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Contribution to the Special 'Managing flatback turtles for the future'

Predicting core areas of flatback turtle hatchlings and potential exposure to threats

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ABSTRACT: The lack of data on distribution of juvenile marine species can limit conservation efforts. As hatchlings, marine turtles are too small to track using satellite telemetry, so their at-sea distribution remains unknown. This knowledge gap is critical, as hatchlings already experience high mortality in coastal zones. In addition, further risks to their survival may occur beyond these areas, linked to threats associated with in-water artificial infrastructure and/or attraction to artificial lights and thus increased mortality from higher risk of predation or exhaustion from disorientation. To fill this gap, we used particle tracking forced by an ocean circulation model to predict the dispersal of flatback turtle *Natator depressus* hatchlings from 12 nesting sites off the coast of Western Australia. We used the model outputs to calculate the distribution of these 'virtual hatchlings' and infer the core area of hatchling use over 3 dispersal phases (1–4, 10–15 and 25–30 d). We then calculated the overlap between core areas and 2 anthropogenic threats (in-water artificial infrastructure and light pollution). Core areas were predominately located on the continental shelf during all dispersal phases, supporting the hypothesis that flatback turtles remain in neritic areas. Most (70–80%) of the core area during early dispersal (Days 1–4 and 10–15) contained at least one threat. However, less than half of the area used between Day 25 and 30 was exposed to threats. In the absence of empirical data on hatchling distribution, our results have predicted the core areas used by early life stage flatback turtles to assist in conservation management of these threatened species.

KEY WORDS: Flatback turtle · Particle tracking · Ocean circulation model · Artificial light · In-water artificial infrastructure · ozROMS

1. INTRODUCTION

Distribution and movement data is lacking for juveniles of many marine species (Hazen et al. 2012, Hays et al. 2016). Although satellite tracking has allowed us to unlock many mysteries about the movement behaviour of marine megafauna (Horton et al. 2017, Sequeira et al. 2018, Barkley et al. 2019, Queiroz et al. 2019, Grémillet et al. 2022), these studies have mainly focused on identifying the movements of adult organisms. Ideally, knowledge on the distribution of every life stage should be available to enable effective conservation.

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Sea turtles are one such example where most information on their distribution comes from studies on adult females as they are easily accessible for satellite tagging and observable during surveys when they come ashore to nest (Godley et al. 2008, Hays & Hawkes 2018). Fewer studies have focused on juveniles and males from foraging areas (Hays et al. 2010a, Arendt et al. 2012, Putman & Mansfield 2015, Briscoe et al. 2016, Fuentes et al. 2020). There is information for some species on the distribution of early life stages (>3 mo old) (Mansfield et al. 2014, Putman & Mansfield 2015, Mansfield et al. 2017) but this is limited for most areas and, in particular, for post-hatchlings (<3 mo old) after they leave the beach (Wildermann et al. 2018).

When organisms are too small to track their movement with telemetry devices, oceanographic circulation models coupled with particle tracking models are one alternative option to predict their dispersal and distribution (Putman & Naro-Maciel 2013, Putman et al. 2014, Wildermann et al. 2017, Rogers et al. 2021). In these models, virtual particles simulating juvenile organisms are transported passively by ocean currents and forced by atmospheric forecasts or hindcasts and predicted tides to determine how these features influence their distribution (van Sebille et al. 2018). Particle tracking has been used to determine the dispersal of larvae of numerous taxa (e.g. fish: Simpson et al. 2013; corals: Wood et al. 2014; crustaceans: Everett et al. 2017, Kolbusz et al. 2022; and molluscs: Kim et al. 2013).

