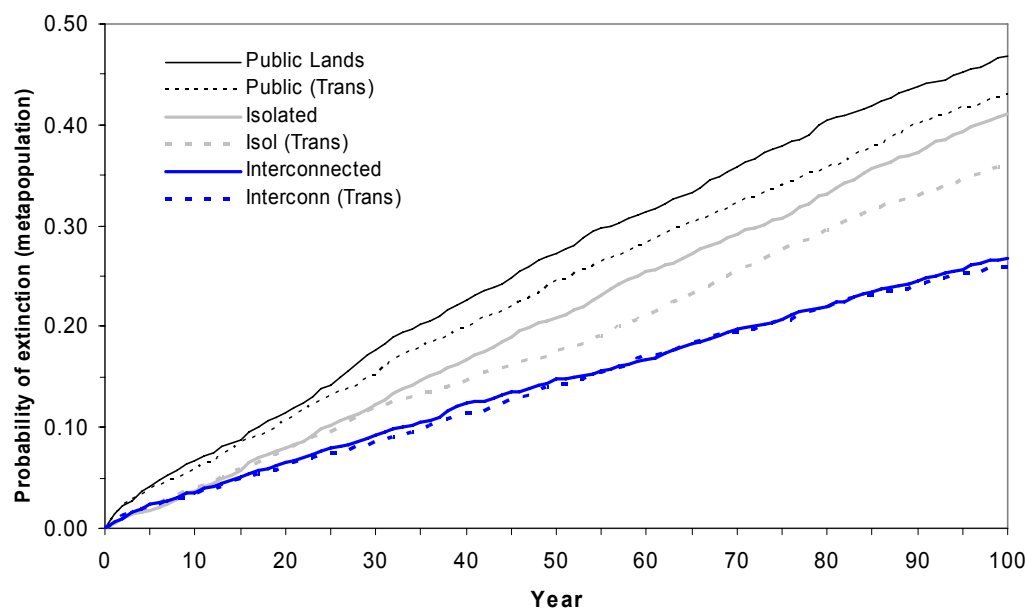


Figure 4. Probability of metapopulation extinction over time, for Interconnected, Isolated and Public Lands populations (with and without translocation).

The efficacy of translocation in ameliorating the risk of metapopulation extinction was tested by modifying the three previous scenarios to include translocation. The addition of translocation had no effect on the probability of metapopulation extinction when model units were interconnected (baseline model), which already allowed ABM movement between adjacent model units. In scenarios without connectivity, translocation decreased the probability of metapopulation extinction significantly if only moderately (Fig. 4). The failure of translocation to decrease metapopulation extinction risk to the level of the baseline model suggests that, despite the large carrying capacity of the individual model units, the reduction of inbreeding depression within model units resulting from gene flow among subpopulations plays an important role in metapopulation persistence. This inbreeding is the result of sequential bottlenecks occurring after hurricanes and is evidenced by the more rapid loss of gene diversity in isolated smaller populations that are more vulnerable to hurricane impacts (Table 2).

Local population extinction is most likely to occur following severe hurricanes. In such situations, FWS agreed that significant habitat recovery would be required before translocation of ABM into the area would be attempted. Workshop participants chose to model translocation with the requirement that the habitat (carrying capacity) of the recipient population must have recovered to at least 80% of its maximum (original) value before translocation could occur. To evaluate the effect of this requirement, additional scenarios were run for which translocation could occur when $K \geq 0.50K_{\max}$ and $K \geq 0.20K_{\max}$. The choice of whether to translocate after 80%, 50%, or 20% recovery of the habitat after a catastrophe made very little difference to the probability of metapopulation extinction. However, there was a trend toward lower extinction probabilities with earlier intervention (Table 3).

Table 3. Probability of metapopulation extinction over 100 years in the three management scenarios with and without translocation.

