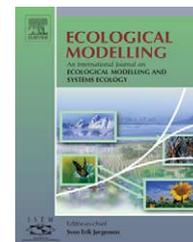


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The role of dispersal in Florida Key deer metapopulation dynamics

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ABSTRACT

Metapopulation dynamics of species that occur in patchy or island subpopulations are an important consideration in the conservation of endangered species. Key deer (*Odocoileus virginianus clavium*) are endemic to the Florida Keys and occur on 11 island-complexes in the Lower Keys from Big Pine Key to Sugarloaf Key. While deer numbers have increased notably, the majority of the population occurs on two of the islands, Big Pine and No Name Keys. Deer dispersal between islands is possible due to short distances between islands and shallow water. Key deer have been documented to actively disperse between islands but at very low rates (11% males, 3% females). However, increased population densities could possibly increase dispersal rates as island populations on Big Pine and No Name Keys approach carrying capacity. We examined the probability of deer colonization of peripheral islands using a sex- and stage-structured metapopulation model. Our objectives were to (1) evaluate the effects of distance and dispersal rate on Key deer island subpopulations and (2) estimate the probability of Key deer colonizing surrounding islands with viable populations. Results suggest that over the next 20 years, the Key deer population could colonize 6 of the 11 island-complexes with viable populations. However, of the remaining five islands, three lack the resources to support a minimum viable population, and while Cudjoe and Sugarloaf Keys have the potential to support >200 deer each, they are not projected to increase to above 50 deer by 2021 regardless of dispersal rate due to distance from source population.

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1. Introduction

Metapopulation theory is commonly applied in the understanding and conservation of endangered species by wildlife conservationists. A metapopulation is a collection of local populations occupying separate patches of habitat in a landscape linked by emigration and immigration (Levin, 1979; Meffe and Carroll, 1997). Though the concept of metapopulation has been studied in the past (e.g., Howe et al., 1991;

Rolstad, 1991; Wootton and Bell, 1992; Akçakaya et al., 1995; Dias, 1996; Donovan et al., 1995; Hanski, 1997), few studies have evaluated the metapopulation dynamics of large and long-lived animals (Beier, 1993; Doak, 1995; Harrison and Taylor, 1997; Gaona et al., 1998; Walters, 2001), particularly in landscapes fragmented due to urban development. Landscape fragmentation and habitat deterioration typically result in the establishment of new metapopulations with varying rates of movement between subpopulations (Hanski, 1997).

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34 The rate of emigration and immigration between subpopulations depends on the species ability to disperse and the
 35 juxtaposition of patches. Dispersal plays an important role in
 36 the metapopulation dynamics of a species, and can be altered
 37 with dramatic landscape changes (e.g., urban development).
 38

39 The Florida Keys archipelago is a collection of island habitat
 40 patches occupied by the endangered Florida Key deer. Previous
 41 researchers have described the Key deer as a metapopulation
 42 comprised of local island subpopulations in the Lower Florida
 43 Keys (Lopez, 2001). Deer dispersal between islands is possible
 44 due to short distances and shallow water; however, little is
 45 known about the role of dispersal in the Key deer population.
 46 Lopez (2001) reported that Key deer actively dispersed between
 47 Big Pine and No Name Keys but at very low rates (11% males,
 48 3% females; Lopez, 2001). It is unknown whether Key deer dis-
 49 perse to other islands or at what rates. Understanding Key
 50 deer dispersal and its effects on the dynamics of the metapop-
 51 ulation is essential for the management of this endangered
 52 species. For example, the colonization of peripheral islands is
 53 a necessary step in the recovery of Key deer (USFWS, 1999). By
 54 modeling Key deer metapopulation dynamics, we examined
 55 the possibility of future colonizations under various dispersal
 56 scenarios.

57 Social animals, such as white-tailed deer, form matrilineal
 58 groups where females remain in their natal area. While previ-
 59 ous research has shown varying degrees of male deer disper-
 60 sal, female dispersal is usually rare, even during times of high
 61 population density and low reproductive fitness (Greenwood,
 62 1980; Halls, 1984; Clutton-Brock et al., 1985; Lopez, 2001). How-
 63 ever, Albon et al. (1992) studied an island metapopulation of
 64 red deer and found that as population density increased, fam-
 65 ily bonds began to break down and dispersal increased. Other
 66 research has suggested that Key deer lack strong philopatry
 67 (family ties) exhibited by other white-tailed deer due to the
 68 absence of predators and migration (Hardin et al., 1976) and
 69 these weaker social bonds may enhance dispersal of Key deer
 70 to other islands. Thus, we examined the effects of various
 71 dispersal scenarios on Key deer metapopulation dynamics.
 72 Specifically, we evaluated the probability of deer coloniza-
 73 tion of peripheral islands using a sex- and stage-structured
 74 metapopulation model. Our objectives were to (1) evaluate the

75 effects of dispersal rates on Key deer island subpopulations
 76 and (2) estimate the probability of Key deer colonizing sur-
 77 rounding islands with viable populations.

