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Overwater Movement of Raccoons (*Procyon lotor*) in a Naturally Fragmented Coastal Landscape

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Abstract - *Procyon lotor* (Raccoon) is a major predator of beach-nesting and colonial waterbirds on the Virginia barrier islands. An understanding of water as a barrier to inter-island movement by Raccoons will be essential to effective management of these predators in this naturally fragmented coastal environment. We examined 4 independent lines of direct evidence for Raccoon movement between 1999 and 2007: 1) locations of recaptured, ear-tagged Raccoons on both the islands and the adjacent mainland, 2) overland movements of radio-collared Raccoons, 3) inter-island movements of radio-collared resident Raccoons, and 4) movements of translocated Raccoons. We recaptured 78 of 177 ear-tagged island Raccoons, all on the same island as the initial capture. We also tagged and released 65 mainland Raccoons, none of which was ever recaptured on an island. We often observed overland movements >1 km per day by radio-collared animals on both the islands and the mainland. Nevertheless, only 3 of 51 (6%) collared animals (2 males and 1 female) moved overwater from the location where they were captured. None of the 4 Raccoons radio-collared on the mainland moved to an island. Although Raccoons in this system are highly mobile, overwater movements seem to be infrequent events; only 3 of 234 tagged/collared island individuals moved between islands, and none of the 69 tagged/collared mainland individuals moved to an island. Finally, we observed return movements by 22 of the 32 (69%) animals (11 males and 11 females) that were translocated either from the mainland to a nearby island or between adjacent islands. Translocated animals exhibited a much greater tendency than resident animals to make overwater crossings. In all cases of overwater movement, the water channels were relatively shallow and relatively slow moving. None of the 335 marked animals in this study crossed a tidal inlet. The mobility observed here is consistent with the idea that the distribution of Raccoons on the islands has expanded in recent decades. Predation management on these islands will require a strategic approach that takes into account both island isolation and Raccoon mobility.

Introduction

Mammalian predators, including *Procyon lotor* L. (Raccoon), have caused the decline and/or extinction of countless populations of island-nesting waterbirds and seabirds (Burger and Gochfeld 1994). The avifaunas of entire archipelagos have been altered dramatically by the introduction of mammalian predators (e.g.,

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Bailey 1993). The Virginia barrier islands support a diverse assemblage of beach-nesting and colonial waterbirds (Williams et al. 2007). Sandy beaches, overwash fans, dunes, and shrub thickets provide extensive habitat for 27 species of herons, egrets, ibises, pelicans, gulls, terns, oystercatchers, skimmers, and plovers. Most of these birds are ground-nesters, and thus are highly vulnerable to mammalian predation. *Charadrius melodus* Ord (Piping Plover) and *C. wilsonia* Ord (Wilson's Plover) are both state-endangered species in Virginia; the Piping Plover is a federally threatened species (Terwilliger 1991). The Conservation Action Plan for the Avian Communities in the Virginia Barrier Island System (Barrier Island Avian Partnership 1996) identified mammalian predators as one of the primary continuing threats to the success of avian conservation on the islands.

Numerous studies cite predation by Raccoons as a major cause for the precipitous decline in numbers of beach-nesting and colonial waterbirds on the Virginia barrier islands during the past 50 years (Boettcher et al. 2007; Brinker et al. 2007; Wilke et al. 2007; Williams et al. 1990, 2005, 2007). Erwin et al. (2001) proposed that the distribution of the Raccoon on these islands has expanded during this time, thus exposing more nesting habitat and more avian colonies to the effects of predation. Most islands are owned and managed to provide nesting habitat for shorebirds and colonial waterbirds by The Nature Conservancy (TNC), the US Fish and Wildlife Service (USFWS), the Virginia Department of Game and Inland Fisheries (VDGIF), and the Virginia Department of Conservation and Recreation (VDCR). In an effort to reduce predation pressure on nesting birds, TNC, USFWS, VDGIF, and US Department of Agriculture Wildlife Services (WS) have instituted an extensive program to remove Raccoons from the Virginia barrier islands. Predation management has become an ongoing part of conservation activity on these islands.

Effective management of Raccoons and other meso-predators requires an understanding of animal movement across the landscape (Martin et al. 2010, Roth et al. 2008, Waldstein 2010). In particular, management of island populations requires information about the role of water as a barrier to movement. Previous studies provide conflicting information about the propensity of Raccoons to cross water channels. Gehrt (2003) reported that Raccoons can cross water easily and that they probably move overwater frequently in some areas. In contrast, Kauhala (1996) and Rosatte et al. (2010) reported that water can be a barrier to movement by Raccoons. Although many researchers have studied movement of Raccoons in eastern North America (Gehrt 2003)—in part, a result of the growing interest in control of disease transmission by this species (Rosatte et al. 2009, 2010)—only a few studies have reported information about island populations on the Atlantic coast (Waldstein 2010). Moreover, these studies did not focus on movement between islands.

