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The Sea Turtle Rookery at Gnaraloo Bay, Western Australia: Using Nocturnal Observations to Validate Diurnal Track Interpretations

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ABSTRACT. – **Critical gaps remain in our understanding of many sea turtle nesting aggregations in remote or undeveloped regions. Here, we summarize the first 8 yrs of systematic monitoring of the rookery at Gnaraloo Bay, Western Australia. Diurnal track surveys on this approximately 7-km mainland beach were conducted daily during nesting seasons 2008/09 to 2015/16. The total number of emergences (i.e., nests and failed nesting attempts) recorded per season ranged from 480 to 813 (mean = 679.0, SE = 49.1), whereas the number of nests ranged from 305 to 522 (mean = 376.0, SE = 26.7). Peak nesting activity occurred between mid-December and late January, with approximately 70 emergences and 35 nests recorded on average per week during this time. The majority (97%) of emergences and nests were from loggerhead turtles (*Caretta caretta*), whereas the remainder (3%) were from green turtles (*Chelonia mydas*). The number of loggerhead turtle emergences recorded per season declined significantly over the course of the study, wheras the number of nests did not, although we suspect that nest detection errors contributed to the difference between trends. We conducted nocturnal surveys (i.e., direct observations) during parts of seasons 2010/11 to 2015/16 to validate diurnal track interpretations and assess potential biases in the diurnal data set. Diurnal nest counts for loggerhead turtles were underestimates in all seasons but one, with an average nest detection bias of –13.0% (SE = 3.0). After accounting for this bias, we estimate that approximately 405 nests are dug by 85 female loggerhead turtles in the Gnaraloo Bay survey area annually. A similar or slightly lower amount of loggerhead turtle nesting activity occurs at the Cape Farquhar survey area, also located on the Gnaraloo coast; thus, this region contains previously underreported nesting aggregations of this species. The Gnaraloo rookeries may play an important role in the dynamics of the southeast Indian Ocean loggerhead turtle subpopulation and may still be depleted relative to historic levels due to historical predation by introduced foxes. Monitoring, research, and the protection of Gnaraloo beaches are, therefore, critical at this juncture.**

KEY WORDS. – **Cape Farquhar; detection probability; Gnaraloo Turtle Conservation Program; green turtle; loggerhead turtle; Ningaloo**

Monitoring and protecting nesting beaches is critical for the successful conservation of sea turtles. Although some rookeries around the world are now well studied (e.g., Chaloupka et al. 2008; Witherington et al. 2009), many other nesting aggregations, especially those in remote or undeveloped regions, remain undescribed or poorly monitored (Wallace et al. 2011). The tendency to focus on a few well-protected, high-density nesting sites is a risky conservation strategy for two reasons (McClenachan et al. 2006). First, large-scale sea turtle population declines occurred throughout much of the world prior to the onset of quantitative monitoring (Jackson 1997). Therefore, we lack an adequate understanding of the historical sizes and importance of rookeries that may currently comprise relatively few individuals. Thus, if we assume that small present-day rookery sizes reflect historical abundances, we risk accepting depleted population levels as normal (i.e., shifted baselines [Pauly 1995]). Second, by focusing conservation efforts on one or a few high-density nesting beaches, we risk significant population consequences if extreme events (e.g., storms, disease) cause abrupt, large-scale nest loss at these sites or if negative nesting trends on these beaches cannot be reversed (McClenachan et al. 2006). Thus, attention should also be given to identifying, monitoring, and protecting smaller rookeries, particularly in understudied regions.

The loggerhead turtle (*Caretta caretta*), which is our primary focus here, has been divided into 10 suggested regional management units (RMU) based on available nesting, genetic, and movement data (Wallace et al. 2010). The southeast Indian Ocean RMU is among the least well studied of these. All known nesting by loggerhead turtles in the southeast Indian Ocean occurs in Western Australia (WA) (Dodd 1988; Baldwin et al. 2003; Conant et al. 2009; Limpus 2009). However, because of the location of many nesting sites on remote islands and mainland beaches in this sparsely populated state, few data sets are

available to allow assessment of abundance trends over meaningful spatial and temporal scales. Furthermore, the complementary biological data needed to develop models of population dynamics and inform management planning (e.g., clutch frequencies, remigration intervals, survival rates, migratory routes) are still lacking for this region (Hamann et al. 2013). A critical step toward filling these knowledge gaps is to identify breeding locations in remote parts of WA and establish long-term monitoring programs at these sites.

The Ningaloo Coast World Heritage Area is an International Union for Conservation of Nature (IUCN) World Heritage Site that stretches over the 260-km-long Ningaloo Reef. At the southern extreme of the Ningaloo Coast lies Gnaraloo Station, a pastoral station that is situated adjacent to 65 km of coastline of the Ningaloo Marine Park including several remote beaches where sea turtle nesting is known to occur (Hattingh et al. 2011; Riskas 2014). Systematic, diurnal track surveys of a 7.2-km beach at Gnaraloo Bay during the nesting season commenced in 2008/09. However, no detailed description of this rookery or analysis of temporal nesting trends at this location has yet been published in the peer-reviewed literature.

