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Long-Term Trends in Loggerhead (*Caretta caretta*) Nesting and Reproductive Success at an Important Western Atlantic Rookery

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Abstract. – The Archie Carr National Wildlife Refuge (ACNWR), located along the central east coast of Florida (USA) in the western North Atlantic, hosts one of the largest loggerhead (*Caretta caretta*) nesting assemblages in the western Hemisphere. Sea turtle nesting activity has been continuously monitored on this beach for $>$ 31 yrs, representing one of the longest sea turtle reproductive data sets in the world. Between 1982 and 2012, an estimated 358,243 nests were deposited on the ACNWR with an estimated annual mean plus 95% confidence interval of 11,556 ± 1,129 nests. This constitutes 25.4% ± 0.8% of the mean annual Florida Index Nesting Beach Survey loggerhead complement. Mean annual clutch size was 113.9 ± 1.4, resulting in a 55.1% ± 4.0% mean annual hatching success rate and a mean emerging success rate of 53.3% ± 3.7%. The only egg-fate that was statistically correlated with emerging success were eggs washed out by erosion. The loss of eggs by erosion was significantly greater during storm and poststorm years, compared with nonstorm years. Among individual first-time nesting females that were measured, mean straight carapace length was 91.2 ± 0.15 cm and mean curved carapace length was 98.2 ± 0.15 cm. These data suggest that the ACNWR supports the greatest loggerhead nest density per kilometer in Florida, underscoring the importance of the ACNWR as one of the most important nesting habitats for loggerhead turtles in the Western Hemisphere.

Key Words. – Reptilia; Testudines; long-term study; nesting; morphometrics; interseason recaptures; erosion; armoring

Peninsular Florida constitutes the center of nesting abundance by the loggerhead turtle (*Caretta caretta*) in the Atlantic Basin (Witherington et al. 2006), hosting 53,000–98,000 nests per yr (Ehrhart et al. 2003; Florida Fish and Wildlife Conservation Commission 2013). The distribution of loggerhead nesting in the western Atlantic is marked by concentrations on 4 Florida Atlantic beaches and 1 on the Gulf of Mexico (Witherington et al. 2009). Prominent among them is the nesting beach in the northern section of the Archie Carr National Wildlife Refuge (ACNWR), located within Brevard County, Florida. The relative importance of this beach, on a hemispheric or global scale, was not recognized until the latter part of the 20th century (Carr and Carr 1978). Despite the fact that a number of prominent American zoologists of the late 19th century (Frank Chapman, Outram Bangs, John Jenks, among others) traveled there and based their specimen collecting trips at ''Oak Lodge'', a site adjacent to the beach now recognized as the ACNWR, there is nothing quantitative in the early literature (prior to 1978) regarding marine turtle nesting abundance in this region. Frank Chapman, a noted ornithologist/mammalogist, barely mentions loggerheads in his letters and journals (Austin 1967). On 15 November 1889 he did, however, read a report about loggerhead nesting behavior, written by Mrs Latham, the proprietor of Oak Lodge, before a meeting of the Linnaean Society of New York (Latham 1889); however, no sea turtle nest numbers were presented.

In the 1970s, an off-road vehicle group flipper-tagged marine turtles on a portion of the current ACNWR beach. This group used Monel flipper tags provided by Dr Archie F. Carr, then at the University of Florida. Between 1972 and 1978, 2910 individual loggerheads were tagged, but no data concerning the level of nesting activity were collected. It was not until the mid-1970s, when David and Peggy Carr conducted aerial censuses of marine turtle tracks on beaches of the southeastern United States, Puerto Rico, and the Virgin Islands, that the extent of nesting was quantified (Carr and Carr 1978). They concluded that, ''Both in terms of absolute numbers and relative density of nests, Brevard County is by far the most important county in the state'' for nesting of loggerhead turtles. In response to the Carrs' aerial census results, the University of Central Florida's Marine Turtle Research Group (UCFMTRG) began systematic, season-long daytime surveys in the summer of 1982. Results of the first 3 yrs of work generally affirmed the Carrs' conclusions and suggested that the south Brevard County seaboard constituted the best loggerhead nesting beach on the western rim of the Atlantic Ocean (Ehrhart and Raymond 1987). Nesting surveys on this beach have been carried out continuously since 1982. These data formed the basis of a proposal to establish a National Wildlife Refuge on the central Atlantic coast of Florida, specifically intended to protect this important sea turtle nesting