Given the contradictory evidence about overwater movement outlined above, and the paucity of information about movement in coastal island populations, our objective was to obtain gender-specific estimates of the timing, frequency, and trajectory of movements by Raccoons in this coastal system. Specifically, we sought to determine 1) how frequently Raccoons move between the mainland and islands or between islands, 2) the influence of island isolation, measured as the width of a water gap, on the probability of movement, 3) whether males and females are equally likely to move, 4) whether movements vary seasonally, and 5) whether there is a tendency for animals to move from islands of low habitat quality to islands with higher quality habitat. Based on our observations, we assessed the likelihood that the distribution of Raccoons has recently expanded on the islands.

Study Area

Study sites included 9 locations on the mainland of the southern Delmarva Peninsula and 12 of the barrier islands that extend ≈150 km along the seaward margin of the Peninsula. The islands are centered at approximately 37º30'N and 75º40'W in Accomack and Northampton counties, VA (Fig. 1). This 1000-km^2 landscape is a dynamic, highly fragmented mosaic of open bays, marshes, marsh islands, back barriers, and barrier islands (Hayden et al. 1991). The islands are located 0.4–12.1 km offshore, range from 1 to 10 m in elevation, and vary from 27–7029 ha in area. Vegetation types are diverse and include emergent sandbars, low-lying marsh, grasslands with extensive overwash zones, and shrub thickets and mature forests on elevated islands (McCaffrey and Dueser 1990). The islands are separated by estuarine marshes and bays that connect to the Atlantic Ocean through deep inlets (Oertel et al. 1989). As measured from the National Oceanic and Atmospheric Administration (NOAA) Coastal Change Analysis Program (C-CAP) land-cover data layers for the lower Delmarva Peninsula (Virginia and Maryland) for the year 2001 (http://www.csc.noaa.gov/crs/lca/ccap.html), the average distance between nearest-neighbor islands was 808 m (SE = 162), and the average distance between adjacent islands that are separated by deep, swift-running inlets was 518 m (SE = 84). The average distance from the mainland was 5835 m (SE = 745; range = 351–12,868 m). Given the rates of erosion and accretion in this dynamic environment, the distances between nearest-neighbor islands might be subject to changes on the order of tens of meters in any given year.

Several islands have been occupied by humans sporadically since the 1600s but have been deserted since a series of severe storms in the early 1930s (Badger and Kellam 1989, Barnes and Truitt 1997, Graham 1976a). Except for a few small, scattered private in-holdings, the islands are held in public ownership by the USFWS or the Commonwealth of Virginia or are owned by TNC. TNC holdings comprise the Virginia Coast Reserve (VCR), a National Science Foundation (NSF) long-term ecological research (LTER) site, a Man and the Biosphere reserve, and a Western Hemisphere International Shorebird Reserve Network site (Badger 1978, 1991, 1997).

At least 11 islands, including Assateague, Cedar, Chincoteague, Fishermans, Hog, Mockhorn, Parramore, Revel, Skidmore, Smith, and Wallops, support potential source populations of Raccoons (Fig. 1; Keišs 2001). Raccoons also occur occasionally on at least 13 other islands, including Assawoman, Chimney Pole, Cobb, Fowling Point, Holly Bluff, Little Cobb, Metompkin, Mink, Myrtle, Raccoon, Rogue, Ship Shoal, and Wreck (Fig. 1). This study focuses on the islands