2. Background information

78 Endangered Key deer are endemic to the Florida Keys and
 79 occur on 11 island-complexes in the Lower Florida Keys from
 80 Big Pine Key to Sugarloaf Key (Fig. 1) (Hardin et al., 1984). An
 81 island-complex is a collection of islands in close proximity
 82 to each other separated by shallow waters. Islands within a
 83 complex are “bridged” together during low tides (i.e., sea bot-
 84 tom is exposed), thus, can be considered to be a functionally
 85 single island (Folk, 1992). The majority of Key deer (approx-
 86 imately 75%) reside on Big Pine and No Name Key (Lopez,
 87 2001). Over the last 30 years, Big Pine and No Name Keys have
 88 experienced a 10-fold increase in human population growth
 89 and urban development (Monroe County Growth Management
 90 Division, 1992). Urban development and its associated risks
 91 are considered the greatest threat to Key deer (Lopez et al.,
 92 2003). Key deer are also at risk to environmental catastrophes
 93 such as hurricanes (Lopez et al., 2000). While the Key deer
 94 populations on these two islands have increased, the majority
 95 of the metapopulation occupies a small geographic area. The
 96 establishment of additional deer populations on other islands
 97 is a management goal of the U.S. Fish and Wildlife Service
 98 (USFWS) and a necessary step in Key deer recovery (USFWS,
 99 1999).

3. Model overview

100 The model represents the dynamics of the Key deer metapop-
 101 ulation in the 11 island-complexes of the Florida Keys. The
 102 model consists of 11 submodels (one for each island-complex).
 103 The model parameters are based on the estimates from the
 104 main island, Big Pine Key. Each submodel is identical to the
 105 main model except for the initial population abundance and
 106 carrying capacity. The model is driven by the dispersal rate of
 male and female yearling and adult deer from the main island.



Fig. 1 – Map of the Lower Florida Keys, Florida.

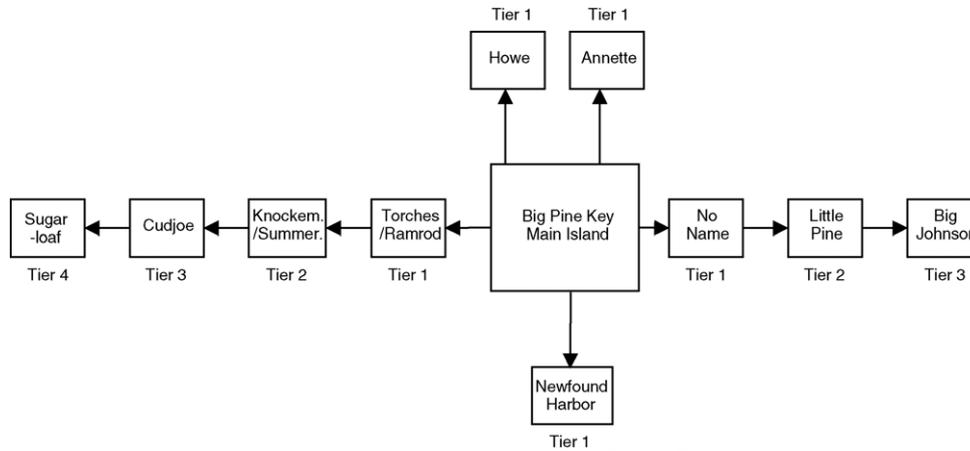


Fig. 2 – Conceptual model representing the dispersal routes of Key deer among the 11 island-complexes in the Lower Florida Keys.

107 Dispersal rates for each of these sex and stage classes are held
 108 constant for all 11 island-complexes. Dispersal from the main
 109 island, Big Pine Key, flows out to the five island-complexes
 110 surrounding it in a “stepping-stone” fashion following a tier-
 111 system (Fig. 2). Dispersal between tiers can only occur in suc-
 112 cessive, ascending fashion (i.e., dispersal from tier 1 would
 113 occur to tier 2 followed by tier 3, etc.).