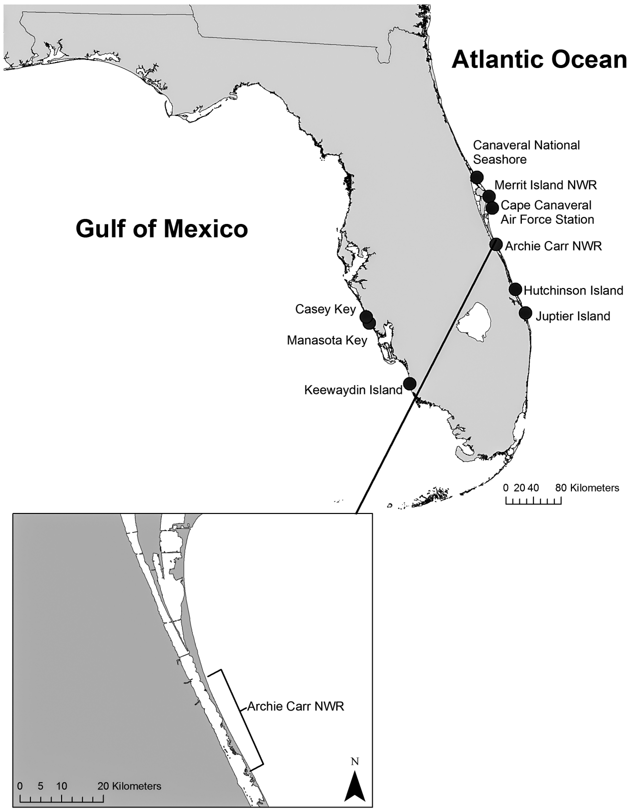

Figure 1. Location of the Archie Carr National Wildlife Refuge and the locations of nesting beaches in Florida where turtles were originally tagged, and then found nesting in the Archie Carr NWR during a subsequent nesting season.

habitat. The ACNWR was authorized by the US Congress in 1989, dedicated to the protection of marine turtle nesting habitat and, more broadly, to protect the world's populations of marine turtles. Here we present the long-term results of the UCFMTRG beach surveys and related nesting beach research in the 31-yr period from 1982 to 2012. Data in this study represent one of the longest, continuous data sets for sea turtle reproduction in the United States and internationally.

The objectives of this ongoing study are to determine long-term trends in reproductive output among loggerhead turtles nesting on the ACNWR, and to decipher long-term trends in the reproductive success of loggerhead clutches on the ACNWR.

METHODS

Study Area. — The nesting beach study site, hereafter referred to as the ACNWR, comprises the present-day Brevard County portion of the Archie Carr National Wildlife Refuge on the Atlantic Coast of Florida, USA (Fig. 1). It extends 21 km from a point south of the town of Melbourne Beach (28.04251°N lat, 80.54502°W long) to the northern boundary of Sebastian Inlet State Park (27.87390°N lat, 80.45419°W long). It is a high-energy beach consisting of a friable mixture of terrigenous and carbonate sand types. Of the 21 km of beachfront in the ACNWR, 34.5% is in public ownership, 49.8% is private residential, 12.6% is commercial, and the remaining 3.1% consists of gaps between parcels used for beach access (Brevard County Natural Resources Management, unpubl. data, 2013). Beachfront structures consist primarily of single-family homes, condominiums, small motels, and restaurants. The study area is divided into 0.5-km sections for georeferenced data collection.

Nesting Beach Surveys. — Survey periods and the number of days per week surveyed have varied over the years due to the constraints of the academic year and funding. From 1982 to 1984 and 1986 to 1988, surveys were conducted 5 d/wk from the second week of May to the first week of September. Weekly nest totals for those years were derived by simple extrapolation, using the mean number of nests enumerated on survey days to estimate the number of nests on nonsurvey days. These are termed the ''estimated seasons'' in the ''Results'' section.

In 1985 and from 1989 through 1997, surveys were conducted daily from the first week of May into the second week of September. From 1998 to 2004, surveys were conducted daily from 1 May through 31 August, with surveys every second day in April and September, during which all fresh turtle tracks were counted. Starting in 2005, surveys were conducted daily from 1 March through 31 October. These are referred to as the ''observed seasons'' in the ''Results'' section. The mean nest counts for estimated, observed, and combined seasons include a 95% confidence interval.

All surveys started just before dawn and were performed by trained personnel using all-terrain vehicles (ATV). Marine turtle species and nesting or nonnesting emergences (false crawls) were differentiated using track and nest-site characteristics. ATV tire marks were laid over the turtle tracks of all of the previous night's emergences so they would not be tallied during subsequent surveys. Both nesting and nonnesting emergences were recorded within each 0.5-km section of the ACNWR, as were incidences of nest depredation.

The relative density of nests in the ACNWR as compared with other nesting beaches in Florida was determined by using Index Nesting Beach Survey (INBS) data supplied by the Fish and Wildlife Research Institute (FWRI) under the Florida Fish and Wildlife Conservation Commission (FWC). The INBS program was initiated in 1989 by the FWRI and the US Fish and Wildlife Service (US FWS) to collect data on marine turtle nesting in the state using a standardized protocol between 15 May and 31 August. Initially there were 26 core beaches totaling 320 km, including the Brevard County portion of the ACNWR (A. Meylan, *pers. comm.*, July 2014). These core beaches account for approximately 70% of the loggerhead nesting in Florida (Turtle Expert Working Group [TEWG] 2009). Seven more beaches were added to the INBS program between 1990 and 1999, bringing the total length of survey beaches to 396 km. Those additional beaches have contributed a mean 1.0% ± 0.1% to the 1999–2012 INBS nest totals. ACNWR loggerhead nests tallied using INBS protocol were calculated as a percentage of the total INBS nest counts for each nesting season from 1989 through 2012.

The FWRI also coordinates a statewide nesting beach survey (SNBS) on approximately 200 beaches during the entire nesting season of loggerheads (vs. the 109-d INBS season). The ACNWR loggerhead nest total from 1 April through 31 October 2012 was compared with the SNBS total for 2012.