Although diurnal track surveys represent a simple method of monitoring sea turtle rookeries, the data collected are indirect indices of nesting behavior, which are subject to errors because identifying successful nests based on track characteristics can sometimes be challenging even for experienced observers (Schroeder and Murphy 1999). Nest detection errors, which may result from track degradation or masking (e.g., attributable to high winds or the presence of dense vegetation) or observer misinterpretation, can have important implications for conservation and management decision making (Pfaller et al. 2013). As such, it is important for monitoring programs that rely on visual track interpretation to attempt to validate track assessments and evaluate the effect of observation error on nest counts (Schroeder and Murphy 1999).

Here, our goals are to 1) provide the first detailed description and trend analysis for the sea turtle rookery at Gnaraloo Bay based on 8 yrs (2008/09 to 2015/16) of diurnal track surveys conducted daily throughout the nesting season; and 2) use direct observations of turtle nesting activity obtained via nocturnal surveys during part of 6 nesting seasons to validate track interpretations and assess potential biases in the diurnal data set. Thus, we aim to fill an important knowledge gap for sea turtles in the Ningaloo region while simultaneously advancing nesting beach survey methodology more broadly.

METHODS

Study Site and Species. — Gnaraloo Station is a pastoral station that covers 81,044 ha on the central west coast of Australia roughly 1100 km north of the city of Perth. After 1 July 2015, land tenure on the Gnaraloo coastline reverted to the WA state government following previous pastoral tenure. Gnaraloo Bay (Fig. 1) is a shallow, 7.2-km embayment on the Gnaraloo coast that provides nesting habitat for loggerhead turtles, green turtles (*Chelonia mydas*), and possibly (see "Methods: Diurnal Track Surveys") hawksbill turtles (*Eretmochelys imbricata*) (Hattingh et al. 2011). The topography of the Gnaraloo Bay shoreline ranges from wide and flat, low-energy beaches at the southern end to narrow and steep, high-energy beaches backed by large, dynamic dune systems at the northern end. Vegetation is sparse, primarily comprising low-lying shrubs on or behind the dunes, and the beaches are fringed by rocky and coral reef interspersed with sand-bottomed channels. Here, we report on surveys conducted along 6.7 km of Gnaraloo Bay (–23.76708° S, 113.54584° E to –23.72195° S, 113.57750° E) located adjacent to and immediately north of the Gnaraloo Bay Marine Sanctuary Zone of the Ningaloo Marine Park (hereafter the Gnaraloo Bay survey area). Although some nesting is also known to occur outside these limits, we restricted surveys to this stretch of beach because of operational, logistical, and financial considerations.

Diurnal Track Surveys. — We conducted diurnal track surveys at Gnaraloo Bay beginning at sunrise for 120 consecutive days between 1 November and 28 February during each nesting season from 2008/09 to 2014/15, although minor deviations from this timing occurred. Specifically, season 2008/09 began on 1 December 2008, whereas season 2010/11 ran from 13 November 2010 to 4 February 2011, with one additional day missed because of a cyclone. Thus, numbers for these seasons may be conservative. Four days were missed during season 2011/12, and 1 d was missed during season 2012/13. Overall, the mean number of days surveyed per season was 110.9 (SE = 5.5).

A seasonal field team of scientific observers, usually comprising 2 to 6 people, was recruited and trained in turtle track interpretation at the beginning of each season following established protocols (Schroeder and Murphy 1999). We divided the Gnaraloo Bay survey area into subsections, and an observer walked each subsection at the high tide line every morning to record and interpret turtle tracks. We grouped nesting activities into 1 of 3 classes based on visual inspection of tracks (Schroeder and Murphy 1999): 1) nests; 2) unsuccessful nesting attempts, in which the turtle appeared to dig one or more body pits but abandoned the nesting attempt without laying; and 3) U-tracks, in which a turtle emerged from the ocean but appeared to return without attempting to dig. We use the term "failed nesting attempts" to refer to unsuccessful nesting attempts and U-tracks collectively. A GPS position was recorded for each activity, and once recorded, the activity was crossed off to avoid being counted on subsequent days.