4. Model description

114 The metapopulation model was developed as a stochastic
 115 compartment model based on difference equations ($\Delta t=1$
 116 year) and consists of 11, structurally identical, submodels,
 117 each representing a sex- and age-structured subpopulation for
 118 each island-complex:

$$119 N_{i,j,t+1} = N_{i,j,t} + (n_{j,t} - m_{i,j,t} - e_{i,j,t} - r_{i,j,t}) \times \Delta t, \quad \text{for } i = 0 \quad (1)$$

$$121 N_{i,j,t+1} = N_{i,j,t} + (r_{i-1,j,t} - i_{i-1,j,t} - m_{i,j,t} - e_{i,j,t} - r_{i,j,t}) \\ 122 \times \Delta t, \quad \text{for } i > 0 \quad (2)$$

124 where $N_{i,j,t}$ represents the number of females ($j=1$) or males
 125 ($j=2$) in age class i at the beginning of time t ; $n_{j,t}$ the number of
 126 females or males born into age class 0 during time t ; and $m_{i,j,t}$,
 127 $e_{i,j,t}$, $i_{i,j,t}$, and $r_{i,j,t}$ represent the number of females or males in
 128 age class i dying, emigrating from the island, immigrating to
 129 the island, and remaining on the island, respectively, during
 130 time t .

4.1. Natality

132 We initially assumed a sex ratio at birth of 41% females and
 133 59% males (Hardin, 1974), and a mean maximum natality rate
 134 ($k_{1,max}$) of 1.05 fawns per reproductively mature female per
 135 year, including yearlings (1–2 years old) and adults (≥ 2 years
 136 old) (Hardin, 1974); Key deer fawns (<1 year old) are not repro-
 137 ductively active (Hardin, 1974; Folk and Klimstra, 1991). We

then represented natality as:

$$n_{j,t} = \sum_{i=2}^{i=2} (0.41 \times k_{1,t}) \times N_{i,1,t}, \quad \text{for } j = 1 \quad (3)$$

$$n_{j,t} = \sum_{i=2}^{i=2} (0.59 \times k_{1,t}) \times N_{i,1,t}, \quad \text{for } j = 2 \quad (4)$$

141 where $k_{1,t}$ represents a stochastic, density-dependent natal-
 142 ity rate (fawns born per reproductively mature female per
 143 year); the mean value of $k_{1,t}$ is equal to $k_{1,max}$ until the island-
 144 complex deer population reaches K , and then decreases lin-
 145 early from $k_{1,max}$ to 0 as the population increases from K to
 146 $2 \times K$ (Table 1). Each year of simulated time, the value of $k_{1,t}$
 147 for each island-complex is drawn randomly from a normal
 148 distribution (truncated at 0 and 1) (Akçakaya, 1991; Grant et
 149 al., 1997) generated by the density-dependent mean value
 150 of $k_{1,t}$ and a standard deviation of mean natality rate calcu-
 151 lated from data in Hardin (1974, p. 156). Estimates of K were
 152 obtained following the methodology used previously for No
 153 Name and Big Pine Keys (Lopez, 2001; Lopez et al., 2004b);
 154 each island-complex was classified into 6 habitat types using dig-
 155 ital vegetation coverages, the area (ha) of each habitat type
 156 was multiplied by the corresponding Key deer habitat selec-
 157 tion ratio (a weighting factor based on relative deer use),
 158 and carrying capacity was estimated as the sum of these
 159 values.

4.2. Mortality

161 Estimates of age- and sex-specific mortality rates were based
 162 on survival estimates (proportion of individuals surviving to
 163 the next age class, $k_{2,i,j}$) obtained from Key deer studies con-
 164 ducted on Big Pine and No Name Keys (Hardin, 1974; Silvy,
 165 1975; Lopez, 2001) (Table 2). Survival estimates for yearlings
 166 and adults were calculated from radiocollared animals using a
 167 known-fate model (Program MARK, White and Burnham, 1999;
 168 Lopez, 2001); fawn survival was estimated by adjusting the
 169 model-fitted estimates to compensate for presumed overesti-

Table 1 – Carrying capacities (K) of the 11 island-complexes estimated following the methodology used previously for No Name and Big Pine Keys (Lopez, 2001; Lopez et al., 2004b)

Tier (island-complex)	Deer carrying		
	Area (ha)	Capacity (K)	Deer Density
Main			
Big Pine	2549	517	406
Tier 1			
Annette	222	26	6
Howe	373	50	16
Newfound Harbor	76	12	10
No Name	471	90	78
Torches/Ramrod	1714	287	94
Tier 2			
Knockemdown/Summerland	1019	155	8
Little Pine	382	61	16
Tier 3			
Big Johnson	154	19	0
Cudjoe	1319	217	6
Tier 4			
Sugarloaf	1399	224	6

Also presented are areas and estimates of Key deer abundance in the year 2001 (Lopez et al., 2004a; R. Lopez, unpublished data). Island-complexes are classified into tiers based on distance from Big Pine Key.

170 mation due to small sample sizes (Lopez, 2001, p. 160).