To compare the relative density and trend of loggerhead nesting by the Peninsular Florida subpopulation to the other 4 subpopulations that constitute the western North Atlantic loggerhead population (TEWG 2009), the estimated nesting data presented by Richards et al. (2011) were used.

Reproductive Success. — An evaluation of reproductive success was accomplished by marking a representative sample of nests each season from 1985 through 2012. Nest inventory protocol was standardized in 1988; therefore, only data from 1988 onward were used in our analyses. During each season, the distribution of marked nests within the study area was determined by the spatial/temporal distribution of nests observed over the previous 5 yrs. The sample size of nests inventoried each season necessarily varied from 58 to 260 due to resource constraints, vandalism of stakes marking nests, and the loss of marked nests to storms. The contents of these nests were inventoried after all viable hatchlings had emerged per endangered-species permit guidelines. Six classifications of egg-fates were recognized: depredated by raccoons (*Procyon lotor*), depredated by ghost crabs (*Ocypode quadrata*), washed out by erosion, addled (spoiled), arrested development, and other (pipped eggs, infertile eggs, live and dead hatchlings, infiltration by plant roots). Nests that were known to have been washed out by erosion or completely depredated by raccoons before hatchling emergence occurred were included. In instances where a clutch had not been precounted, the mean number of eggs per clutch for that season was used. We collected data on clutch hatching success (the number of hatchlings that extricated themselves from the egg) and emerging success (the number of hatchlings that emerged from the nest onto the surface of the beach). The mean of each of the 6 egg-fates for inventoried nests, as well as hatching success and emerging success, were calculated for each season.

Spearman *r* correlation was used to determine whether there was a relationship between each of the egg-fates and emerging success. We used Kruskal-Wallis nonparametric analysis of variance (ANOVA) to compare the percentage of eggs in sampled nests lost with each of these egg-fates during nesting seasons affected by major storm events such as tropical storms, hurricanes, and frontal boundaries (storm); no or a few minor storm events (nonstorm); and seasons following major storm events (poststorm). The poststorm category was included because of the increased vulnerability of nests to being washed out during nesting seasons following major storm events. This vulnerability was due to the narrowing of the berm and reduced beach habitat as documented in reports and field notes. The emerging success during storm, nonstorm, and poststorm years was also compared. Dunn's multiple-comparison test was used to determine which, if any, of the data sets were significantly different.

Hatchling emergence was estimated for the ACNWR from 1982 through 2012 by multiplying the total number of nests by the mean of the yearly emerging success rate (1988–2012) and by the mean of the yearly clutch size (1988–2012). The 95% confidence interval (CI) of the hatchling emergence was obtained by multiplying the CIs of the mean emerging success and mean clutch size by the total number of nests.

Tagging and Measuring. — One to 3 pairs of researchers monitored the study beach nightly throughout the season. Effort averaged 4–5 hrs per night. Surveys included marking a subsample of nests for reproductive studies, as well as collecting standard morphometric data and flipper-tagging all turtles encountered. Metal flipper tags were applied to the trailing edge of one or both front flippers. The use of Passive Integrated Transponder (PIT) tags began on a consistent basis in 2010. The standard insertion site was in the right front flipper proximal to the wrist joint. The straight carapace length (SCL), from notch to tip, was measured with forestry calipers. The curved carapace length (CCL), from notch to tip, was measured by using a fiberglass cloth tape. All measurements were to the nearest 0.1 cm.

Interseason Recapture Intervals. — Intervals between captures were determined as the number of years between an individual's reproductive seasons, based on observed recaptures of known tagged individual turtles during subsequent nesting seasons.

RESULTS

Nesting Beach Surveys. — Figure 2 depicts the number of loggerhead nests per year in the ACNWR. Nest numbers during the 1982–1984 and 1986–1988 estimated seasons ranged from 7753 to 10,745. Based on nest counts during daily surveys from 1 April through 30 September 1998–2012, 0.5%–5.7% of loggerhead nesting occurred outside of the survey periods during the estimated seasons (mean = 1.4% ± 0.7%). The observed season nest counts in 1985 and 1989 through 1997 ranged from 9381 to 16,918. Based on the 1998–2012 data, 0.05% to 1.5% of loggerhead nesting may have occurred outside the survey periods (mean = 0.25% ± 0.21%). The nest totals during 1989–2012 observed seasons ranged from 6405 to 17,629. During the 31-yr study period the estimated seasons had a mean of 9091 ± 1186 nests and the observed seasons had a mean of 12,148 ± 1285 nests. The combined

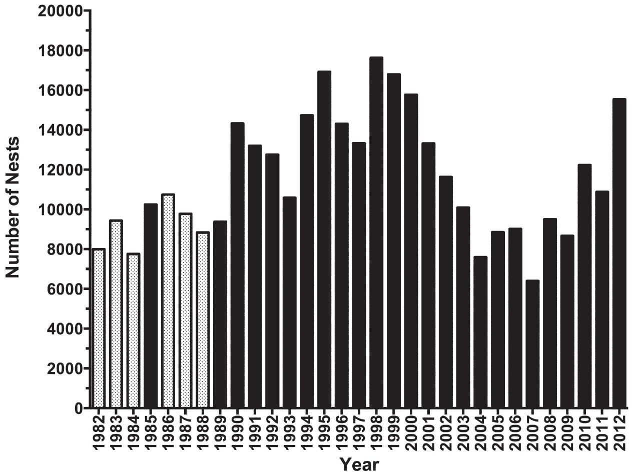

Figure 2. Nest counts per year in the Archie Carr National Wildlife Refuge. The gray bars are estimates extrapolated from 5-d/wk surveys. The black bars are nest numbers enumerated on 7-d/wk surveys.

estimated and observed nest counts had a mean of 11,556 ± 1129 nests. The annual mean number of nests per km ranged from 305 in 2007 to 839 in 1998, with an overall mean of 550 ± 53.8 nests/km.