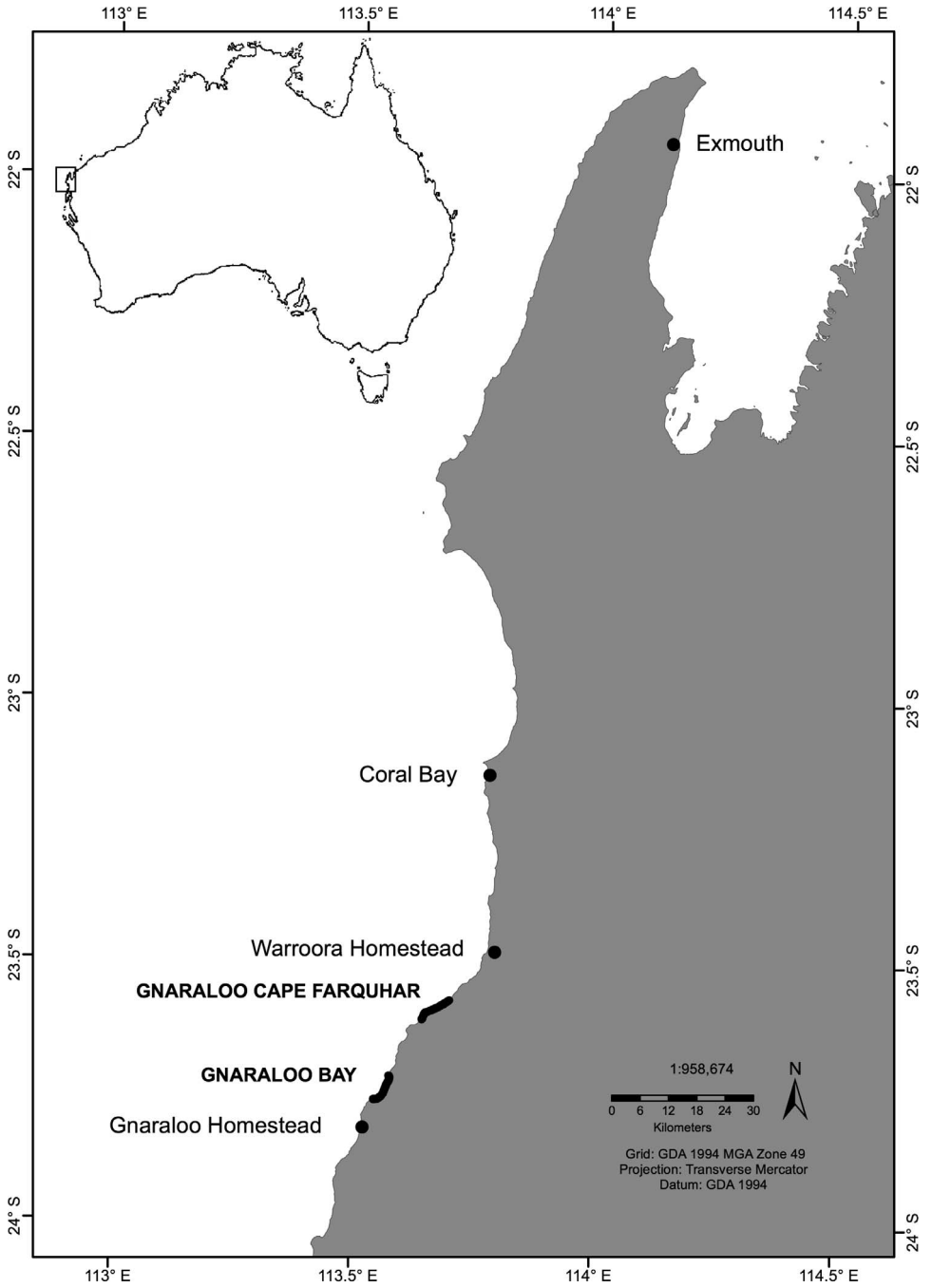

Figure 1. Map showing the location of Gnaraloo Bay and Gnaraloo Cape Farquhar on the central Western Australia coast.

Hawksbill turtles are known to nest at some sites on the Ningaloo Coast—although much more rarely than green and loggerhead turtles (Markovina 2015)—but had not been confirmed at Gnaraloo prior to the start of our study. Because hawksbill turtle tracks can be extremely difficult to distinguish from small loggerhead turtle tracks, and loggerhead turtles are much more common in the region, hawksbill track classifications in our study had considerable potential for error. A significant number of tracks in the Gnaraloo Bay survey area were initially suspected to be from hawksbill turtles (14, 78, 2, 0, 1, 5, 0, and 2 suspected hawksbill turtle tracks recorded by observers during seasons 2008/09 to 2015/16, respectively). However, nocturnal surveys (see "Methods: Nocturnal Direct Observation Surveys") began in 2010/11, and we have since directly observed 441 turtles in the Gnaraloo Bay survey area (this would include multiple sightings of the same turtles because they were not tagged; hence, individuals could not be recognized). No hawksbill turtles have been seen. In contrast, the low proportion of tracks ascribed to green turtles during diurnal surveys has aligned closely with the proportion of green turtles seen during nocturnal surveys. Furthermore, the proportion of tracks ascribed to loggerhead turtles during diurnal surveys was

initially lower than the proportion seen during nocturnal surveys but was equivalent if putative hawksbill tracks were reclassified as loggerhead turtle tracks (see "Results: Species Composition"). Based on this evidence, we retroactively changed all hawksbill turtle tracks in the diurnal data set to loggerhead turtle tracks prior to data summary and analysis to minimize species identification errors.

Nocturnal Direct Observation Surveys. — We conducted nocturnal surveys during a subset of seasons 2010/11 to 2015/16 (at the start of each season) to validate diurnal track assessments and quantify possible nest detection bias in the diurnal data set. During these surveys, the northern end of the Gnaraloo Bay survey area, where the majority of nesting activity is known to occur (Hattingh et al. 2011), was searched systematically by 2 researchers for up to 6 hrs per night with the goal of verifying as many activities as possible. When a turtle was located, it was observed until the species and nesting activity could be verified. For a nest to be considered verified, the turtle had to be encountered during the laying phase at the latest and witnessed depositing eggs into the egg chamber. For an unsuccessful nesting attempt to be considered verified, the turtle had to be encountered during the egg chamber phase at the latest and observed returning to the ocean without laying. For a U-track to be considered verified, the turtle had to be encountered during the emergence phase at the latest and witnessed returning to the ocean without attempting to dig. Nesting activities where the turtle was seen after these respective stages (e.g., while returning to the ocean) were excluded to maintain zero error in the nocturnal survey data set. No communication regarding nesting activities was allowed between nocturnal and diurnal observers to ensure independence of the observations.