171 Each year of simulated time, a value for each k_{2ij} is drawn
 172 randomly from the normal distribution (truncated at 0 and
 173 1) (Akçakaya, 1991; Grant et al., 1997) generated by the mean
 174 and standard error corresponding to that age- and sex-class
 175 (Table 2).

176 Thus,

$$177 m_{i,j,t} = (1 - k_{2ij}) \times N_{i,j,t} \quad (5)$$

178 4.3. Emigration and immigration

179 Estimates of age- and sex-specific emigration rates (proportion
 180 of individuals leaving the island-complex per year, k_{3ij}) were

181 based on estimates of dispersal from Big Pine to No Name Key
 182 (Lopez, 2001) (Table 2). Each year of simulated time, a value
 183 for each k_{3ij} is drawn randomly from the normal distribution
 184 (truncated at 0) generated by the mean and standard deviation
 185 corresponding to that age- and sex-class (Table 2).

186 Thus,

$$187 e_{i,j,t} = k_{3ij} \times N_{i,j,t} \quad (6)$$

188 Estimates of age- and sex-specific immigration ($i_{i,j,t}$) to the dif-
 189 ferent island-complexes were based on geographical location
 190 and the assumption that all emigrating individuals move away
 191 from Big Pine Key. Big Pine is the main source population and
 192 is the only population that disperses to more than one other

Table 2 – Estimates of age- and sex-specific survival and natality rates for Key deer on Big Pine and No Name Keys (Hardin, 1974; Silvy, 1975; Lopez, 2001), and estimates of age- and sex-specific emigration rates for Key deer moving from Big Pine to No Name Key (Lopez, 2001)

Sex (j) age class ^a (i)	Mean (S.E.) survival (prop. surviving per year)	Mean (S.D.) emigration (prop. emigrating per year)	Mean (S.D.) natality ^b (births per doe per year)
Female (j = 1)			
Fawn (i = 0)	0.470 (0.061)	0.000 (0.000)	0.000 (0.000)
Yearling (i = 1)	0.824 (0.071)	0.032 (0.047)	1.100 (0.300)
Adult (i = 2)	0.842 (0.030)	0.032 (0.047)	1.100 (0.300)
Male (j = 2)			
Fawn (i = 0)	0.470 (0.061)	0.000 (0.000)	0.000 (0.000)
Yearling (i = 1)	0.569 (0.089)	0.107 (0.056)	0.000 (0.000)
Adult (i = 2)	0.597 (0.054)	0.107 (0.056)	0.000 (0.000)

^a Age classes defined as fawn (0–1 year), yearling (1–2 years), and adult (≥ 2 years).

^b Model adjusted mean natality for female yearlings and adults based on model calibration and actual deer population growth estimates (Lopez et al., 2004a). Standard deviation based on age-specific female natality reported by Hardin (1974, p. 156).

193 island-complex. Individuals emigrating from Big Pine are dis-
 194 tributed among adjoining (tier 1) island-complexes (Fig. 2); No
 195 Name, Newfound Harbor, and Howe each received 25% of the
 196 Big Pine emigrants ($i_{i,j,t} = 0.25 \times e_{i-1,j,t}$) because of their close
 197 proximity, and Torches and Annette each received 12.5% of
 198 the Big Pine emigrants ($i_{i,j,t} = 0.125 \times e_{i-1,j,t}$) because of their
 199 further distance from Big Pine. All emigrants from island-
 200 complexes other than Big Pine are immigrants ($i_{i,j,t} = e_{i-1,j,t}$)
 201 to the island-complex in the next tier to which they are con-
 202 nected (Fig. 2).

203 The number of individuals in each age- and sex-class
 204 remaining on the same island-complex (and advancing age
 205 class $i + 1$) during time t is calculated as:

$$206 \quad r_{i,j,t} = N_{i,j,t} - m_{i,j,t} - e_{i,j,t}. \quad (7)$$

5. Model calibration

207 We calibrated the model by adjusting the mean maximum
 208 natality rate ($k1_{max}$) such that simulated population growth
 209 on Big Pine Key from 1971 to 2001 compared favorably with
 210 field estimates of population size (167 individuals in 1971 and
 211 406 individuals in 2001; Lopez et al., 2004a). We calculated
 212 mean simulated population size in 2001 based on 120 replicate
 213 stochastic (Monte Carlo) simulations, which were sufficient to
 214 detect a difference of 30 deer in the metapopulation and 2 deer
 215 in the smallest island-complex populations (Annette, Cudjoe,
 216 Sugarloaf Keys) at $\alpha = 0.05$ (Grant et al., 1997); we initialized
 217 each simulated population at 167 individuals in 1971. As ini-
 218 tially parameterized ($k1_{max} = 1.05$), the model underestimated
 219 observed population size (a simulated mean of 331 versus the
 220 field estimate of 406 individuals). Setting $k1_{max}$ at 1.10, 1.15,
 221 and 1.20 resulted in simulated population sizes of 405, 475,
 222 and 528, respectively; thus, we set $k1_{max}$ at 1.10 for subsequent
 223 simulations.