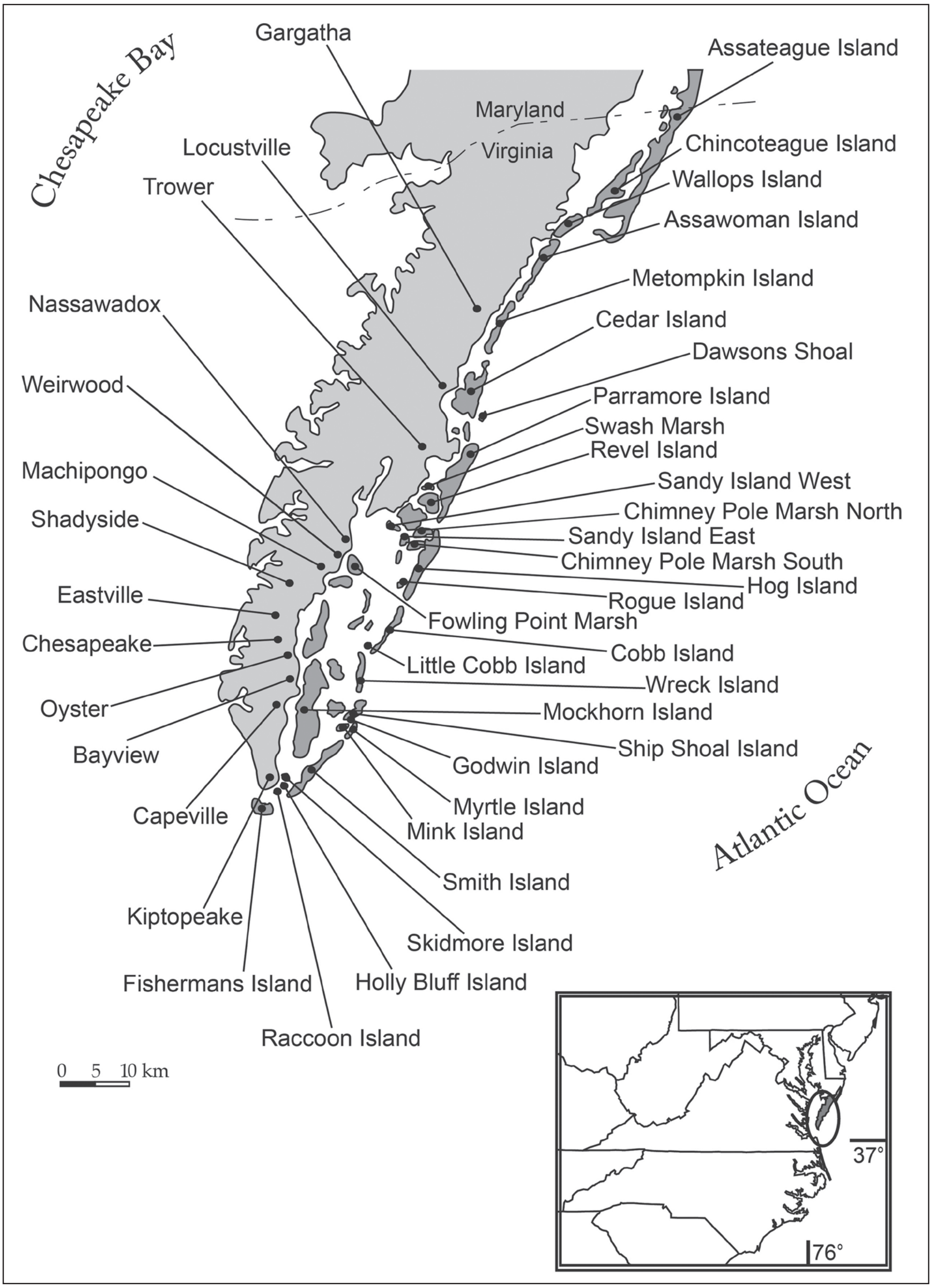

Figure 1. Location of islands and marshes of the Virginia barrier island complex and selected sites on the adjacent mainland.

from Parramore southward to Fishermans. Fishermans is connected to the southern tip of the Delmarva Peninsula by a highway bridge, but all the other islands in this study are accessible only by boat. Additionally, tidal conditions restrict the timing and duration of access to these islands. The study islands include marsh (Fowling Point, Mink, Swash), grassland (Myrtle, Ship Shoal), shrubland (Hog, Holly Bluff, Rogue) and forested (Fishermans, Parramore, Revel, Skidmore, Smith) habitats. Given the effects of area and elevation, habitat complexity on these islands is cumulative, so that forested islands also have areas of shrubland, grassland and marsh; shrubland islands have grassland and marsh; and grassland islands have marsh (Dueser and Brown 1980).

Methods

We obtained and examined 4 independent lines of direct evidence about movements of Raccoons on Virginia barrier islands and the adjacent mainland between June 1999 and December 2007: 1) locations of recaptured Raccoons based on mark-release-recapture sampling, 2) overland movements of radio-collared Raccoons presumed to be resident on specific islands or on the mainland, 3) inter-island movements of radio-collared Raccoons, and 4) movements of translocated Raccoons. Each data set included males and females, mainland and island animals, and animals on different islands, and each involved long-term monitoring. The use of multiple, independent data sets provided diverse opportunities, circumstances, and time spans for observing overwater movement.

Mark-release-recapture

Raccoons were trapped, tagged, and released using the methods of Keišs (2001) and Martin (2007). Large single-door cage traps (90 x 30 x 25 cm, Tomahawk Live Trap Company, Tomahawk, WI) were baited during summer with canned cat food, sardines, and maple syrup and during autumn with fruits of *Diospyros virginiana* L. (Common Persimmon), apples, fish, and shrimp. Traps were set during the day and inspected the following morning. To avoid captured animals becoming overheated, we covered traps with vegetation collected on-site. Each animal was immobilized by intramuscular injection of ketamine/acepromazine solution (10 mL of 100 mg/mL ketamine + 1 mL acepromazine), using 0.1 mL solution per 1 kg of animal. Body mass was estimated subjectively before immobilization. Age was estimated as subadult or adult using tooth wear (Grau et al. 1970), body size, and external reproductive attributes. Gender was determined, and females were palpated for signs of pregnancy or lactation. Each Raccoon was weighed using a 5-kg spring-balance with 0.05-kg precision, and a numbered ear-tag (Monel #3, National Band and Tag Company, Newport, KY) was attached to each ear.

Between June 1999 and July 2006, we ear-tagged and released Raccoons on 9 islands (Fishermans, Hog, Mink, Mockhorn, Myrtle, Parramore, Revel, Skidmore, and Smith; Fig. 1). We also tagged and released Raccoons at 9 mainland sites (Capeville, Gargatha, Kiptopeake, Locustville, Machipongo, Nassawadox, Oyster, Shadyside, and Trower; Fig. 1). There was the potential for these tagged animals to be recaptured on the islands during an extensive predation management program conducted by TNC, USFWS, VDGIF, and WS during 2001–2007. They trapped (either annually or semi-annually) and euthanized all Raccoons and *Vulpes vulpes* L. (Red Foxes) captured on 12 islands, including Assawoman, Cedar, Fishermans, Metompkin, Mockhorn, Myrtle, Parramore, Revel, Ship Shoal, Smith, Wallops, and Wreck (Fig. 1).