Data Summary. — When errors were identified in diurnal track assessments based on comparison with nocturnal observations, they were corrected (i.e., replaced with nocturnal data) prior to summary and analysis. The dates and locations of failed nesting attempts were not recorded during diurnal surveys in 2008/09, and some emergences occurred outside the standard survey area and monitoring period during that season. Therefore, for 2008/09, only the nest total is reported (emergence total omitted). All necessary data were recorded for all activity types in the remaining seasons.

Species composition was calculated, using both diurnal and nocturnal data, by dividing the number of emergences or nests observed for a given species by the total number of emergences or nests observed within each season for all species pooled. Activities for which the species could not be confidently determined were excluded from these calculations. Subsequent analyses were restricted to loggerhead turtles owing to the paucity of observations of other species (see "Results: Species Composition"). Loggerhead turtle nesting success was calculated, using both diurnal and nocturnal data, by dividing the number of nests by the total number of emergences within each season. Unidentified activities were excluded from nesting success calculations.

To evaluate nest detection bias in the diurnal data set, we extracted all verified nocturnal loggerhead turtle observations and their corresponding diurnal track interpretations. This included cases in which a verified nesting activity was missed entirely (e.g., tracks covered by blown sand) during diurnal surveys or was incorrectly assigned to another species. The nocturnal nest count for a given season, N_i, was taken to represent the true (i.e., expected) value and the diurnal nest count, D_i, the experimental (i.e., observed) value. We calculated the percent error between the two (i.e., nest detection bias) as $(D_i - N_i)/N_i \times 100$. Because of low sample size in 2011/12, we pooled data for all years before calculating and applying a nest detection bias correction factor (c) to unverified diurnal nest counts. We calculated c as $\Sigma N_i/\Sigma D_i$. To estimate the bias-adjusted number of loggerhead turtle nests laid in the Gnaraloo Bay survey area per season (N_e), we used the following formula: $N_e = (\Sigma N_{vi} + c \times \Sigma N_{ui})/8$, where N_{vi} and N_{ui} are the season-specific verified and unverified nest counts, respectively, c is the nest detection bias correction factor, and 8 is the number of seasons surveyed.

To estimate the number of female loggerhead turtles likely nesting in the Gnaraloo Bay survey area, we consulted the literature for clutch frequency estimates derived from satellite telemetry. We used telemetry-based estimates because they more accurately reflect true clutch frequency than survey-based estimates because nesting events may be missed during beach surveys if they are outside a prescribed survey area or period or are simply not detected (Tucker 2010). We calculated the mean and SD of the estimated clutch frequencies (ECF) found in currently available studies (see "Results: Estimated Number of Females"). We then divided the total number of nests observed during diurnal surveys within each season, as well as N_e, by the mean ECF and the mean ECF $\pm$ 1 SD.

Trend Analysis. — We used generalized linear regression models with Poisson-distributed errors in R v. 3.0.2 (R Core Team 2013) to evaluate variation in the number of loggerhead turtle emergences and nests recorded during diurnal surveys in the Gnaraloo Bay survey area across seasons. If overdispersion was detected in initial regression models, we refitted the models using a quasi-Poisson error structure (Zuur et al. 2009). We used general linear regression models in R to evaluate variation in the loggerhead turtle nesting success rate and nest detection bias across seasons. Seasons were coded as integer data, with the first season for each data set coded as 0.

RESULTS

Abundance and Timing of Nesting Activity. — The total number of emergences recorded in the Gnaraloo Bay survey area per season ranged from 480 to 813

Table 1. Summary of nesting activity in the Gnaraloo Bay survey area during 2008/09 to 2015/16. The estimated number of females (loggerhead turtles only) was obtained by dividing the season-specific nest count by a telemetry-derived mean estimate of clutch frequency (ECF) and the mean ECF ± 1 SD.

Species	Nesting season	Emergences (diurnal surveys)	Nests (diurnal surveys)	% of emergences (diurnal surveys, identified spp. only)	% of nests (diurnal surveys, identified spp. only)	Estimated no. of females (lower, upper error bounds)
Loggerhead	2008/09	—	319	—	98.2	67 (61, 74)
	2009/10	731	480	92.4	94.1	100 (92, 111)
	2010/11	758	399	98.1	98.0	83 (76, 92)
	2011/12	700	324	93.0	92.8	68 (62, 75)
	2012/13	672	303	98.5	97.7	63 (58, 70)
	2013/14	635	424	98.4	98.6	89 (81, 98)
	2014/15	528	328	100.0	100.0	69 (63, 76)
	2015/16	479	304	100.0	100.0	64 (58, 70)
Green	2008/09	—	6	—	1.8	—
	2009/10	60	30	7.6	5.9	—
	2010/11	15	8	1.9	2.0	—
	2011/12	53	25	7.0	7.2	—
	2012/13	10	7	1.5	2.3	—
	2013/14	10	6	1.6	1.4	—
	2014/15	0	0	0.0	0.0	—
	2015/16	0	0	0.0	0.0	—
Unidentified	2008/09	—	11	—	—	—
	2009/10	22	12	—	—	—
	2010/11	28	14	—	—	—
	2011/12	16	0	—	—	—
	2012/13	17	2	—	—	—
	2013/14	7	2	—	—	—
	2014/15	11	3	—	—	—
	2015/16	1	1	—	—	—

(mean = 679.0, SE = 49.1; Table 1), whereas the total number of nests recorded ranged from 305 to 522 (mean = 376.0, SE = 26.7; Table 1). Nesting in the Gnaraloo Bay survey area began on 2 November at the earliest and ended on 28 February at the latest, although some nesting likely occurred outside these dates. Peak nesting activity occurred between mid-December and the end of January (Fig. 2). During this time, the Gnaraloo Bay survey area received an average of approximately 70 emergences and 35 nests per week.