For some species that can actively swim, behaviours such as swimming speed and direction have been applied to the particles to examine their role on the dispersal predictions (Putman et al. 2014, Staaterman & Paris 2014, Putman & Mansfield 2015, Wildermann et al. 2017, Kolbusz et al. 2022). However, much of the behavioural information (e.g. rate of travel, time spent swimming, swimming direction) is usually lacking for young life stages of many marine megafauna species. This is particularly the case for hatchlings of sea turtles as they are too small for current satellite tracking equipment. For hatchling turtles, knowledge of their behaviour when they first leave the beach comes from lab studies (Wyneken et al. 1990, Salmon et al. 2009) or from studies in the nearshore that utilise active tracking or acoustic telemetry techniques (Witherington & Salmon 1992, Scott et al. 2014, Thums et al. 2016), providing insight into their early life history but only for a very limited duration (minutes–hours).

Although information on the dispersal of some species of marine turtle has been gathered through models or field studies (Witherington et al. 2012, Le Gouvello et al. 2020), the early life history of flatback turtles *Natator depressus* is largely unknown (Wildermann et al. 2018). Of high interest is the limited evidence indicating that these turtles remain in neritic areas around northern Australia throughout their entire life cycle, often in waters less than 50 m deep (Walker & Parmenter 1990, Walker 1991, Bolten 2003, Limpus 2007, White & Gill 2007). Particle tracking to predict their initial dispersal pathways in eastern Australia has confirmed that flatback turtle hatchlings can remain in shallow waters during their early dispersal, even without swimming (Hamann et al. 2011, Wildermann et al. 2017). In Western Australia, particle tracking has been used to select release sites for rehabilitated juvenile turtles to ensure favourable currents may transport them to suitable sites (Robson et al. 2017). However, it has not been used to predict hatchling distribution in this region and there has only been a handful of wild sightings of flatback turtle post-hatchlings or juveniles in existence. Hatchings are a key life stage for which we lack spatial data whereas the distribution of adult females is relatively well known (Whittock et al. 2016) and information on the distribution of adult males is also emerging (DBCA pers. comm.). While satellite telemetry methods have been developed for captively reared hard shelled turtle hatchlings when they are large enough to carry a satellite tag (>3 mo old; Mansfield et al. 2014), these methods (gluing the tag to the carapace) are less successful for flatback turtles due to their soft carapace, even when they reach sufficient size to carry a tag. Consequently, the next best option to determine the distribution of early life stages of flatback turtles is to use numerical models. Considering there is little behavioural data to inform particle tracking models beyond the nearshore, and field observations suggest they spend a large proportion of time floating after entering the water (Bell & Pendoley 2014), a passive approach could be used to initially investigate their potential pathways and distribution to assist in managing threats to all life stages of this vulnerable species.

Threats are often concentrated in neritic waters due to the large number of anthropogenic activities that occur there, such as oil and gas exploration, coastal and offshore development, shipping, fishing, etc., that have the potential to impact marine fauna (e.g. through habitat disturbance/change, light pollution, etc.) (Pauly et al. 2005, Davies et al. 2014, Halpern et al. 2015, Rodríguez et al. 2017, Schoeman et al. 2020, Fossette et al. 2021a). For hatchling turtles, artificial light sources at sea or on coastal infrastructure such as jetties, as well as in-water artificial infrastructure, which can act as fish attraction devices (Rilov & Benayahu 2000), have been identified as threats as they can delay dispersal and increase the naturally high predation rates in coastal waters (Gyuris 1994, Reising et al. 2015, Wilson et al. 2018, 2019).

In the Pilbara region of Western Australia, approximately 50% overlap exists between flatback turtle nesting areas and artificial light (Fossette et al. 2021a). In addition, overlap exists between industrial activity related to the resources sector (iron ore ports, shipping and oil and gas extraction) and the internesting distribution (ranging from 0 to 94 %; Whittock et al. 2014, Thums et al. 2018) and foraging grounds (ranging from 3 to 69.4 %; Whittock et al. 2016; Thums et al. 2018) of the adult flatback turtles in north-west Australia. Given this, we hypothesise that overlap between hatchling areas and these threats will occur and may result in increased mortality due to predation and/or exhaustion from disorientation that could impact turtle populations. Therefore, identifying areas where early life stage flatback turtles are most likely to be found and quantifying overlap with known threats are crucial first steps to focus management and research needs for this International Union for Conservation of Nature listed vulnerable species (Red List Standards & Petitions Subcommittee 1996, IUCN 2021).