6. Population projections

6.1. Experimental design model parameterization

224 To evaluate the effect of dispersal rates on the Florida Key deer
 225 population, we projected metapopulation dynamics over the
 226 20-year period from 2001 to 2021 under three scenarios assum-
 227 ing (1) low ($f = 0, m = 0$), (2) medium ($f = 0.03, m = 0.11$), and (3)
 228 high ($f = 0.06, m = 0.22$) dispersal rates; the “medium” rates are
 229 those reported by Lopez (2001) and the “high” rates are dou-
 230 ble the “medium” rates. For each scenario, we ran 120 Monte
 231 Carlo simulations.
 232

233 Initial abundances in 2001 were determined from mark-
 234 resight estimates based on 247 road count surveys conducted
 235 from 1998 to 2001 on Big Pine Key (Lopez et al., 2004a). Initial
 236 densities on the other islands were estimated using trip cam-
 237 eras and Lincoln–Peterson mark-recapture statistics (R. Lopez,
 238 unpublished data). A stable age distribution was assumed for
 239 the Big Pine Key population and the other island populations
 240 were proportionally divided into each sex- and stage-class
 241 (0.125 for female and male fawns and yearlings and 0.25 for
 female and male adults) (Table 1).

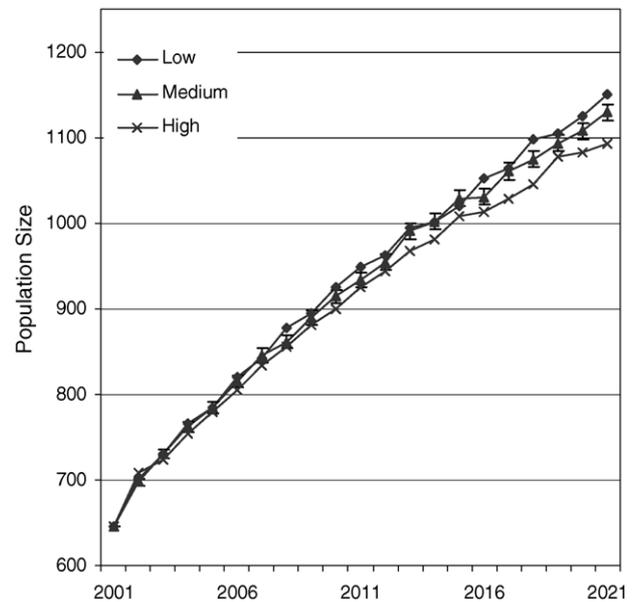


Fig. 3 – Model projected Key deer metapopulations under three dispersal scenarios (low, $f = 0, m = 0$; medium, $f = 0.03, m = 0.11$; and high, $f = 0.06, m = 0.22$) in the Lower Florida Keys, 2001–2021. Vertical bars represent ± 1 S.E. of the mean, based on 120 replicate stochastic simulations under medium dispersal.

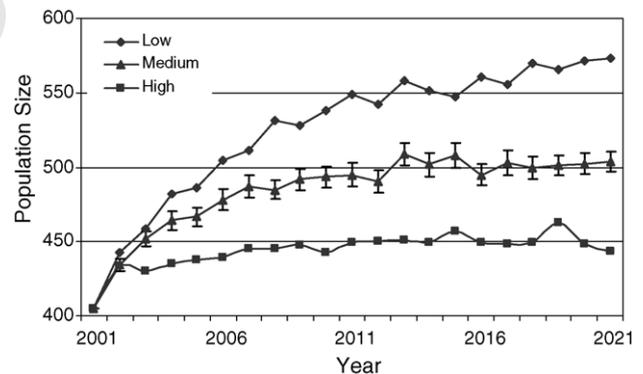


Fig. 4 – Model projected Big Pine Key deer populations under three dispersal scenarios (low, $f = 0, m = 0$; medium, $f = 0.03, m = 0.11$; and high, $f = 0.06, m = 0.22$) in the Lower Florida Keys, 2001–2021. Vertical bars represent ± 1 S.E. of the mean, based on 120 replicate stochastic simulations under medium dispersal.