Species Composition. — Based on diurnal survey track assessments, loggerhead turtles constituted an average of 97.2% (SE = 1.2) of emergences and 97.4% (SE = 0.9) of nests in the Gnaraloo Bay survey area. Green turtles constituted the remaining 2.8% (SE = 1.2) of emergences and 2.6% (SE = 0.9) of nests (Table 1). These estimates do not include the small proportion of tracks that could not be identified to species (Table 1). Similarly, based on nocturnal observations ($n = 441$), loggerhead turtles constituted an average of 97.8% (SE = 2.0) of emergences and 97.9% (SE = 2.1) of verified nests, while green turtles constituted the remaining 2.2% (SE = 2.0) of emergences and 2.1% (SE = 2.1) of verified nests. Because of the paucity of green turtle observations, only loggerhead turtle data are analyzed in subsequent sections.

Emergence and Nesting Trends. — The number of loggerhead turtle emergences recorded in the Gnaraloo Bay survey area declined significantly from 2009/10 to 2015/16 ($\chi^2_1 = 91.30$, $p < 0.01$; Fig. 3), whereas the number of loggerhead turtle nests recorded showed no trend from 2008/09 to 2015/16 ($\chi^2_1 = 10.88$, $p = 0.34$; Fig. 3).

Nesting Success. — Based on diurnal track surveys, an average of 58.0% (SE = 3.4, range = 46.6–67.7) of loggerhead turtle emergences resulted in a nest. Based on verified nocturnal observations, an average of 69.3% (SE = 2.1, range = 61.1–76.3) of loggerhead turtle emergences resulted in a nest (Fig. 4). The nesting success rate showed no significant trend when estimated using diurnal survey data from 2009/10 to 2015/16 ($F_{1,5} = 0.45$, $p = 0.53$, $r^2 = 0.08$) or nocturnal survey data from 2010/11 to 2015/16 ($F_{1,4} = 1.88$, $p = 0.24$, $r^2 = 0.32$; Fig. 4).

Nest Detection Bias. — During seasons 2010/11 to 2015/16, we verified a total of 327 loggerhead turtle nesting activities in the Gnaraloo Bay survey area via direct observation during nocturnal surveys. Nest counts obtained from nocturnal direct observation surveys were consistently higher than counts derived from diurnal track surveys during the overlapping sampling period, with the exception of season 2015/16 (0% nest detection bias; Table 2). The season-specific percent error between nocturnal nest counts and diurnal nest counts ranged from − 21.4% to 0.0% (mean = –13.0, SE = 3.0; Table 2) and declined significantly in magnitude from 2010/11 to 2015/16 ($F_{1,4} = 14.77$, $p = 0.02$, $r^2 = 0.79$; Table 2). In total, 64 misclassifications involved nests. Of the 46 errors that led to negative nest detection bias, 30 (65.2%) resulted from nests being misclassified as failed nesting attempts, 11 (23.9%) arose from nests being missed entirely, 3 (6.5%) involved loggerhead turtle nests being ascribed to green