From 1989 through 2012, the ACNWR accounted for 25.4% ± 0.8% of the mean annual INBS loggerhead nest totals (Fig. 3), yet its beach length is only 5.3% of the INBS total. An examination of Fig. 3 shows that the trend of annual nesting in the ACNWR from 1989 though 2012 follows that of the INBS beaches.

In 2012, there were 98,601 loggerhead nests on 1322 km of beaches participating in the SNBS. Although the ACNWR Beach made up only 1.6% of total length of SNBS beaches, it accounted for 15.8% of the SNBS loggerhead nest total.

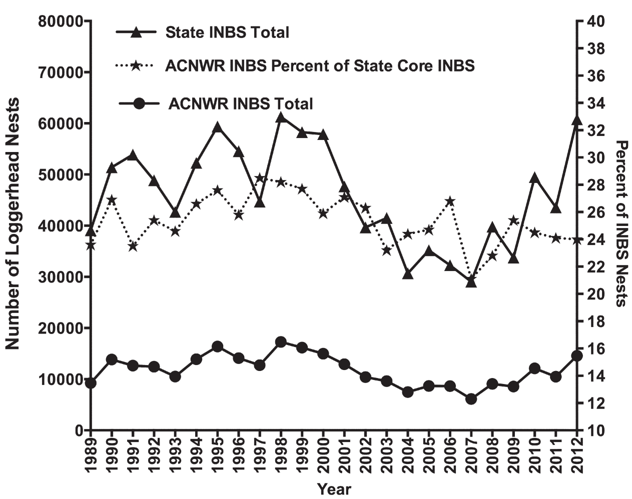

Figure 3. The total number of nests laid each year 1989–2012 by loggerheads on the Index Nesting Beach Survey (INBS) beaches, the Archie Carr National Wildlife Refuge (ACNWNR) INBS nest numbers each year, and the ACNWR percent of the INBS total each year (Fish and Wildlife Research Institute [FWRI]).

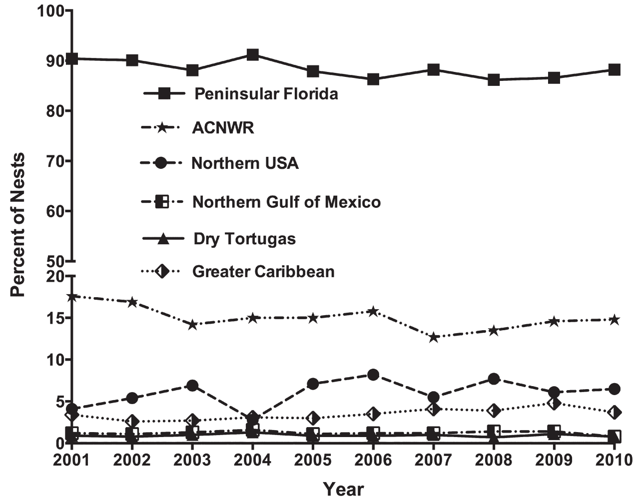

Figure 4. The percent of estimated western North Atlantic loggerhead population total number of nests laid each year, 2001–2010, by females in each of the subpopulations (Richards et al. 2011) and in the Archie Carr National Wildlife Refuge.

Based on data from Richards et al. (2011), the Peninsular Florida subpopulation nesting beaches, which include the ACNWR, accounted for an estimated 88.3% of mean annual loggerhead nesting in the western North Atlantic from 2001 through 2010 (Fig. 4). Of the estimated 645,098 nests laid by all 5 of the western North Atlantic loggerhead subpopulations during that 10-yr period (Richards et al. 2011), the ACNWR contributed approximately 14.5% to the total during that period (using the 93,678 INBS nest counts for the ACNWR; Fig. 4).

Reproductive Success. — Hatching success of inventoried nests (1988–2012) ranged from 33.6% in 2008 (n = 210) to 75.9% in 1988 (n = 58), with a mean of 55.1% ± 4.0%. Emerging success ranged from 32.7% in 2008 (n = 210) to 69.0% in 1988 (n = 58), with a mean of 53.3% ± 3.7%. The mean clutch size from 1988 through 2012 was 114 ± 0.8 eggs (n = 2,868). Clutch sizes ranged from 6 to 194 eggs. An estimated 22,054,148 ± 21,151 hatchlings emerged from all nests over the 31-yr study period. A summary of annual egg-fates for inventoried nests from 1988 through 2012 is in Table 1.

An analysis of the egg-fates of sample nests during storm, poststorm, and nonstorm nesting seasons revealed that the egg-fate classification ''washed out'', as well as the hatching and emerging success rates, varied significantly between the three weather impact categories, while other, addled, arrested development, and depredation by raccoons and ghost crabs did not (Table 2). As expected, the percentage of washed out eggs was significantly greater during storm and poststorm years, compared with nonstorm years, as were the hatching and emerging success rates. The only significant correlation between the 6 egg-fate classifications and emerging success was that with washed out eggs ($r = -0.6986$, 2-tailed $p =$ 0.0001).