Translocation method	Scenario		
	Interconnected	Isolated	Public Only
No translocation	0.268	0.412	0.468
$K \geq 0.80K_{\max}$	0.260	0.360	0.430
$K \geq 0.50K_{\max}$	0.261	0.349	0.415
$K \geq 0.20K_{\max}$	0.255	0.349	0.408

Legend for Table 4:

PE = the probability that the population is extinct after 100 years, estimated from the proportion of simulation iterations in which the population did not have mice of both sexes.

SE(PE) = standard error of probability of extinction (measure of precision)

Mean N = mean population size projected at the end of 100 years for those populations that did not go extinct

SD(N) = standard deviation of final N across iterations (measure of variability)

SE(N) = standard error of mean N (measure of precision)

GD = mean gene diversity (expected heterozygosity) at 100 years, as a proportion of the initial diversity

Median Time to Extinction = median year at which the population first goes extinct (blank if the population goes extinct in fewer than 50% of the iterations). Note that often locally extinct populations are later recolonized.

Table 4. Results for each model unit and the metapopulation after 100 years for all scenarios.

Model Unit	PE	SE(PE)	Mean N	SD(N)	SE(N)	GD	Median TE
Interconnected Populations							
Fort Morgan	0.418	0.011	662	579	13	0.57	88
Single Family	0.339	0.011	2089	2050	46	0.61	139
Multi-Family	0.276	0.010	1062	838	19	0.65	649
Perdue	0.274	0.010	3212	2343	52	0.65	0
West Beach	0.339	0.011	441	390	9	0.61	37
Gulf St. Park	0.999	0.001	491	141	3	0.00	24
Metapopulation	0.268	0.010	7053	5738	128	0.66	0
Isolated Populations							
Fort Morgan	0.998	0.001	1071	646	14	0.24	87
Single Family	0.996	0.001	2401	2490	56	0.29	87
Multi-Family	0.819	0.009	1099	799	18	0.37	505
Perdue	0.465	0.011	3230	2365	53	0.64	0
West Beach	1.000	0.000	92	0	0	0.39	23
Gulf St. Park	1.000	0.000	0	0	0	0.00	24
Metapopulation	0.412	0.011	3297	2653	59	0.62	0
Public Lands Only							
Fort Morgan	0.995	0.002	721	607	14	0.15	79
Perdue	0.470	0.011	3220	2322	52	0.65	0
Gulf St. Park	1.000	0.000	46	0	0	0.00	24
Metapopulation	0.468	0.011	3218	2327	52	0.65	0
Interconnected Populations with Translocation (at $K \geq 0.80K_{max}$)							
Fort Morgan	0.411	0.011	643	590	13	0.57	100
Single Family	0.326	0.010	1912	1970	44	0.61	127
Multi-Family	0.270	0.010	988	809	18	0.65	711
Perdue	0.266	0.010	3093	2312	52	0.66	0
West Beach	0.328	0.010	415	394	9	0.61	36
Gulf St. Park	0.580	0.011	318	213	5	0.51	23
Metapopulation	0.260	0.010	6855	5742	128	0.66	0
Isolated Populations with Translocation (at $K \geq 0.80K_{max}$)							
Fort Morgan	0.602	0.011	758	595	13	0.49	87
Single Family	0.595	0.011	2511	2125	48	0.52	100
Multi-Family	0.453	0.011	1115	834	19	0.44	491
Perdue	0.416	0.011	3262	2374	53	0.64	0
West Beach	1.000	0.000	0	0	0	0.00	23
Gulf St. Park	0.658	0.011	328	205	5	0.49	24
Metapopulation	0.360	0.011	6170	5525	124	0.63	0
Public Lands Only with Translocation (at $K \geq 0.80K_{max}$)							
Fort Morgan	0.617	0.011	782	594	13	0.46	102
Perdue	0.432	0.011	3308	2327	52	0.64	0
Gulf St. Park	0.657	0.011	327	203	5	0.49	24
Metapopulation	0.430	0.011	4023	2941	66	0.64	0