Radiotelemetry

We also trapped, tagged, radio-collared, and released a separate set of Raccoons on 9 islands (Fishermans, Hog, Mink, Mockhorn, Myrtle, Parramore, Rogue, Skidmore, and Smith; Fig. 1) and 2 mainland sites (Capeville and Nassawadox) between June 1999 and July 2006. Collared animals were tracked repeatedly from fixed geographic locations with a collapsible, hand-held Yagi antenna and a Wildlife Materials TRX-1000S radio-receiver. Island animals were tracked as often as possible, given the constraints of weather and tides. Mainland animals were tracked periodically for 12 weeks following release. We attempted to take $\geq$3 bearings for each individual on each tracking occasion, to facilitate triangulation of animal locations. We were able to take $\geq$3 bearings on ≈80% of the tracking occasions, sufficient to identify the island on which an animal was located. Capture, release, and tracking locations were recorded with a handheld Garmin 12 Map GPS unit. Bearings were determined with an azimuth model Suunto precision compass graduated to 1/2°. Animal locations were computed with program "Locate" (http://www.locateiii.com/index.htm) and mapped on 1999 Landsat 7 (ETM+) imagery of the study area.

The collars were designed to have a provisional line-of-site range of ≈3.0 km on this relatively flat, low-lying terrain. In reality, however, several tests indicated that we were usually within 1–2 km of the re-sighted animal. We defined the maximum distance moved by an individual as the greatest straight-line distance between any pair of locations ever observed for the animal. These maximum movement distances were tested for location differences (mainland vs. island), gender differences (all males vs. all females), and gender differences for island animals only with nonparametric Mann-Whitney 2-sample rank tests adjusted for tied ranks (Zar 1999). Maximum movement distances were also tested for differences among islands (Parramore vs. Hog-Rogue vs. Smith) with a Kruskal-Wallis single-factor analysis of variance by ranks adjusted for tied ranks (Zar 1999). Although analyses were based on ranks, we report maximum movement distances as means and standard errors for purposes of comparison.

Translocations

We implemented a translocation study between May 2001 and July 2003 using another separate set of Raccoons. Individuals were captured from a "source" area (Nassawadox, Parramore, Revel, Rogue; Fig. 1), translocated to an adjacent "release" area (Fowling Point, Hog, Parramore, Revel, Swash; Fig. 1), and monitored frequently by means of radio-telemetry. We captured animals in upland habitat on the source area and released them into upland habitat on the release area. Release areas were adjacent to the source area, free of nesting waterbirds, and occupied by Raccoons at the time of the study, but separated by a water channel on all tides. All translocations involved distances greater than the closest possible distance between source and release areas. Average translocation distance was ≈5.4 km (range = 1.8–7.4 km), from a point on the upland of the source area to a point on the upland of the release area.

Our methods followed the 1998 guidelines of the American Society of Mammalogists for the use of mammals in research (Animal Care and Use Committee 1998). All procedures conformed to Utah State University Institutional Animal Care and Use Committee policies (protocol 952).

Results

Mark-release-recapture

We ear-tagged and released 177 Raccoons on 9 islands and recorded 122 recaptures (Table 1), ranging from 1 to 7 recaptures per individual (mean = 0.7). We recaptured 78 individuals (37 males and 41 females) at least once through December 2007. All recaptures occurred on the same island where the Raccoon had been tagged and released originally. No individual was observed to move between islands. The number of days between first and last capture (i.e., total period of observation for a recaptured individual) ranged from 1 to 1413 d (mean = 307 d, SE = 34). We also ear-tagged and released 65 Raccoons at 9 mainland sites (Fig. 1): Capeville (2 individuals), Gargatha (9), Kiptopeake (10), Locustville (9), Machipongo (4), Nassawadox (26), Oyster (2), Shadyside (1), and Trower (2). Despite the capture of 936 Raccoons on Cedar, Fishermans, Metompkin, Mockhorn, Myrtle, Parramore, Revel, and Smith islands during extensive removal-trapping between 2001 and 2007, none of the tagged mainland individuals was ever recaptured on an island.

Table 1. Recapture locations of 177 ear-tagged *Procyon lotor* (Raccoons) on 9 Virginia barrier islands 1999–2007. *n* = number of individuals tagged and released.