Table 1. Summary of mean annual clutch fates for loggerhead nests inventoried in the Archie Carr National Wildlife Refuge (ACNWR) 1988–2012. The years during which storms had a direct impact on the ACNWR are highlighted in dark gray, the post-storm years are highlighted in light gray, and the non-storm years are not highlighted. *n* = number of nests, Rc = raccoons, GC = ghost crabs, WO = washed out, A = addled, AD = arrested development, O = other, HS = hatching success, ES = emerging success.

Year	*n*	Rc	GC	WO	A	AD	O	HS	ES
1988	58	3.4%	1.1%	1.7%	15.1%	4.7%	4.9%	75.9%	69.0%
1989	77	15.6%	1.1%	0.0%	15.4%	6.0%	2.1%	59.9%	59.7%
1990	97	14.7%	2.8%	0.0%	15.8%	3.0%	3.5%	61.1%	60.1%
1991	95	11.7%	1.7%	0.0%	21.4%	9.3%	1.6%	54.5%	54.2%
1992	113	9.7%	3.8%	0.8%	19.3%	3.2%	2.8%	60.8%	60.3%
1993	214	14.8%	2.5%	0.0%	15.0%	5.1%	2.6%	60.7%	60.0%
1994	118	8.7%	4.7%	0.0%	16.2%	3.0%	3.3%	64.3%	64.1%
1995	92	1.3%	3.7%	10.1%	26.1%	5.3%	3.7%	50.0%	49.8%
1996	144	12.4%	4.0%	2.5%	25.3%	3.4%	2.2%	50.4%	50.1%
1997	152	8.0%	11.3%	2.1%	23.4%	3.2%	3.0%	49.7%	49.0%
1998	145	8.3%	4.9%	1.4%	22.5%	5.4%	7.7%	51.4%	49.8%
1999	135	7.4%	1.6%	2.2%	8.4%	14.0%	8.4%	63.1%	57.9%
2000	200	4.0%	5.1%	3.5%	13.4%	7.1%	4.8%	62.6%	62.1%
2001	102	10.6%	5.4%	24.8%	7.7%	6.5%	4.1%	43.1%	40.9%
2002	141	10.8%	5.7%	16.4%	11.2%	2.5%	4.8%	51.2%	48.6%
2003	134	4.5%	8.8%	1.2%	15.3%	3.8%	3.9%	63.9%	62.6%
2004	79	1.0%	6.1%	30.7%	14.5%	3.1%	3.0%	42.4%	41.6%
2005	134	6.0%	4.0%	15.6%	13.8%	5.4%	5.7%	51.5%	49.6%
2006	162	4.6%	3.2%	2.4%	18.1%	6.1%	3.7%	68.7%	61.9%
2007	177	6.1%	3.1%	12.2%	18.1%	4.8%	4.0%	52.1%	51.7%
2008	210	5.8%	6.1%	37.9%	10.6%	5.0%	2.0%	33.6%	32.7%
2009	260	9.4%	2.5%	11.8%	22.7%	6.3%	6.0%	43.5%	41.3%
2010	167	4.0%	1.5%	4.8%	24.7%	9.4%	7.5%	52.6%	48.1%
2011	148	2.8%	3.2%	19.0%	19.7%	7.2%	4.2%	45.6%	44.0%
2012	99	5.5%	1.2%	6.0%	19.7%	2.5%	1.7%	63.7%	63.3%
	Mean 95% CI	7.6% ± 1.7%	4.0% ± 1.0%	8.3% ± 4.3%	17.3% ± 2.1%	5.4% ± 1.1%	4.1% ± 0.8%	55.1% ± 4.0%	53.3% ± 3.7%

Tagging and Measuring. — Metal flipper tags were applied to 6341 individual loggerheads; a combination of flipper tags and PIT tags were applied to 1187 individuals, and 2 turtles received only a PIT tag. The mean SCL from 5640 first-time captures was 91.2 ± 0.15 cm, and ranged from 69.6 to 111.0 cm. The mean CCL from 7014 first-time captures was 98.2 ± 0.15 cm, and ranged from 74.3 to 120.0 cm.

Interseason Recapture Intervals. — There were 837 recaptures of individual loggerheads during subsequent

Table 2. Comparison of the annual mean of each of the loggerhead turtle egg-fates, hatching success, and emerging success between those that occurred during storm, poststorm, and nonstorm years using Kruskal-Wallis (KW) nonparametric ANOVA. S = storm, PS = poststorm, NS = nonstorm, ns = not significant.