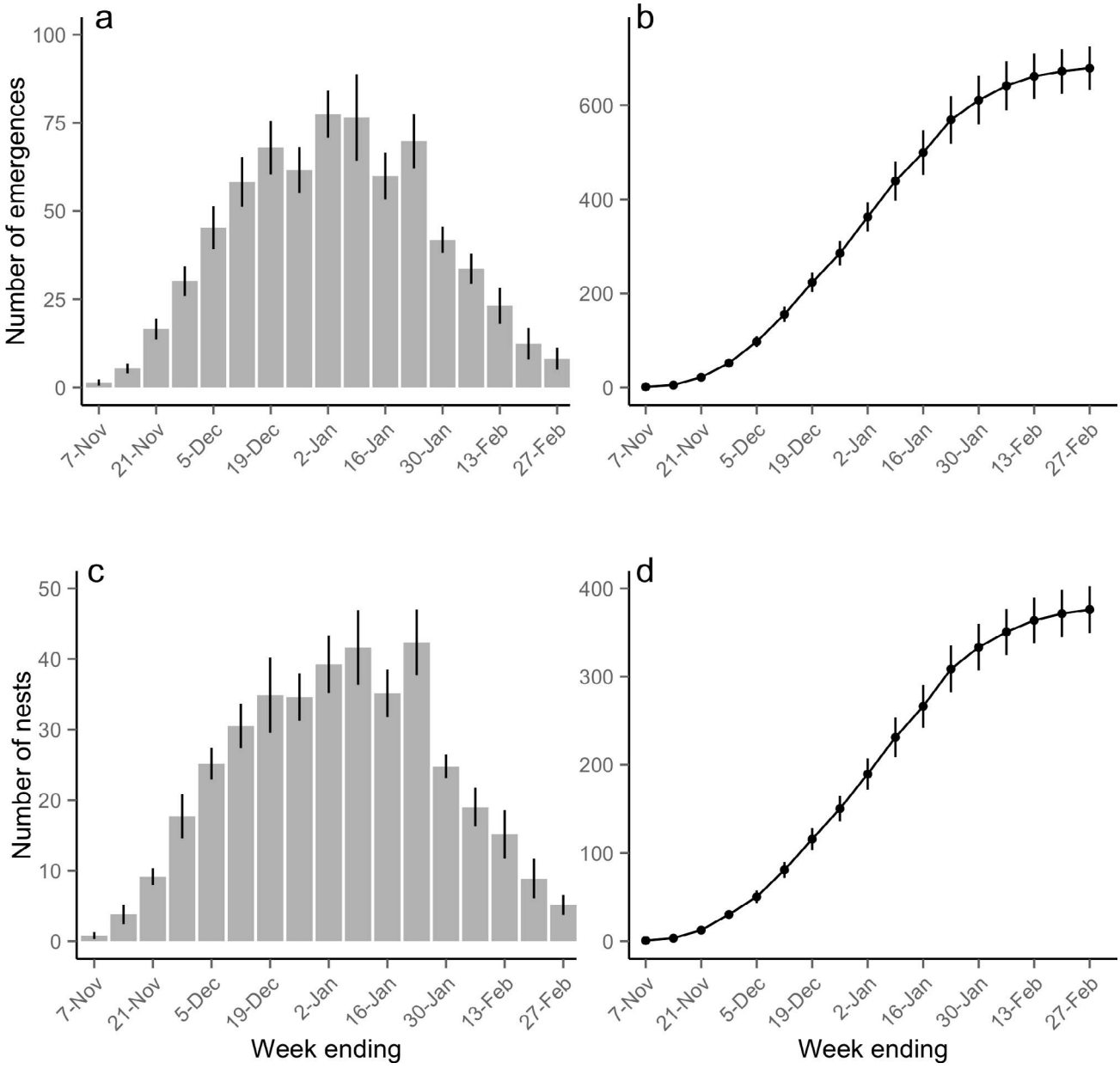

Figure 2. Weekly emergences (a), cumulative weekly emergences (b), weekly nests (c), and cumulative weekly nests (d) for all species pooled from diurnal track surveys in the Gnaraloo Bay survey area from 2008/09 to 2015/16. Note that the dates and locations of failed nesting attempts were not recorded in 2008/09; therefore, this season's data are not included in a and b. Weeks with incomplete surveys were excluded from a and c. Error bars are ± 1 SE.

turtle, and 2 (4.3%) resulted from tracks being designated as unknown activities. Of the 18 errors that led to positive nest detection bias, all consisted of failed nesting attempts being misclassified as nests. The nest detection bias correction factor (c) for all seasons pooled was 1.14, and the bias-adjusted estimated number of loggerhead turtle nests per season (N_e) was 405.

Estimated Number of Females. — Four available telemetry-based loggerhead turtle clutch frequency estimates (Scott 2006; Rees et al. 2008, 2010; Tucker 2010) yielded a mean value of 4.78 (SD = 0.45). Season-specific estimates of the number of nesting female loggerhead turtles per season are provided in Table 1. Using the bias-corrected estimate of 405 loggerhead turtle nests per season, we estimate that 85 female loggerhead turtles nest in the Gnaraloo Bay survey area annually (uncertainty based on the mean ECF ± 1 SD = 77–94).

DISCUSSION

The conservation status of loggerhead turtles based on IUCN Red List criteria has recently been downgraded globally from Endangered to Vulnerable (Casale and Tucker 2015) and assessed as Near Threatened for the southeast Indian Ocean RMU (Casale et al. 2015). However, these assessments note that the species is now largely dependent on conservation efforts and that data

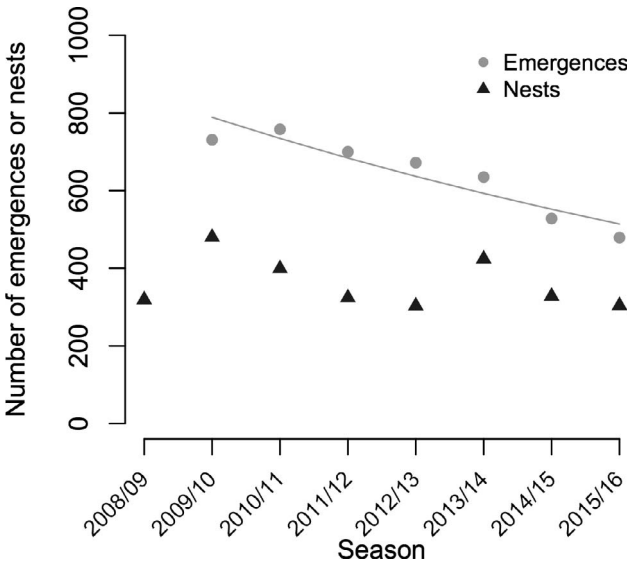

Figure 3. Interseasonal variation in the total number of loggerhead turtle emergences and nests recorded in the Gnaraloo Bay survey area from 2009/10 to 2015/16 (emergences) and 2008/09 to 2015/16 (nests).