In the present study, we used an oceanographic model together with particle tracking simulations to predict the passive dispersal pathways and distribution of newly emerged flatback turtle hatchlings from several key rookeries in northwestern Australia. To do this, we released simulated hatchlings during the peak hatching season (Jan–Feb) into a particle tracking model forced by ocean surface currents to determine potential hatchling trajectories during the frenzy period (i.e. their first 4 d at sea; Salmon et al. 2009), and during 2 other periods (10–15 d and 25–30 d) up to their first 30 d at sea. We used predicted locations from the model to quantify the potential distribution of flatback turtle hatchlings and areas of highest use and to determine if passive movement is sufficient to retain individuals in shallow waters as has been shown for east coast populations (Hamann et al. 2011, Wildermann et al. 2017). Our aim was to estimate areas where early life stage flatback turtles are most likely to be found during these periods and to calculate their spatial overlap with 2 identified threats for hatchlings: in-water artificial infrastructure and artificial light.

2. MATERIALS AND METHODS

2.1. Study area and local oceanography

The study area (Fig. 1) experiences semidiurnal tides with a tidal range of 2–3 m near the town of Onslow, and in excess of 10 m east of Port Hedland (Pattiaratchi & Wijeratne 2009). The continental shelf widens in this area reaching 140 km width at Port Hedland (Holloway 1983), narrowing to <20 km wide at NW Cape, west of Onslow (Pattiaratchi & Wijeratne 2009) (Fig. 1). Tropical cyclones are common in northwestern Australia (~2–3 yr^{-1} during cyclone season Nov–Apr) and result in changes in sea level (storm surge) and strong currents due to their circulating winds (Hearn & Holloway 1990). During the summer months (Dec–Feb), when hatchling emergence peaks, prevailing winds approach largely from the west (Holloway & Nye 1985).

The oceanography of the study area is dominated by 3 main currents: the Holloway Current, the Leeuwin Current and the Ningaloo Current (Woo et al. 2006a, Bahmanpour et al. 2016, Wijeratne et al. 2018). On a regional scale, the Holloway Current flows to the southwest from the Kimberley Region (east of the region depicted in Fig. 1) onto the NW Shelf, where it contributes to the Leeuwin Current which flows southwards along the Western Australia coast (Bahmanpour et al. 2016, Wijeratne et al. 2018). During summer (Dec–Feb), the southwest monsoon winds transport water along the Western Australian coastline towards the northeast, and when these winds weaken (in Mar/Apr), this water flows back southwards along the Western Australian coastline, transported by the Holloway Current and merging with the Leeuwin Current (Bahmanpour et al. 2016). The main drivers of surface water transport in northwestern Australia during summer are the monsoon winds and the Ningaloo Current which is a wind driven surface current that moves water northward from NW Cape (Woo et al. 2006a). The wide continental shelf north of NW Cape, together with the prevailing south westerly winds, results in surface currents inshore of the 50 m depth contour flowing to the northeast and predominately parallel to shore at speeds of approximately 0.25–0.3 m s^{-1}. Beyond this depth contour, there is an offshore component to surface flow (Fig. 1). South of NW Cape, the surface currents move offshore during this time due to the combination of winds and Coriolis force, resulting in Ekman flow (Woo et al. 2006b).