Egg-fate	KW statistic	KW *p*-value	Dunn's multiple-comparisons test
Raccoons	1.138	0.566	ns
Ghost crabs	1.109	0.574	ns
Washed out	14.28	0.0008	NS vs. S: $p = 0.01$ NS vs. PS: $p = 0.05$ S vs. PS: $p > 0.05$
Addled	1.296	0.523	ns
Arrested development	0.645	0.724	ns
Other	5.097	0.078	ns
Hatching success	13.69	0.001	NS vs. S: $p = 0.01$ NS vs. PS: $p = 0.05$ S vs. PS: $p > 0.05$
Emerging success	16.20	0.0003	NS vs. S: $p = 0.01$ NS vs. PS: $p = 0.01$ S vs. PS: $p > 0.05$

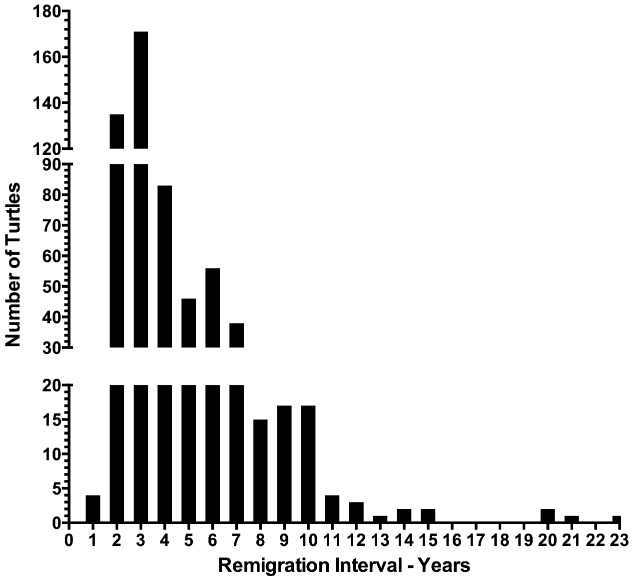

Figure 5. Interseason recapture intervals of loggerhead females observed on the Archie Carr National Wildlife Refuge.

nesting seasons on the ACNWR. The interval between first capture and most recent recapture ranged from 1 to 23 yrs (Fig. 5). Our data showed a sharp decline in the probability of encountering a flipper-tagged turtle > 7 yrs after the first encounter with her. Of the 837 encounters of loggerheads previously tagged on the refuge, 757 (90.4%) had originally been tagged 7 or fewer yrs previously. It was not possible to quantify changes in remigration intervals over time because of the low probability of encountering individual tagged turtles during a given nesting season, and the possibility of external flipper tag loss as evidenced by tag scars of the front flippers.

Turtles Originally Tagged on Other Nesting Beaches. — We encountered 34 loggerheads on the ACNWR that were originally tagged on other nesting beaches. These include 2 from Bald Head Island, North Carolina, USA, 1 each from Jupiter Island and Hutchinson Island in southeast Florida; 1 from Keewaydin Island in southwest Florida; 9 from western central Florida; and 20 from eastern central Florida relatively close to the ACNWR. Table 3 lists the tag numbers, location of original encounter, original encounter date, and the ACNWR encounter date of the turtles tagged on other nesting beaches.

DISCUSSION

The western North Atlantic loggerhead nesting aggregation (WNALNA) is 1 of only 2 worldwide that have > 10,000 females nesting per yr (TEWG 2009); perhaps rivaled in density by that of Masirah Island, Oman (Dodd 1988; Baldwin et al. 2003). The Peninsular Florida subpopulation produces between 80% (TEWG 2009) and 88% (this article) of the nests within the WNALNA (Fig. 4). Of the nesting beaches utilized by the Peninsular Florida aggregation, our data suggest that the ACNWR supports the greatest nest density per kilometer. The rigorous protocol of the INBS program provided data on the nesting trends of the Peninsular Florida loggerheads: over 24 yrs the ACNWR contributed 21.2% to 28.6% of the annual INBS nest totals. For 18 yrs of the 24-yr period, the percentage of ACNWR contribution ranged between 24.2% and 27.0% (Fig. 3). Nest estimates covering 10 yrs for the entire WNALNA (Richards et al. 2011) suggest that the ACNWR supported approximately 14% of the total nesting in the western North Atlantic. These data underscore the importance of the ACNWR as critical loggerhead nesting habitat (US FWS 2014).

The National Research Council's report on the assessment of sea turtle status and trends (2010) emphasized the fact that sea turtles are long-lived and utilize terrestrial, oceanic, neritic, and estuarine habitats as they progress from one life-history stage to another. Nest counts cannot be relied upon solely to judge the overall status of a population (i.e., evidence of a catastrophic decline in juvenile populations may not be seen on the nesting beaches for 10, 20, or more years). The nesting beach habitat, however, is critical to the sea turtle oviparity mode of reproduction and therefore the recovery of the species.

One of the greatest threats to the ACNWR, and other loggerhead nesting beaches globally in the coming decades, is climate change (Hawkes et al. 2009; Fuentes et al. 2010). The Intergovernmental Panel on Climate Change (IPCC; in press) noted that, as a result of climate change, the global sea level has risen 146 mm over the past 112 yrs, the rate of sea-level rise is accelerating, and that sea-level rise will continue beyond the 21st century. Walsh et al. (2014) stated that a 203-mm increase in sea-level rise has occurred since 1880, the rate of rise is accelerating, and sea level may rise another 0.3–1.2 m by the year 2100. Although storm frequency may not increase as a result of climate change, storm intensity may, resulting in larger waves and higher storm surges that would result in coastline erosion (Walsh et al. 2014; IPCC, in press).