6.2. Simulation results

242 The model predicted an increase in the total metapopulation
 243 under each scenario with low dispersal producing the highest
 244 population increase and high dispersal producing the smallest
 245 increase (Fig. 3). Big Pine Key (where the majority of the Key
 246 deer population resides) also increased under each dispersal
 247 scenario (Fig. 4). Big Pine Key deer density was projected at
 248 111% K with low dispersal, 98% K with medium dispersal, and
 249 86% K with high dispersal.
 250

251 In analyzing model results, we defined a viable island popu-
 252 lation as ≥ 50 deer. We chose 50 as the minimum viable popu-

Table 3 – Model projected Key deer populations for each island-complex under three dispersal scenarios (low, $f = 0$, $m = 0$; medium, $f = 0.03$, $m = 0.11$; and high, $f = 0.06$, $m = 0.22$) in the Lower Florida Keys, 2001–2021

Tier (island-complex)	Low dispersal			Medium dispersal			High dispersal		
	Mean	S.D.	% of K^a	Mean	S.D.	% of K^a	Mean	S.D.	% of K^a
Main									
Big Pine	573	77.6	111	504	76.1	98	443	74.9	86
Tier 1									
Annette	14	3.9	54	18	3.8	68	19	3.1	72
Howe	64	9.0	128	65	8.9	131	65	8.8	130
Newfound Harbor	20	3.8	169	21	4.2	178	22	4.2	184
No Name	110	17.3	123	108	14.2	121	103	15.8	115
Torches/Ramrod	214	52.3	74	205	43.2	72	194	37.5	68
Tier 2									
Knockemdown/Summerland	43	18.4	28	70	20.4	45	92	26.7	59
Little Pine	67	12.1	109	75	10.5	123	76	10.5	125
Tier 3									
Big Johnson	7	6.4	35	22	6.7	115	28	4.5	149
Cudjoe	19	8.1	9	21	8.1	10	30	13.4	14
Tier 4									
Sugarloaf	19	7.6	9	19	8.7	9	19	7.5	9
Metapopulation	1150	107.4	n/a	1129	105.6	n/a	1092	113.0	n/a

^a K , island carrying capacity; percentages >100 are due to demographic stochasticity.

lation size because, historically, it is the lowest known Key deer population size which resulted in an increase (Dickson, 1955). We defined a successful colonization as having a deer population at $\geq 50\%$ K . Model results varied based on the input dispersal scenario (Table 3). Number of successful colonizations and viable populations, respectively, by dispersal scenario were as follows: low 7 and 5; medium 8 and 6; and high 9 and 6.

To evaluate the risk of quasi-extinction, we calculated the probability of each island-complex having <50 deer during each timestep (2001–2021) and under each dispersal scenario (low, medium, and high). Big Pine, No Name, and Torches/Ramrod had 0% probability of dropping below 50 deer under all dispersal scenarios from 2001 to 2021. Newfound

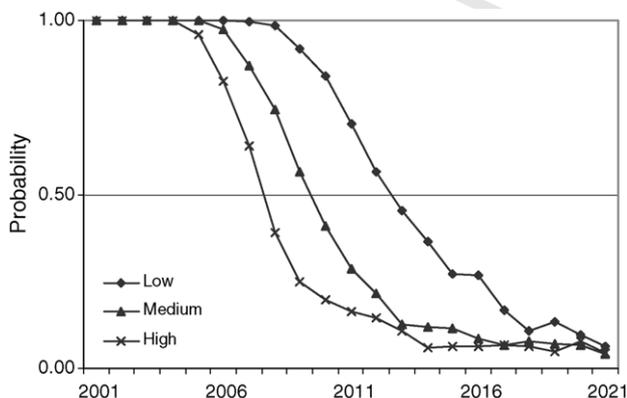


Fig. 5 – Model projected probability of Howe Key (tier 1, Fig. 2) dropping below 50 Key deer under three dispersal scenarios (low, $f = 0$, $m = 0$; medium, $f = 0.03$, $m = 0.11$; and high, $f = 0.06$, $m = 0.22$) in the Lower Florida Keys, 2001–2021.

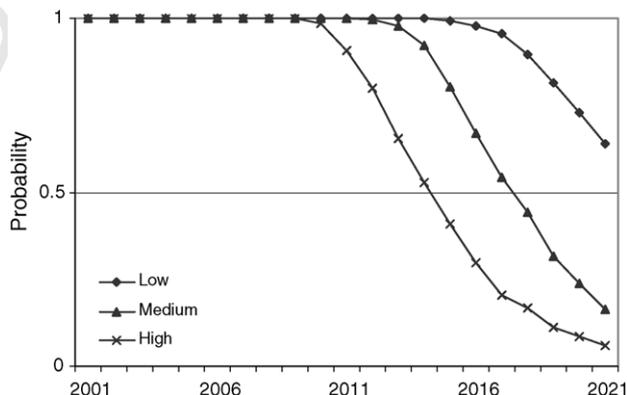


Fig. 6 – Model projected probability of Knockemdown/Summerland Complex (tier 2, Fig. 2) dropping below 50 Key deer under three dispersal scenarios (low, $f = 0$, $m = 0$; medium, $f = 0.03$, $m = 0.11$; and high, $f = 0.06$, $m = 0.22$) in the Lower Florida Keys, 2001–2021.