Summary of PVA Results

The best available data and expert knowledge were used to revise the ABM *Vortex* model and to project the viability of ABM populations under current and potential future development/erosion scenarios. Given current ABM population status and habitat availability, the Alabama beach mouse has about a 27% risk of metapopulation extinction over the next 100 years. Mean size of surviving populations average about 38% of estimated carrying capacity, but tend to fluctuate widely over time. After 100 years inbreeding accumulates to a population level greater than that of one generation of full-sib mating. However, it must be noted that 100 years is approximately 205 generations. *Vortex* does not model mutational input, which could be substantial for a population with an effective population size as large as that estimated for the ABM metapopulation (approximately 250) over 200 generations.

Much of the extinction risk is due to the impact of hurricanes on ABM populations and habitat, which can result in relatively frequent and severe population declines. The habitat mosaic utilized by beach mice may help to buffer storm impacts by providing refugia for a portion of the population, and the high reproductive potential of the species makes it possible for the population to rebound as new habitat is regenerated. The connectivity of ABM habitat areas provides the opportunity for mice to recolonize heavily impacted areas following storms. The Perdue Unit of Bon Secour National Wildlife Refuge is likely to act as a core source population for ABM, providing a large, central population protected on public land that can augment ABM subpopulations to the east and west. In contrast, ABM are faced with almost certain extinction in the isolated habitat of Gulf State Park.

Land development can lower ABM viability by reducing habitat and exacerbating the effects of hurricanes by reducing high elevation refugia. Land development can also lower viability by reducing connectivity among habitat patches. Modeling the same six model units as contained in the baseline model (Fort Morgan, Single Family, Multi-Family, Perdue, West Beach, and Gulf State Park), but without the possibility of ABM movement among the units, increased the risk of extinction of the metapopulation significantly to $41.2\% \pm 1.1\%$ (from 26.8%). Mean population size of the surviving metapopulations without migration is $< 50\%$ of that of the interconnected (baseline) model and the remaining gene diversity is about 62% of that in the starting population.

A more extreme form of habitat loss potentially facing ABM is the total loss of private lands as suitable habitat, limiting the species to public lands in the Fort Morgan, Perdue, and Gulf State Park model units with no migration possible among the units. This leads to a further significant, but more modest, increase in the probability of metapopulation extinction to $46.8\% \pm 1.1\%$.

Translocation of mice from habitat patches where the population persists to patches where they are extinct should help to reduce overall extinction risk of the metapopulation. Translocation, as modeled here, had a relatively small but positive and statistically significant effect on extinction risk. For the baseline model (where natural migration could occur), the effects of translocation were (not surprisingly) non-significant and the estimated risk of metapopulation extinction was $25.5\% \pm 1.0\%$ (as opposed to 26.8% without translocation). In the Isolated Populations scenario, the probability of metapopulation extinction with translocation was $34.9\% \pm 1.1\%$ (as opposed to

41.2% without translocation). In the Public Lands Only scenario, the probability of metapopulation extinction with translocation was $40.8\% \pm 1.1\%$ (as opposed to 46.8% without translocation). In both cases where there was no natural ABM movement, the probability of metapopulation extinction was ameliorated by the addition of translocation. However, translocation as modeled here was never as efficient as natural rates of migration in rescuing the metapopulation from extinction. Repeated translocations, from multiple donor populations, will likely be necessary to maintain a similar risk of metapopulation extinction for the ABM in the absence of natural habitat corridors.

Caveat Regarding Results of Simulation Modeling

General Caveats to Any Model

The results presented in this report provide general indications about the expected population performance and those factors that have the greatest impact on population projections and viability. The accuracy of this result will depend on the accuracy of the values that were put into the model. For many of the model parameters, available data allow only approximate estimates of the true values. Thus, simulation results can be misleading regarding the most likely fate of a population. However, even if the mean prediction from a model is biased because of inaccurate values of some parameters describing the species biology or habitat, comparisons among models that change one or a few parameters (such as a test of the effect of a loss of some habitat) would still be expected to provide robust estimates of the relative shift in extinction probabilities or mean population size.