			# of individuals recaptured			
Island	*n*	# of recaptures on same island	on same island	on different island	Recaptured males	Recaptured females
Fishermans	2	0	0	0	0	0
Hog	22	3	3	0	2	1
Mink	1	0	0	0	0	0
Mockhorn	8	2	2	0	1	1
Myrtle	4	0	0	0	0	0
Parramore	92	63	46	0	24	22
Revel	2	2	2	0	1	1
Skidmore	24	43	17	0	6	11
Smith	22	9	8	0	3	5
Total	177	122	78	0	37	41

Overland movements

To learn about overland movement of Raccoons, we radio-collared and released 30 adult and sub-adult individuals (18 males and 12 females) on 5 islands and at 2 locations on the adjacent mainland in June 1999 (Table 2). We monitored the locations of these animals as often as possible through June 2000. During this period, we used 120-g whip-antenna collars purchased from 2 suppliers: AVM Instrument Company (AVM) and Wildlife Materials, Inc. (WMI). Many of the 20 AVM collars were no longer detectable after only a brief period of exposure to this wet, salty environment. On average, an animal wearing an AVM collar was no longer detectable after 25 d (SE = 5.3), whereas an animal wearing a WMI collar was detectable for an average of 293 d (SE = 77.0). Either there was mass movement of animals wearing AVM collars to locations where they could not be detected, or many of these collars simply failed after only a short time in the field. The latter interpretation is supported by the observations for 12 animals on Parramore; none of the 3 males and 3 females collared with AVM collars was detectable after September 1999, whereas the 4 males and 2 females fitted with WMI collars were still detectable on the island 9 months later in June 2000.

Given our inability to detect many of the 20 AVM collars shortly after they were deployed, we actually monitored overland movements of 24 of the 30 collared Raccoons (15 males and 9 females) between June 1999 and June 2000 (Table 2). Tracking effort per individual ranged from 6 to 17 d on the islands and from 45 to 50 d on the mainland. Tracking period ranged from 1–321 d following release (mean = 87 d). We resighted 276 Raccoons on the islands and 194 on the mainland. None of these animals was observed to move between islands or between the mainland and an island. Maximum distances moved ranged from 316 to 5550 m.

Table 2. Number of *Procyon lotor* (Raccoons) successfully radio-tracked on 9 islands and 2 mainland sites (1999–2006). Ten collars were undetectable after release. The number of Raccoons radio-collared and released is in parenthesis.

	Year					
Location	1999	2002	2003	2005	2006	Total
Islands						
Fishermans	-	0 (2)	-	-	-	0 (2)
Hog	3 (3)	-	-	-	-	3 (3)
Mink	-	1 (1)	-	-	-	1 (1)
Mockhorn	-	4 (4)	-	-	-	4 (4)
Myrtle	0 (2)	0 (1)	1 (1)	-	-	1 (4)
Parramore	9 (12)	-	-	-	-	9 (12)
Rogue	1 (1)	-	-	-	-	1 (1)
Skidmore	-	1 (1)	-	10 (10)	10 (10)	21 (21)
Smith	7 (8)	0 (1)	-	-	-	7 (9)
Mainland sites						
Capeville	1 (1)	-	-	-	-	1 (1)
Nassawadox	3 (3)	-	-	-	-	3 (3)
Total	24 (30)	6 (10)	1 (1)	10 (10)	10 (10)	51 (61)

Rankings of movement distance did not differ ($U = 58.5 < U_{0.05\,(2),20,4} = 66$, $P = 0.141$) overall between males (1236 m, SE = 124) and females (1847 m, SE = 610). Rankings of movement distance did not differ between mainland (2666 m, SE = 1072) and island animals (1225 m, SE = 173; $U = 68 < U_{0.05(2),15,9} = 101$, $P = 0.99$), or between island males (mean = 1267 m, SE = 141) and island females (mean = 1147 m, SE = 443; $U = 59 < U_{0.05(2),13,7} = 71$, $P = 0.303$). Ranked movement distances did differ among islands: 1261 m (SE = 261, $n = 7$) on Smith, 752 m (SE = 130, $n = 4$) on Hog and Rogue, and 1051 m (SE = 294, $n = 9$) on Parramore, but not significantly so ($H_c = 2.675 < X^2_{0.05,3} = 7.815$, $P < 0.50$). None of these distances were great enough to represent a constraint imposed by the size of the island. The longest 1-day, straight-line movement for an island animal was 1788 m in 24 hours by male number 8-7 on Smith. The longest 1-day movement for a mainland animal was 3044 m in 12 hours by female number 88-89 at Nassawadox. The longest movement observed overall was by female number 87-86 who traveled 5550 m south from Capeville toward the southern tip of the Peninsula over a period of 6.5 months, where she was road-killed on 27 February 2000.

Inter-island movements

To study inter-island movements, we radio-collared an additional 31 adult and sub-adult Raccoons (12 males and 19 females) on 6 islands between July 2002 and June 2006 using only WMI collars (Table 2). These included 11 animals (4 males and 7 females) on 6 islands during July to August 2002 and during August 2003 (Table 2); we monitored 7 of these animals for 3–434 d following release (mean = 233 d). We collared and monitored 10 additional animals (4 males and 6 females) on Skidmore between May and August 2005 (Table 2). Finally, we collared and monitored 10 more animals (4 males and 6 females) on Skidmore between June and August 2006 (Table 2). We monitored all 20 of the Skidmore animals successfully for the duration of the study period (66 d in 2005 and 58 d in 2006).

Four of the 31 collars failed within 4 d of release. We thus monitored the post-release locations of 27 individuals (11 males and 16 females). The most intense periods of monitoring were 1) May 2002–August 2003 (14 tracking days, 7 individuals, 286 re-sightings), when we were looking for movement along specific potential inter-island pathways, and 2) May–August 2005 (8 tracking days, 10 individuals, 64 re-sightings) and May–August 2006 (19 tracking days, 10 individuals, 190 re-sightings), when we were closely monitoring the population on Skidmore.