Harbor, Annette, Big Johnson, Cudjoe, and Sugarloaf had a 100% probability of dropping below 50 deer under all dispersal scenarios. Howe, Knockemdown/Summerland, and Little Pine had variable probabilities of dropping below 50 deer depending on dispersal scenario (Figs. 5–7).

7. Discussion

The ability of Key deer to swim between islands has been documented (Hardin, 1974; Silvy, 1975; Lopez, 2001). Lopez (2001) reported two translocated Key deer swam a 2.4-km channel between Little Pine and No Name Keys. Key deer dispersal

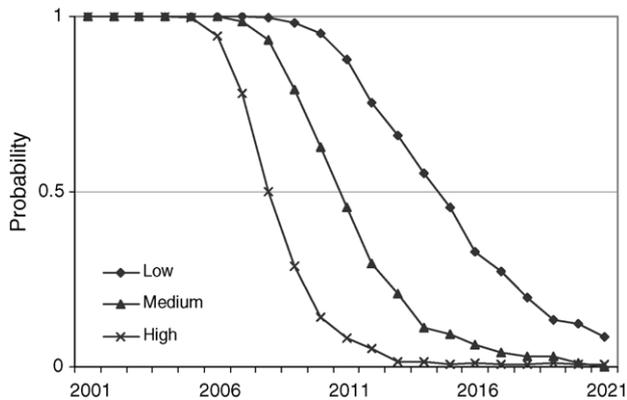


Fig. 7 – Model projected probability of Little Pine Key (tier 2, Fig. 2) dropping below 50 Key deer under three dispersal scenarios (low, $f=0$, $m=0$; medium, $f=0.03$, $m=0.11$; and high, $f=0.06$, $m=0.22$) in the Lower Florida Keys, 2001–2021.

support a deer population ≥ 50 deer based on our estimate of carrying capacity. Because of the low deer densities that these islands (Big Johnson, Annette, and Newfound Harbor) could support, they are considered supporting islands which can contribute habitat resources and genetic migration during times of hardship. The remaining eight islands can or do support viable deer populations according to our estimates. Big Pine, No Name, and Torches/Ramrod each had initially estimated deer populations ≥ 50 in 2001. Under the medium dispersal scenario, Howe, Knockemdown/Summerland, and Little Pine island-complexes were projected to increase to viable populations (≥ 50). Under high dispersal, no other island-complexes were projected to increase to viable populations in 20 years. Furthermore, all model simulations suggest that Cudjoe and Sugarloaf will have low deer densities (< 50) despite their relatively high carrying capacities (217 and 224, respectively). Projected populations for Cudjoe (tier 3) and Sugarloaf (tier 4) were similar under all dispersal scenarios (Table 3) suggesting that dispersal rate (whether low, medium, or high) will have little effect on population size and that distance from the main island (tier level) and the size of intermediate islands will have the greatest effect on population size within the 20-year timeframe of the model.

Model projections suggest that the tier of islands extending to the northeast from the main island (Big Pine Key) will reach K carrying capacity within the next 20 years (Fig. 8). However, the small size of these islands indicates that only two of these islands will be able to support viable deer populations. Further, we estimate that the northeast tier as a whole can support < 200 deer while the southwest tier can support over five times as many deer (Table 1). The high K carrying capacity and geographic location of the southwest tier of island-complexes make it the most logical choice for focusing future Key deer conservation efforts (Fig. 8). While model results suggest that deer populations on the Torches/Ramrod and Knockemdown/Summerland island-complexes will increase to viable populations by 2021, deer populations on the furthest islands, Cudjoe and Sugarloaf Keys, will not (Fig. 8). The potential benefits of establishing additional Key deer populations on Cudjoe and Sugarloaf Keys, are numerous. First, the current greatest threat to Key deer is urban development and its associated risk factors (e.g., loss of habitat, habitat fragmentation, and increased deer mortality due to vehicle collisions). The majority of Key deer reside on Big Pine Key where high urban development in the south has created an ecological sink primarily due to high roadkill mortalities of Key deer (Harveson et al., 2004). While measures are underway to reduce deer roadkill mortality on Big Pine Key, the effects of future policy (e.g., the pending Habitat Conservation Plan and lifting of the building moratorium) are unknown. Second, the Florida Keys are prone to hurricanes and while impacts on Key deer during previous hurricanes have been minimal (Lopez et al., 2000), the potential exists for a hurricane to severely impact the population because of its limited geographic range. Sugarloaf and Cudjoe are the furthest islands from Big Pine making them desirable choices for increasing the populations range to minimize the potential catastrophic effects of a hurricane. Finally, additional local populations on Cudjoe and Sugarloaf Keys will provide increased population growth and genetic