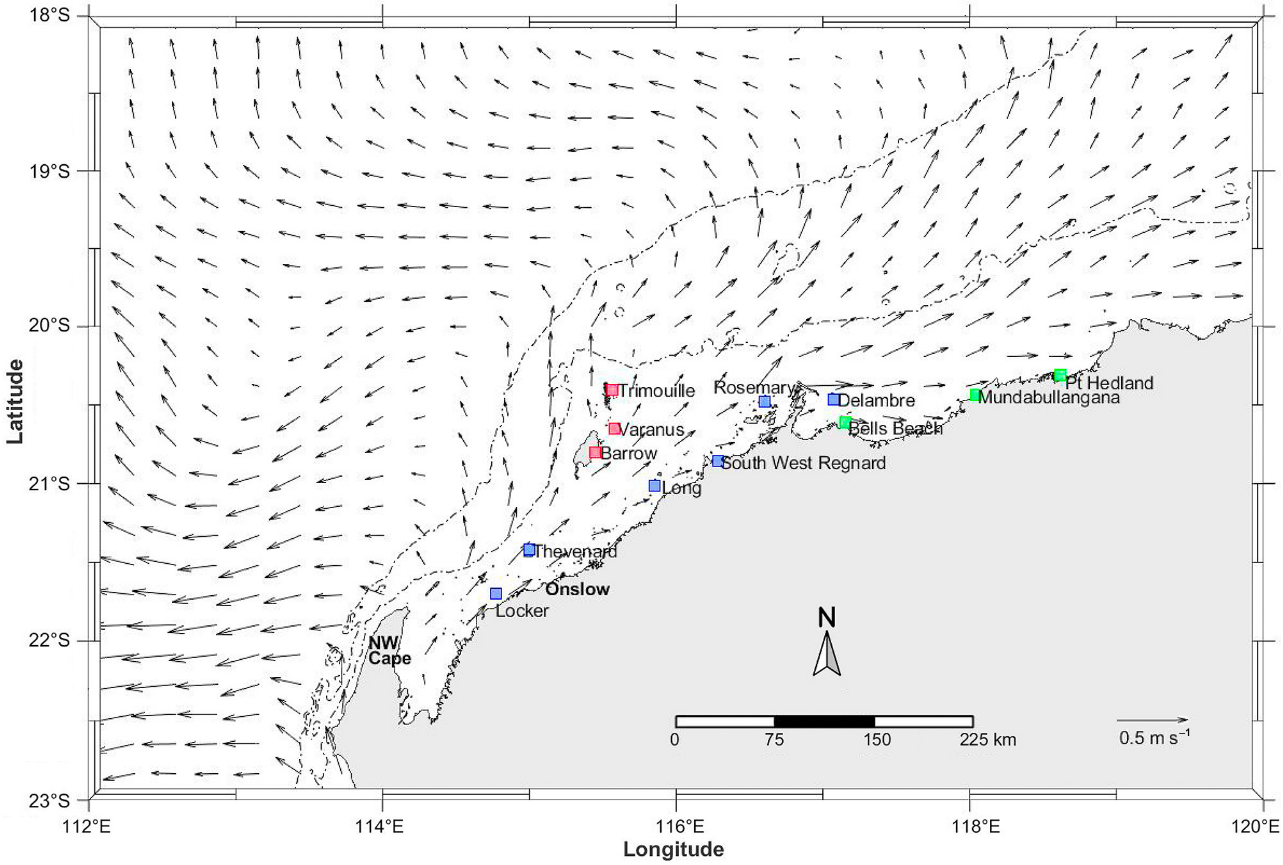

Fig. 1. Study area showing the main town and peninsula (in bold) and the particle release locations (as coloured squares—red: offshore islands, blue: coastal islands, green: mainland sites); dashed lines: 50 and 200 m depth contours; black arrows: average surface currents (0–15 m) in January–February across 2007, 2008 and 2009 (obtained from ozROMS: Wijeratne et al. 2018). The size of the arrow indicates ocean surface current speeds (see scale arrow)