Between June 2002 and June 2006, the island location of the average animal was known for 101 d (SE = 21, range = 1–434 d). We detected only 3 inter-island movements, all by adult animals (Table 3): female number 236-237 moved from Mink to Myrtle in July 2002, male number 529-530 moved from Myrtle to Mink in August 2003, and male number 95001 moved from Skidmore to Holly Bluff, and then to the mainland in July 2005. These movements occurred approximately 2, 3, and 66 d post-release, respectively. The minimum overwater distances involved in these movements were 0.5 km (Mink–Myrtle), 0.4 km (Skidmore–Holly Bluff), and 0.2 km (Holly Bluff–mainland). No mainland-island or inter-island movement was detected for the other 24 radio-collared animals between June 2002 and June 2006.

Translocations

To further investigate overwater movement, we translocated 32 Raccoons (16 males and 16 females) between 7 areas in 2001–2003 (Table 4). All translocations were conducted during the warm season, (May–August). We monitored the post-release movements for 1–385 d (mean = 190 d). No signal was ever detected for 2 adult males that were translocated from Parramore (1 to Revel and 1 to Swash), and 1 adult male died within 3 d of being moved from Parramore to Swash. Eight animals (3 males and 5 females) remained on the release area for 2–259 d (mean = 170 d), and 21 animals left the release area (Table 4). Nineteen island animals (9 males and 10 females) returned to the source area within

Table 3. Inter-island movements of 31 radio-collared *Procyon lotor* (Raccoons) captured and released on 6 Virginia barrier islands, 2002–2006. Four collars on 3 islands (Fishermans, *n* = 2; Myrtle, *n* = 1; and Smith, *n* = 1) were no longer detectable within 4 days of release. *n* = number of individuals collared and released. # that moved = number of individuals that moved to a different island.

Island	*n*	# that remained	# that moved	% that moved
Fishermans	2	uncertain	uncertain	uncertain
Mink	1	0	1	100
Mockhorn	4	4	0	0
Myrtle	2	uncertain	1	50
Skidmore	21	20	1	5
Smith	1	uncertain	uncertain	uncertain
Total	31	24	3	10

Table 4. Inter-island and island-mainland movements of 32 *Procyon lotor* (Raccoons) translocated 2001–2003. No post-release signal was received for 1 animal translocated from Parramore to Revel or for 1 animal translocated from Parramore to Swash. Source location is the site of initial capture. *n* = number of individuals collared and translocated. # that stayed = the number of individuals that stayed at the release location, and # that returned = the number of individuals that moved back to the source location.

Source location	*n*	Release location	# that stayed	# that returned	# moved to a third location
Parramore	9	Revel	3	5	0
Parramore	6	Swash	0	4	1
Revel	11	Parramore	4	7	0
Revel	3	Swash	1	2	0
Rogue	1	Hog	0	1	0
Nassawadox	2	Fowling Point	0	2	0
Total	32		8	21	1

1–221 d (mean = 39 d). Six of these individuals returned within 1–2 d and 15 within ≤15 d. The animals that returned were still present on the source area from 5–385 d (mean = 164 d) days following their return.

Island female number 189-188 moved from Swash to Revel rather than back to Parramore. Both mainland males, numbers 163-164 and 173-172, returned from Fowling Point to the mainland within 5 d, where they stayed for the next year. Animal number 163-164 made at least 1 return visit to Fowling Point during this period. Altogether then, at least 70% of the translocated animals for which post-release observations are available either returned to the source location or moved to a third location following release. Minimum upland-to-upland distances involved in these returns were 0.5 km (Parramore to Revel), 2.4 km (Parramore to Swash), 3.5 km (Revel to Swash), 0.7 km (Rogue to Hog), and 0.9 km (Nassawadox to Fowling Point).

Discussion

Raccoons in our study were capable of crossing at least 3 km of open water and marsh to reach an island. Translocated animals routinely made overwater forays of 1 km or more to return to their presumed home island. Nevertheless, movement between islands was relatively rare for resident (non-translocated) animals, even during the warm season of the year.

Both island and mainland Raccoons made extensive overland movements. The observed maximum distances moved by island males (2.1 km) and females (3.5 km) suggest that the extent of movement typically was not constrained by island size. Several mainland animals moved distances that would have been long enough to reach several of the islands, if the trajectory of those movements had been across open water. Overall average movements of males (1.3 km) and females (1.8 km) are comparable to average overland movements (mean = 1.54 km) reported by Rosatte et al. (2010) for Raccoons in southeastern ON, Canada.

None of the distances moved by mainland Raccoons would have been long enough for an animal to disperse directly from the mainland to a remote island (e.g., Parramore or Hog). Nonetheless, several of the distances would have been long enough to move from the mainland to a nearby island over open water (e.g., Mockhorn or Skidmore). Considering only the observed mobility and the absolute distances involved, 13 islands in this system appear to be within overwater dispersal range (≈3 km) of mainland Raccoons. In contrast, 20 islands appear to be most accessible by movement between islands.