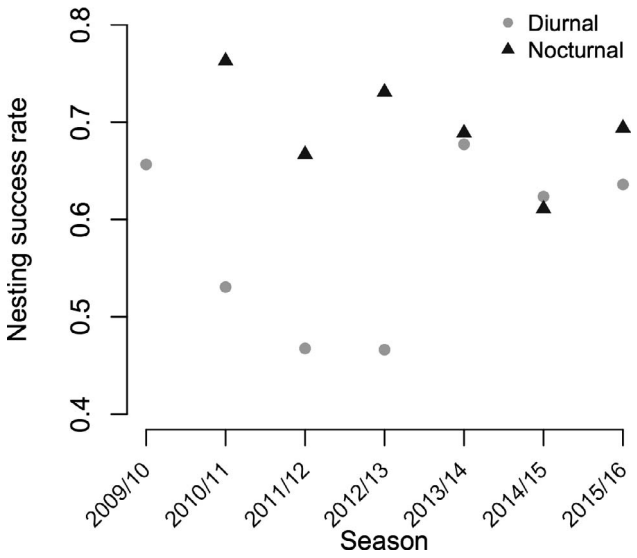

Figure 4. Interseasonal variation in the loggerhead turtle nesting success rate in the Gnaraloo Bay survey area based on diurnal track surveys (2009/10 to 2015/16) and nocturnal direct observation surveys (2010/11 to 2015/16).

gaps preclude the evaluation of the southeast Indian Ocean subpopulation under most IUCN criteria. Furthermore, a recent review of the status of the southeast Indian Ocean loggerhead turtle RMU identified major gaps in our understanding of the nesting biology and demographic parameters of this subpopulation (Hamann et al. 2013). Therefore, substantial work remains to be done to facilitate more rigorous status assessments and inform management in this region. We have taken a step in this direction by summarizing the first 8 yrs of systematic surveys of a significant mainland loggerhead turtle rookery at Gnaraloo Bay, Western Australia.

The majority of loggerhead turtle nesting in WA occurs on Dirk Hartog Island, which is located at the mouth of Shark Bay, approximately 200 km southwest of Gnaraloo Bay (Baldwin et al. 2003). An estimated minimum of 1000–3000 females nest on beaches at the northern end of this island annually (Limpus 2009; Reinhold and Whiting 2014). However, several smaller rookeries also exist at the Muiron Islands and mainland sites along the Ningaloo Coast near Exmouth (Baldwin et al. 2003). The Ningaloo Turtle Program (NTP) has monitored sea turtle nesting from Exmouth Gulf to Coral Bay (Fig. 1) since 2002. The timing of sea turtle nesting appears largely consistent between Gnaraloo and NTP-monitored sites further north, with nesting activity increasing in mid-December and peaking in mid- to late January (Hattingh et al. 2011; Riskas 2014; Markovina 2015). Loggerhead, green, and hawksbill turtles nest on NTP-monitored beaches, although nesting in different divisions of the study area is typically dominated by one species or another (Markovina 2015). Similarly, loggerhead and green turtles nest at Gnaraloo Bay, but 97% of nesting activity over 8 yrs was attributed to loggerhead turtles.

After accounting for nest detection bias, we estimate that approximately 405 nests are dug by 85 female loggerhead turtles in the Gnaraloo Bay survey area annually. Additionally, investigatory surveys since 2011/12 have revealed that a similar or slightly lower level of loggerhead turtle nesting activity occurs in the Cape Farquhar survey area, on beaches located approximately 22 km north of the Gnaraloo Homestead, although longer stretches of beach (up to approximately 13 km, abutting the Cape Farquhar Sanctuary Zone of the Ningaloo Marine Park at Gnaraloo) were patrolled during some of the Cape Farquhar surveys (Riskas 2014). It is currently unclear whether there is overlap between these rookeries, with some females nesting at both sites, which has been documented in other parts of the world (e.g., Florida; Bjorndal et al. 1983), or whether they comprise different individuals. However, overall, the results of the surveys conducted at Gnaraloo reveal that the southern extreme of the Ningaloo Coast contains significant and previously underreported nesting aggregations of this species.

Table 2. Nest detection bias calculated from diurnal track surveys and concurrent but independent nocturnal direct observation surveys in the Gnaraloo Bay survey area from 2010/11 to 2015/16.

Nesting season	Nocturnal survey nest count	Corresponding diurnal survey nest count	Nest detection bias (% error)
2010/11	45	37	−17.8
2011/12	14	11	−21.4
2012/13	38	32	−15.8
2013/14	42	37	−11.9
2014/15	44	39	−11.4
2015/16	42	42	0.0

By conducting concurrent but independent diurnal and nocturnal surveys in the Gnaraloo Bay survey area, we were able to quantify detection errors associated with track interpretation, which is commonly used to monitor sea turtle nesting activity due to the logistical simplicity of diurnal surveys (Schroeder and Murphy 1999; Weishampel et al. 2003; Witherington et al. 2009; Pfaller et al. 2013). During 2010/11 to 2015/16, field teams tended to underestimate the abundance of loggerhead turtle nests in the Gnaraloo Bay survey area by approximately 13%, and all seasons except for 2015/16 (0% nest detection bias), each involving different field personnel, experienced negative nest detection bias. This bias resulted in a comparable difference between nesting success estimates based on diurnal and nocturnal surveys, with nesting success being underestimated during diurnal surveys owing to the tendency to miss or misclassify nests. We suspect that the windswept nature of the Gnaraloo coast, with rapid deterioration of track features and, occasionally, covering of entire tracks prior to sunrise when surveys are conducted, contributes to this pattern. However, nest detection bias decreased from 2010/11 to 2015/16, which suggests improvement in track assessment skills at the program level, despite nonoverlapping field teams, attributable to strengthened preseason and in-season training used since 2010/11. Cross-site studies and a detailed analysis of track interpretation errors relative to observer experience, program development, and environmental conditions would provide more detailed insight into this methodological issue.