Even if mean results are accurate, the *mean* result of a model does not guarantee that the actual outcome in nature or in any one simulation will closely approximate that mean result. The high fluctuations in the ABM populations and the great variability among iterated simulations indicate that there is great inherent uncertainty in the future fate of the populations of beach mice. Thus, although the model estimates the probability of extinction to be, for example, $27\% \pm 1\%$, the real population either will go extinct or it will persist for the specified time period. Similarly, in many of the scenarios tested, the standard deviation in population size among iterations was of approximately the same magnitude as the mean population size.

Caveats Related to Impacts Not Modeled

As mentioned repeatedly, hurricanes are the major driving force in models of Alabama beach mouse population dynamics. Hurricanes are widely expected to increase in intensity (i.e., higher proportions of Category 4 and 5 hurricanes), and some believe in general frequency and duration as well (e.g., Webster *et al.* 2005). Because the frequency of strong hurricanes (Categories 3-5) has such a disproportional impact on the probability of extinction in the ABM metapopulation, increases in the frequency of those storms will undoubtedly increase the risk of total extinction of the Alabama beach mouse. It should be noted that the frequency of hurricanes is cyclical and autocorrelations in environmental stochasticity (i.e., bad years are more likely to be followed by bad years) generally increases the risk of extinction (e.g., Reed *et al.* 2003).

A second potential threat, not modeled, is habitat loss due to the spread of cogongrass (*Imperata cylindrica*). This invasive species, originally from Southeast Asia, was designated as the seventh worst weed in the world. Cogongrass has been steadily spreading across Alabama and

Mississippi, ruining habitat for endangered species and muscling out native plants. Treatments against cogongrass are expensive and ineffective. A third threat is potential high mortality rates imposed by predation from domestic cats. None of the scenarios in this revised PVA includes the effects of increased hurricane frequency and/or intensity, the spread of cogongrass, or predation by domestic cats; however, it should be recognized that all three factors represent potentially significant threats to ABM persistence.

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PVA Workshop Participant List

Barbara Allen
USFWS
1208-B Main Street
Daphne, AL 36526
barbara_allen@fws.gov

Michelle Clendenin
USFWS
1208-B Main Street
Daphne, AL 36526
michelle_clendenin@fws.gov

Dave Flemming
USFWS
1875 Century Blvd, Suite 200
Atlanta, GA 30345
Dave_Flemming@fws.gov

Larry Goldman
USFWS
1208-B Main Street
Daphne, AL 36526
larry_goldman@fws.gov

Mike Groutt
USFWS
1208-B Main Street
Daphne, AL 36526
mike_groutt@fws.gov

Darren LeBlanc
USFWS
1208-B Main Street
Daphne, AL 36526
Darren_LeBlanc@fws.gov

Will McDearman
USFWS
6578 Dogwood View Pkwy
Jackson, MS 39213
will_mcdearman@fws.gov

Lori McNease
USFWS
1208-B Main Street
Daphne, AL 36526
lori_mcnease@fws.gov

Jereme Phillips
BSNWR
12295 St. Hwy. 180
Gulf Shores, AL 36542
jereme_phillips@fws.gov

Jodie Smithem
USFWS
1208-B Main Street
Daphne, AL 36526
Jodie_Smithem@fws.gov

Sandra Sneckenberger
USFWS
1601 Balboa Ave
Panama City, FL 32405
sandra_sneckenberger@fws.gov

Elaine Snyder-Conn
USFWS
1208-B Main Street
Daphne, AL 36526
Elaine_Snyder-Conn@fws.gov

Rob Tawes
USFWS
1208-B Main Street
Daphne, AL 36526
robert_tawes@fws.gov

Aaron Valenta
USFWS
1875 Century Blvd, Suite 200
Atlanta, GA 30345
aaron_valenta@fws.gov