Our data indicate that Raccoons have the ability to move >2 km overland on the islands, but resident animals seldom moved between islands. We observed no inter-island movement for 177 (0%) ear-tagged animals (Table 1). This observation is consistent with evidence from other studies (Rosatte et al. 2007, 2010) indicating that, although Raccoons are capable of overland movements of more than 20 km, water crossings are relatively rare events. Rosatte et al. (2007) reported that only 3 of 579 animals (0.5%) crossed the St. Lawrence River.

Additionally, only 3 of 51 collared residents in our study moved overwater, and all such movements were <1 km straight-line distance. In another study of Raccoons on the Virginia barrier islands, Hanlon et al. (1989) observed that 14 of 15 collared Raccoons (6 males and 9 females) on Parramore remained on the island throughout the 9-month study; 1 male moved from Parramore to Revel. Altogether then, between the present study and the study by Hanlon et al. (1989), only 4 of 66 (6%) collared Raccoons have been observed to move between islands in this system, and each recorded movement measured <1 km. Three of these individuals were males and 1 was a female.

In contrast to movements of collared residents, 19 of the 27 translocated island Raccoons for which post-release observations were available either returned from the release island to the source island or moved to a third island, moving overwater distances up to 3.6 km. Similarly, the 2 mainland males translocated to Fowling Point returned to the mainland source area, an overwater distance of at least 0.9 km. Hanlon et al. (1989) also observed that 3 translocated island Raccoons (2 males and 1 female) returned to their source island, covering an overwater distance of at least 0.8 km. Combining the results of the present study and Hanlon et al. (1989), 24 of 32 (75%) translocated Raccoons, including 13 males and 11 females, were observed to move across open water, over distances up to 3.6 km. Both males and females exhibited a tendency to move across water to return to their home island following translocation. Thus, overwater distances of 1–3 km appear to present no challenge to the movement of motivated Raccoons on the Virginia barrier islands.

Previous studies provide conflicting information on the propensity of Raccoons to cross water channels. Kauhala (1996) stated that fresh water bodies only a few hundred meters in width are sufficient to impede Raccoon movement in Europe. Additionally, Rosatte et al. (2010) reported that activities to control the spread of rabies in ON, Canada are designed using rivers as partial barriers to restrict Raccoon movement coming from New York State. On the other hand, Gehrt (2003) conducted an extensive literature search and concluded that Raccoons can cross water easily and that they probably move overwater frequently in some areas. This conclusion is supported by several studies reporting that Raccoons crossed freshwater barriers 300 m–1 km in width (Arjo et al. 2007, Gehrt et al. 1993, Kaufmann 1990, Rosatte et al. 2007) and saltwater barriers between 645 m–950 m in width (Bigler et al. 1981, Hartman and Eastman 1999).

Thus, based on the preponderance of evidence (Arjo et al. 2007, Bigler et al. 1981, Gehrt 2003, Gehrt et al. 1993, Hanlon et al. 1989, Hartman and Eastman 1999, Kaufmann 1990, Rosatte et al. 2007), we expected to observe frequent overwater movement between adjacent islands in the Virginia barrier island complex. Our observations contradict this expectation. We observed no inter-island movements by ear-tagged animals, and no mainland animals were recaptured on the islands. We observed overwater transits by only 3 of 51 (6%) radio-collared animals. We observed no movement of resident animals from Hog, Mockhorn, Parramore, Rogue, or Smith, either to another island or to the mainland.

However, we observed inter-island movements by 19 of 27 (70%) translocated island animals. Translocated Raccoons readily crossed expanses of open water and marsh up to 3.4 km in width to return to their home island.

Our four independent data sets indicate that Raccoons are capable of moving overwater distances equal to the distances between adjacent islands, but they exhibited little inclination to do so unless motivated by displacement from their supposed home island. Among the many possible explanations for these observations, we have data related to two. Movement of individuals from an island might be driven by high Raccoon abundance on that island. Keišs (2001) trapped Raccoons on 8 islands in 1999 and 2000; the highest observed capture rates were on Parramore and Smith, from which no movements were observed over the 8 years of our study. Furthermore, Hanlon et al. (1989) reported an extraordinary Raccoon density of ≈37 Raccoons per square kilometer on Parramore, but only 1 case of inter-island movement by a resident (to Revel). Conversely, the island with one of the lowest capture rates reported by Keišs (2001) was Myrtle, from which 1 animal was observed to move in our study. Based on this limited evidence, there is no obvious direct connection between abundance and inclination for Raccoons to move between islands in this system.

Movement might also be driven by habitat conditions on an island. Keišs (2001) found trapping success to be positively correlated with area of contiguous saltmarsh, area of shrubs and forest, and total island area. Saltmarsh habitat provides a year-round food supply for Raccoons (Waldstein 2010), woody habitat provides year-round shelter (Gehrt 2003), and larger, higher islands with forest habitat provide a measure of protection from storms and overwash (Hayden et al. 1991). Only 1 of the 3 animals that we observed to move between islands left an island of presumably lower habitat quality for a location of higher habitat quality. Mink is a marsh island, Myrtle a grassland island, and Skidmore a forested island; all 3 are relatively small (≤42 ha). A Mink animal moved to Myrtle and a Myrtle animal moved to Mink; neither left an island of high habitat quality, or moved to an island of higher apparent habitat quality. A Skidmore animal moved from a forested island of apparently high habitat quality to Holly Bluff (a shrubland island), and then to comparable forest on the mainland. We believe that shelter is a limiting factor for Raccoon survival—overwinter survival, in particular—in the rigorous environment on these islands. Nevertheless, based on these few cases there is no clear evidence that the trajectory of Raccoon movement is from islands of lower habitat quality to islands of higher habitat quality.