rates between Big Pine and No Name Keys were reported by Lopez (2001), however, deer dispersal rates between other islands are unknown. Density dependence in white-tailed deer populations has been demonstrated in previous studies (McCullough, 1979; Halls, 1984). Current deer estimates suggest that the Big Pine Key deer population is at 78% island carrying capacity and is increasing (Lopez et al., 2004a). We included density dependence in the Key deer metapopulation model to evaluate the dynamics of the population as it approaches K . Deer dispersal was assumed to increase linearly as density increased toward K . We assumed that as deer densities increased that competition for territory and resources would increase the likelihood of dispersal to other islands (Kammermeyer and Marchington, 1976). We assumed an outward dispersal from islands of high density (the main island, Big Pine Key) to islands of lower density. As other island populations increased (due to births and immigration), they were also modeled to disperse with each island population flowing outward from the main population to peripheral islands like stepping stones (Fig. 2). We used this dispersal model to evaluate the possibility of Key deer establishing other viable populations on islands with suitable habitat within the current Key deer range in the Lower Florida Keys.

By modeling various dispersal scenarios, we were able to evaluate the effects of this unknown parameter on population projections for individual island-complexes and the metapopulation. All models predicted successful colonizations on all tier 1 islands (Table 3) suggesting that dispersal has occurred in previous years. In evaluating dispersal scenarios (low, medium, and high), we found that dispersal scenario had little effect on Key deer population growth. Both low dispersal and high dispersal projected deer populations within ± 1 S.D. of the medium dispersal projections for the metapopulation and Big Pine Key (Table 3). Therefore, we will concentrate our discussion using the results from the medium dispersal scenario.

Of the 11 island-complexes we identified in the Lower Keys as possessing suitable habitat for Key deer, three would not

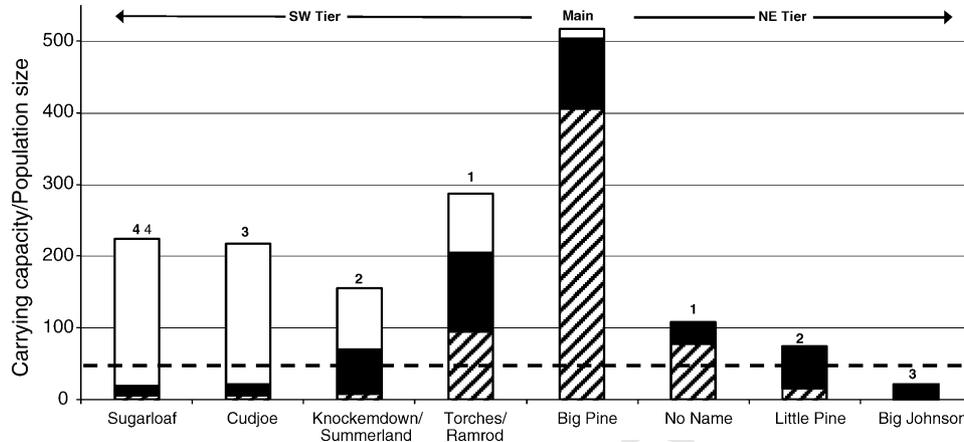


Fig. 8 – Initial Key deer population abundance (2001, hatched-fill) and projected 20 years population growth (2021, black solid-fill) on each island-complex under medium dispersal rates ($f=0.03$, $m=0.11$). Height of bars represents carrying capacity (K) and dotted line represents minimum viable population level (50 deer). The tier 1 islands of Howe, Annette, and Newfound.

374 heterogeneity further bolstering this endangered population
375 towards recovery.

8. Management implications

376 The conservation and management of an endangered species
377 such as Key deer requires a thorough understanding of the
378 demographic and environmental factors influencing its pop-
379 ulation dynamics. While much is known about Key deer biol-
380 ogy (e.g., survival, maternity, habitat use) changes in habitat
381 conditions due to urban development will continue to prove
382 challenging to managers. Habitat loss and fragmentation com-
383 bined with increasing deer densities will have unpredictable
384 effects on parameters such as dispersal. Through the use of
385 simulation modeling, we examined the potential effects of
386 changes in dispersal rates on the Key deer metapopulation.
387 According to our results, under all modeled scenarios the
388 establishment of viable populations on Cudjoe and Sugarloaf
389 Keys by dispersal alone is unlikely within the next 20 years. We
390 recommend the use of other methods (e.g., translocations) to
391 supplement deer numbers on these islands in order to estab-
392 lish viable populations.

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