Sea-level rise and an increase in storm intensity could potentially impact the ACNWR in 2 fundamental ways. The first includes beach erosion and an overall narrowing of the beach berm within refuge boundaries. Currently, egg and nest loss to erosion is the factor that has the greatest negative impact on the emerging success of hatchlings. Emerging success is typically 14% lower during storm and poststorm years compared with non-storm years. If the rate of egg loss due to erosion increases, it will reduce ACNWR reproductive output. Reece et al. (2013) documented a mean 3.22-m decrease in the ACNWR berm width from 1986 to 2006 and found a strong correlation between berm width and nest placement. Loggerheads tend to nest in the middle of the berm (i.e., the wider the berm, the further nests are from the high-tide line; the narrower the berm, the closer they are to the high-tide line). If the berm width continues

Table 3. Loggerheads observed nesting on the Archie Carr National Wildlife Refuge (ACNWR) that were originally tagged on other nesting beaches. CNS = Canaveral National Seashore, MINWR = Merritt Island National Wildlife Refuge, CCAFS = Cape Canaveral Air Force Station.

Tag no.	Location of original encounter - state	Original encounter date	ACNWR encounter date	Intervening days	Intervening years
QQR540 QQR544	Bald Head Isl. - NC	10 Jun 1993	19 Jul 1993	39	0.11
4703471413 RRZ233 RRZ234	Bald Head Isl. - NC	8 Jul 2008	29 May 2011	1055	2.89
D4118 FL1901	CNS - FL	Unknown	12 Aug 1985	—	—
D3951 G1283 H1457	MINWR, CCAFS - FL	7 Jun 1976	17 Jul 1986	3692	10.11
D4116 H1906	MINWR, CCAFS - FL	6 Jun 1978	11 Aug 1985	2623	7.18
H1955	MINWR, CCAFS - FL	12 Jun 1978	26 Jul 1985	2601	7.12
H2237	MINWR, CCAFS - FL	6 Jul 1978	13 Jul 1982	1468	4.02
D3898 P1199	MINWR, CCAFS - FL	2 Jun 1979	29 May 1985	2188	5.99
H2751	MINWR, CCAFS - FL	21 Jun 1979	31 May 1982	1075	2.94
P1069	MINWR, CCAFS - FL	21 Jun 1979	5 Jul 1988	3302	9.04
D3499 H2781	MINWR, CCAFS - FL	25 Jun 1979	25 Aug 1983	1522	4.17
H2781 H3959	MINWR, CCAFS - FL	25 Jun 1979	7 Jun 1989	3635	9.95
D3198 H2808	MINWR, CCAFS - FL	30 Jun 1979	14 Jun 1982	1080	2.96
D3190 H3028	MINWR, CCAFS - FL	17 Jul 1979	14 Jun 1982	1063	2.91
D4040 H3134	MINWR, CCAFS - FL	24 Jul 1979	1 Jul 1985	2169	5.94
D3418 H3542	MINWR, CCAFS - FL	5 Jul 1980	26 Jun 1983	1086	2.97
NAS220 NAS221	MINWR, CCAFS - FL	11 May 2002	25 May 2002	14	0.04
KSC290 W6276	MINWR, CCAFS - FL	29 May 2004	19 Jul 2004	51	0.14
KSC484 W5685 W5686	MINWR, CCAFS - FL	18 Jun 2004	29 Jul 2004	41	0.11
KSC514 W6208	MINWR, CCAFS - FL	1 Jul 2004	29 Jul 2004	28	0.08
AAV302 X3182	Northern Indian River Co., FL	17 Jul 1987	29 May 1992	1778	4.87
K8847 N4468	Northern Indian River Co., FL	15 May 1991	3 Jun 1994	1115	3.05
D3299 JI3171	Jupiter Island - FL	2 Jul 1977	12 Jul 1982	1836	5.03
4B66241A45 HA8253 YYS037	Hutchinson Island - FL	24 Jun 2008	2 Jun 2010	708	1.94
SSZ607	Keewaydin Island - FL	29 May 1999	11 May 2002	1078	2.95
4C12796130 HA9625 PPN594	Manasota Key - FL	4 Jul 1988	4 Aug 2011	8431	23.08
HA3291 SSB404	Manasota Key - FL	12 Jun 1997	25 Jul 2008	4061	11.12
W5222 XXC797	Manasota Key - FL	7 Jun 2000	10 Jun 2004	1464	4.01
N4661 PPH816	Casey Key - FL	26 Jul 1987	5 Jul 1994	2536	6.94
QQE679 QQE680	Casey Key - FL	28 Jun 1990	4 Jul 1992	737	2.02
N6348 QQM149 QQM150	Casey Key - FL	15 Jul 1991	21 Aug 1995	1498	4.10
HA525 QQM963	Casey Key - FL	13 Jul 1996	20 May 2007	3963	10.85
42394B211F EEG387 XXM568	Casey Key - FL	22 Jun 2001	16 Jul 2012	4042	11.07
XXX278 XXX279	Casey Key - FL	6 Jun 2003	28 Jul 2007	1513	4.14

to narrow, a greater proportion of nests will be closer to the high-tide line, thus becoming more vulnerable to erosion.