Nocturnal surveys also helped refine our understanding of species composition in the Gnaraloo Bay survey area. Specifically, nocturnal surveys conducted during parts of six nesting seasons yielded 441 direct turtle sightings, and no hawksbill turtles were seen despite a significant number of suspected hawksbill turtle tracks recorded during diurnal surveys, particularly in the first 2 yrs of the study. This provided the evidential basis for reclassifying these tracks as loggerhead turtle tracks. It remains possible that hawksbill turtles nest at Gnaraloo, but, if it occurs, it appears extremely rare. Refined track interpretation guidelines and on-going nocturnal surveys will help further resolve this issue moving forward. Overall, the comparison of indirect and direct observations of turtle nesting activities at Gnaraloo highlights the importance of implementing validation methods in nesting beach programs where the primary index of nesting activity comes from diurnal track surveys, which are vulnerable to detection errors (Schroeder and Murphy 1999; Pfaller et al. 2013). This is particularly the case if programs use relatively inexperienced track monitors and/or there may be changeover in survey personnel throughout seasons.

The number of loggerhead turtle emergences recorded showed a strong, season-on-season decline over 8 yrs of monitoring. Because no concomitant trend in nesting success—as determined via direct observations during nocturnal surveys—was observed (Fig. 4), we would expect to see a similar decline in the number of nests recorded per season. However, no significant trend in nest totals was detected. We suspect that nest detection bias and minor differences in the duration of monitoring seasons contributed to this pattern. Specifically, nest detection bias decreased over time; thus, nest totals are likely underestimated in the early seasons of the program (including those prior to the start of nocturnal surveys in 2010/11) to a greater degree than in later seasons, which would mask a putative downward trend in nests dug. In addition, the shortened monitoring seasons in 2008/09 and 2010/11 (see "Methods: Diurnal Track Surveys") would lead to underestimated nest totals in these early seasons and further confound accurate trend detection. Overall, the marked decrease in total loggerhead turtle emergences, the lack of a corresponding increase in a direct measure of nesting success, and temporal variation in nest detection probability suggest that a biologically significant decline in use of the Gnaraloo Bay survey area by loggerhead turtles has occurred since 2008/09.

Despite relatively low nesting numbers, small and isolated sea turtle rookeries such as those at Gnaraloo may still play an influential role in the dynamics of populations and, therefore, have high conservation value. Specifically, smaller rookeries that are isolated from high-density nesting sites may serve as important population buffers if extreme events (e.g., storms, disease) cause large-scale nest loss at the primary nesting sites. Furthermore, although many sea turtle rookeries are small at present, some of these may have been considerably larger historically, prior to the onset of various anthropogenic impacts (Jackson 1997; McClenachan et al. 2006). Although loggerhead turtles in WA were not extensively harvested for commercial trade, some level of historical take did occur (Halkyard 2014). Perhaps more important, introduced foxes have exerted significant predation pressure on sea turtle nests at some mainland Australian rookeries since at least the 1960s (Limpus 2009). In Queensland, for example, up to 95% of nests at some mainland sites were dug up by foxes during the 1970s and early 1980s (Limpus 2009). On the Ningaloo Coast, which includes Gnaraloo, data on historical fox predation rates are lacking. However, anecdotal reports suggest that foxes have been active in the region since the 1960s, and fox predation, if not controlled, can cause the loss of the majority of clutches (Baldwin et al. 2003; Limpus 2009). The Gnaraloo Feral Animal Control Program (GFACP) was initiated in December 2008 to reduce fox activity on Gnaraloo nesting beaches. In the first month of the GFACP, 21% of turtle nests were disturbed or predated by foxes (based on tracks and evidence of digging and/or consuming eggs as recorded during diurnal surveys), and this was likely very low compared with a month with no control because baiting began on 10 December, and fox tracks decreased almost immediately (Hattingh et al. 2009). Therefore, a high level of fox predation is likely

to have affected sea turtle nests at Gnaraloo prior to 2008 and is suspected to have extended back several decades. As such, sea turtle nesting numbers in this region may remain depleted relative to historic levels.

Importantly, the impacts of recent fox predation at Gnaraloo have likely not yet fully manifested in turtle nesting numbers. Given this historical context, the eight-year decline in loggerhead turtle nesting activity in the Gnaraloo Bay survey area is noteworthy and potentially concerning. Although the time series is still very short and our results must be interpreted cautiously, it is likely that some of the impacts of historical fox predation are still "in the pipeline" for this rookery; thus, further declines might be expected in coming years. It is also possible that other factors, including fisheries by-catch on migratory routes and feeding grounds (e.g., Poiner et al. 1990) or intensive predation by native ghost crabs (*Ocypode* spp.) at Gnaraloo (Hattingh et al. 2016), have contributed to the apparent decline in rookery use. As such, continued monitoring, research, and protection of Gnaraloo beaches are critical at this juncture.

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