2.2. Release locations and timing

Passive dispersal of flatback turtle *Natator depressus* hatchlings was simulated from 12 flatback turtle nesting sites on islands and on the mainland in northwestern Australia (from Locker Island in the south to Port Hedland in the north, Fig. 1, Table 1), encompassing the nesting range of one distinct genetic stock, the North West (NW) Shelf Stock (FitzSimmons et al. 2020). Islands were classified as either coastal or offshore islands (<30 km or >30 km from the mainland, respectively). Nesting occurs throughout the area in varying levels from October to February with major nesting sites (≥100 tracks night^{-1}) including Delambre, Barrow and Rosemary Islands, and the mainland nesting site at Mundabullangana Station (Pendoley et al. 2016, Fossette et al. 2021a). At each location, the simulated particles were released randomly either from along a 10 km line running parallel to the nesting beach approximately 5 km from shore or within a polygon (site dependent, Table 1). A line release was selected for South West Regnard Island, Bells Beach, Port Hedland and Mundabullangana, as they were located on or very close to the mainland. A line was also used to release particles along the east coast of Barrow Island as flatback turtles primarily nest on that side of the island (Pendoley et al. 2014a) and they have been actively tracked at this distance from shore (Bell & Pendoley 2014). A line was also selected for release on the seaward side of Rosemary Island to reduce the number of particles beaching (hitting land) on Rosemary Island and on the surrounding islands in the Dampier Archipelago. At the northern sites (i.e. Port Hedland and Mundabullangana), the release line was located further from shore (~20 km from the nesting beach) to minimise the number of particles beaching due to the influence of the large tidal range (Pattiaratchi & Wijeratne 2009, Robson et al. 2017), whilst still ending up with similar predicted pathways as particles released closer to shore but remaining as close to the nesting beach as possible. Polygon releases were

Table 1. Nesting site, release type and proportion of particles released (proportional to the relative size of the nesting population; Fossette et al. 2021a). The total number of virtual hatchlings released across the three years was 534 000. Also shown is the number of virtual hatchlings still active at Day 4, 15 and 30

Nesting sites	Group	Release	Prop release (%)	% active Day 4	% active Day 15	% active Day 30
Delambre	Coastal Is	Polygon	27.5	94.0	32.2	20.2
South West Regnard	Coastal Is	Line 5 km from shore	1	32.7	9.1	5.4
Locker	Coastal Is	Polygon	1.4	70.5	42.8	37.4
Long	Coastal Is	Polygon	2.2	63.4	26.6	20.4
Rosemary	Coastal Is	Line 5 km from shore	13.3	77.6	60.9	51.3
Thevenard	Coastal Is	Polygon	7.7	94.0	65.2	58.2
Bells	Mainland	Line 5 km from shore	1.5	73.5	15.1	8.2
Mundabullangana	Mainland	Line 20 km from shore	19.2	85.6	23.7	11.5
Port Hedland	Mainland	Line 20 km from shore	3.3	55.7	13.1	3.5
Barrow	Offshore Is	Line 5 km from shore	18.6	95.6	84.3	75.4
Trimouille	Offshore Is	Polygon	2.5	97.4	95.9	90.0
Varanus	Offshore Is	Polygon	1.8	98.7	91.3	82.4

used for the remaining islands, as the islands were smaller than the model resolution (3–4 km), so the land was not recognised. For these releases, particle locations were generated randomly within a defined area which encompassed the entire island perimeter except at Delambre Island where particles were released from a polygon over nesting areas in the southern part of the island, identified in Thums et al. (2020).

At each location, particles were released at intervals of 4 h every night for 2 mo, beginning at 19:30 h and ending at 03:30 h local time, and then tracked for 30 d. This was designed to cover the time that hatchlings usually emerge (between 19:00 and 04:00 h; Kamrowski et al. 2014b) as well as covering a range of environmental conditions (high/low and spring/neap tides) as the timing of release can influence distribution in particle tracking models (Wildermann et al. 2017). At each 4 h interval (i.e. each release), 1000 particles were released across all 12 sites, with the number of particles released at each site being proportional to the relative size of the nesting population (Fossette et al. 2021a).