The water barriers that the 3 radio-collared residents traversed (between Mink and Myrtle, between Skidmore and Holly Bluff, and between Holly Bluff and the mainland) are relatively shallow and relatively slow moving. It is noteworthy that the translocated animals crossed similar water channels to return to the sites where they were captured. This type of water barrier contrasts dramatically with the deep, fast-flowing tidal inlets that separate the barrier islands (including Parramore, Hog, Myrtle, and Smith) from each other (Oertel et al. 1989). We observed no instance of movement across a tidal inlet by any of the 335 marked animals (177 ear-tagged on islands, 65 ear-tagged on mainland, 61 radio-collared and released at point of capture, 32 radio-collared and translocated). In addition to the width of the water channel, it seems that characteristics such as depth and flow rate also influence overwater movement of Raccoons.

Raccoons on the Virginia barrier islands are capable of routinely crossing at least several hundred meters of open water, and they are at least potentially capable of crossing much greater distances when motivated. Because each of the islands is within <3 km from the nearest island, this potential for Raccoon movement complicates predation management. Even more important, at least 12 of the islands—Assawoman, Cedar, Chimney Pole North, Fishermans, Fowling Point, Holly Bluff, Metompkin, Mockhorn, Raccoon, Skidmore, Smith, and Wallops (Fig. 1) are potentially within dispersal distance directly from the mainland. Predation management on these islands is likely to be an on-going activity.

Raccoon abundance on the islands was probably lower in past decades because of hunting and aggressive game management (Graham 1976a, b), prior to the designation of the islands for conservation purposes (Byers 1976). Anecdotal reports of island hunts in local newspapers in the early 1900s suggest that Raccoons were less abundant in the past (e.g., Peninsula Enterprise, Chincoteague Notes, 26 October 1912: "Our sportsmen have had lots of fun this week, killing coons, … In the memory of the oldest inhabitants a coon was never seen on the Island [Chincoteague] before"). With reduced hunting and human traffic in recent decades, potential source populations of Raccoons may have increased in abundance, particularly on the forested islands that offer year-round shelter, thus increasing the probability of inter-island movement. Increased local abundance may have increased the probability of movement, leading in turn to increased probability of occurrence on more islands.

Is the overwater mobility of Raccoons reported here consistent with the notion that the distribution of Raccoons on the islands has expanded in recent decades, as proposed by Erwin et al. (2001)? They used information on Raccoon distribution from Dueser et al. (1979) as a baseline for their proposal. Dueser et al. (1979) reported Raccoons to be present on only 6 of 11 islands surveyed in 1975 and 1977 (Cobb, Hog, Little Cobb, Parramore, Revel, and Smith). However, this estimate of Raccoon distribution was probably very conservative because it was based only on the direct observation of active, free-ranging animals, rather than on trapped animals, tracks or sign. Erwin et al. (2001), on the other hand, relied on animal sign such as tracks and dens observed during a single field survey in 1998 to establish the presence of Raccoons on an island. They concluded from comparison of the records for 1977 and 1998 that Raccoons had spread to at least 2 additional islands (Wreck and Myrtle) in the interim. It is impossible to say whether these data represent an expansion in island occupancy over those 21 years or simply reflect different survey techniques in 1998. Nevertheless, our observations of Raccoon movement reported here suggest that such expansion might be possible, particularly in conjunction with an overall increase in Raccoon abundance. Furthermore, Raccoons are now known from repeated systematic track surveys (R.D. Dueser and N.D. Moncrief, unpubl. data) to occur at least occasionally on all 5 of the survey islands where active Raccoons were not reported as being present in 1977 (Dueser et al. 1979).

This study required relatively large investments of time and funding for fieldwork and equipment to trap, mark, radio-collar, and monitor individual animals. Additionally, fieldwork in a barrier island system is further hindered by logistics related to boat transportation and tidal water-level fluctuations. Given the economic costs and time required to obtain direct estimates of movement, we recommend the use of recently developed techniques for indirect estimation of movement (least-cost path analysis and landscape genetics) as part of future efforts to investigate overwater movement by Raccoons in this system. Least-cost path analysis allows researchers to model and visualize functional connectivity of populations in studies that examine relationships between landscape characteristics and mobility of organisms (Adriaensen et al. 2003). Landscape genetics combines spatial data with high-resolution genetic markers to evaluate the role that landscape variables play in affecting movement of individuals, which is inferred from genetic diversity and genetic structure of populations (Storfer et al. 2007). Together with the direct observations of overwater movement we report in this study, we believe that these newly available methods for indirectly estimating movement hold great promise for increasing our understanding of the distribution and dynamics of Raccoon populations in this naturally fragmented coastal landscape.

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