The other potential impact is coastal armoring by the installation of seawalls and rock revetments in response to beach erosion (National Marine Fisheries Service [NMFS] and US FWS 2008). Within the refuge, 65.5% of the land adjacent to the beach is under private or commercial ownership. Based on the 2013 market value of 10 randomly selected undeveloped beachfront lots within the ACNWR from the Brevard County Property Appraiser's Web site (https://www.bcpao.us/asp/record.asp), the mean property value along the nesting beach is US$14,100 per linear meter of beachfront, or a total value of approximately US$194,000,000. That amount does not include the value of structures that have been built on individual plots of property, which add tens if not hundreds of millions of dollars to the figure above. Historically, armoring of eroding beaches along the US Atlantic, Gulf of Mexico, and Pacific coastlines has increased over time (Pilkey and Wright 1988; Fletcher et al. 1997; Dugan et al. 2008; Griggs 2010; Noss 2011; Witherington et al. 2011). Armoring can reduce marine turtle nesting success (Mosier 1998; Witherington et al. 2011). It can accelerate beach erosion in front of armored properties and adjacent nonarmored properties (Fletcher et al. 1997; Griggs 2010) and reduce berm width (Pilkey and Wright 1988). Should armoring be used to protect private and commercial properties along the ACNWR beachfront, the resulting loss of the nesting habitat could be catastrophic for this loggerhead rookery. With the projected sea-level rise and increase in storm intensity, the pressure to armor will likely increase not only along the ACNWR, but also along most of the other nesting beaches utilized by the Northern, Peninsular Florida, and Northern Gulf of Mexico subpopulations with the same effect on those rookeries.

With the exception of nesting loggerheads in Columbia (mean SCL: 87.7 cm), the mean SCL of ACNWR loggerheads (91.2 cm) is similar to that reported from other Atlantic rookeries (Kamezaki 2003). The minimum SCL recorded in the refuge (69.6 cm) may be the smallest nesting female reported for the region (TEWG 2009).

We attribute the low recapture rate of turtles after 7 yrs to low encounter rates and to tag loss. Because of high nest density, the linear extent of the study area, and the limited personnel available to patrol the beach at night, the chance of encountering loggerheads tagged in previous years was relatively low as compared with other tagging programs (e.g., Phillips et al. 2014).

Loss of external flipper tags is a phenomenon observed in many marine-turtle research projects (Reisser et al. 2008). The expanded use of PIT tags and distribution of PIT-tag readers will help to alleviate this problem. We began applying PIT tags in the ACNWR on a consistent basis in 2010. Continued use of PIT tags and studies designed to encounter nesting females on the ACNWR will help ''ground truth'' estimates of loggerhead reproductive longevity in the future.

Given the variation in tagging effort on nesting beaches in the southeastern United States, it is difficult to interpret the encounters with nesting females on the ACNWR that were originally tagged on other nesting beaches (Table 3). These efforts range from long-term saturation tagging projects on Bald Head Island, North Carolina, and Keewaydin Island, Florida (TEWG 2009; Phillips et al. 2014), to a long-term project on Casey Key, Florida, where 35%–40% of the turtles on the beach were encountered (A. Tucker, *pers. comm.*, October 2013), to sporadic tagging efforts on Hutchinson and Jupiter islands (P. Eliazar, *pers. comm.*, October 2013). It should be noted that the latter 2 account for approximately 22% of the total INBS loggerhead nesting (FWRI unpubl. data, 2013). An intensive tagging program was conducted on Cape Canaveral Air Force Station and Merritt Island NWR beaches from 1975 through 1981 by the UCFMTRG, but efforts have been sporadic and of low intensity since that time (M. Carroll, J. Provancha, *pers. comm.*, October 2013).

Based on mtDNA analysis, Shamblin et al. (2011) suggested that the Peninsular Florida Recovery Unit identified by the Atlantic Loggerhead Sea Turtle Recovery Team (NMFS and US FWS 2008) be divided into the Central Eastern Florida Recovery Unit, the Southern Florida Recovery Unit, and the Central Western Florida Recovery Unit. This would identify 7 distinct recovery units (RU), the Northeastern United States, the Dry Tortugas, the Northern Gulf of Mexico, and the Greater Caribbean RUs, plus the 3 proposed by Shamblin et al. (2011). Our encounters with the 2 females from the Northeastern RU (Bald Head Island, North Carolina), 3 from the Southern Florida RU (Jupiter Island, Hutchinson Island, and Keewaydin Island), and 9 from the Central Western Florida RU document maternal gene flow from one rookery to another, albeit at what is probably a low level. The other 20 females were first tagged on beaches within the Central Eastern RU.

Summary

The loggerhead recovery plan (NMFS and US FWS 2008) listed sea-level rise and coastal armoring as threats to the nesting beach habitat. The ACNWR arguably supports the greatest density of loggerhead nesting for the western North Atlantic population. The ongoing UCFMTRG nesting beach program at the ACNWR is providing long-term data on nesting and reproductive success, which is a component of the vital rates data required to recover the western North Atlantic population of this threatened species.

The high density of loggerhead nesting and the value of the data obtained by the long-term study underscore the importance of the ACNWR rookery. Representing approximately 14% of the annual western North Atlantic loggerhead reproductive output, the ACNWR serves as an ''indicator'' rookery for the overall population. A strategic plan is required to buffer the ACNWR and other high-density nesting beaches from the impacts of sea-level rise and, if history provides an insight into the future, the urge to armor the beaches that will inevitably arise.

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