2.3. Simulating passive dispersal using a hydrodynamic model

To track the dispersal of passive particles, we used the particle tracking software Ichthyop 3.3.3 (Lett et al. 2008). This software was designed to model ichthyoplankton dispersal, but has also been used to predict the dispersal of marine turtles (Putman et al. 2012, Putman & Mansfield 2015, Robson et al. 2017). Within Ichthyop, we used surface currents from a hindcast application of the Regional Ocean Modelling System (ROMS, www.myroms.org/) (Moore et al. 2011) to move particles, termed ozROMS, that was developed for oceans around Australia for the years 2000–2014 to investigate circulation at high spatial resolution (Wijeratne et al. 2018). Ocean surface currents from ozROMS, simulated on a 3–4 km grid, were available at hourly temporal resolution (hourly mean velocity fields). This temporal resolution allowed for the inclusion of the effect of tides, and the spatial scale allowed higher resolution bathymetry near the coast (up to depths of 15 m), which is not possible in models with coarser spatial scales (for example, ~10 km grid cell [1/12°] from HYCOM; Chassignet et al. 2007). Data from the surface layer (first 0–15 m of the water column) between the 1st of January and the 31st of March for the years 2007, 2008 and 2009 were used to run the model. This covered a range of typical oceanic conditions including El Niño in 2007 and weak La Niña in 2008 and 2009, and encompassed the peak emergence time (Jan/Feb) of flatback turtle hatchlings. To visualise circulation in the study area, mean current vectors from ozROMS were summarised for the peak hatchling emergence time (Jan/Feb) each year and averaged across the 3 yr (Fig. 1).

We used a time step of 30 s in the particle tracking simulations (i.e. a new location was calculated for each particle every 30 s) but used 1 h outputs of particle locations in our analysis to match the temporal resolution of the ozROMS model. To represent turbulent processes that are not resolved by the oceanographic model, we used a horizontal dissipation rate (ε) of 1×10^{-9} m^2 s^{-3} which is related to horizonal diffusion through the Monin & Ozmidov (1981) relationship $K_h = \varepsilon^{1/3} l^{4/3}$, with l being the unresolved subgrid scale taken here as the grid size (Peliz et al. 2007) with particles set to beach (stop moving) if they met the coastline.

The area of particle tracking simulations was restricted between 108° and 140° E and 5° and 28° S, as areas outside of this range were thought to be unrealistic (i.e. in deep oceanic waters, or too far south) and to reduce computation requirements (i.e. the size of the output files). If particles met these boundaries, they remained in the same location (i.e. at the boundary) for the remainder of the simulation.

2.4. Data analysis

2.4.1. Defining distribution and core areas of use for hatchlings

To estimate potential core areas for flatback turtle hatchlings, we quantified particle distribution during the frenzy period (first 4 d at sea; Salmon et al. 2009) and 2 other dispersal phases (10–15 d and 25–30 d). For the frenzy period, all particle locations were used in the analysis from the time they were released up until 96 h (Day 4) after release, except for those that beached. Particles that beached were removed from the analysis of the frenzy period entirely as this was considered an artefact resulting from the model's spatial resolution and/or from releasing passive particles too close to land as newly emerged hatchlings are not seen beaching along the shoreline; they actively swim away from the beach (Thums et al. 2016, Wilson et al. 2018). As some particle release sites had more beaching than others, the number of particle tracks retained at each site was manually adjusted to obtain the original proportions (relative to rookery size, Table 1) and to avoid bias towards sites that had low levels of beaching. For the remaining dispersal periods, we included particle locations from 240 to 360 h (Days 10–15) and 600 to 720 h (Days 25–30) in the analysis. However, if particles met the modelling boundary or if they beached before these periods (i.e. before Day 10 or before Day 25), they were excluded from the analysis, and if particles beached or hit the boundary during these defined periods, their last location (at the coastline or model boundary) was then retained as they may be realistic endpoints, but duplicate locations were removed.

For each of the 3 dispersal phases, we then summed the number of particle (called virtual hatchlings hereafter) locations per 4 × 4 km grid cell across the study region across the 3 yr for each of those periods (note that distributions and core areas are also presented per individual year in in Fig. S4 in the Supplement at www.int-res.com/articles/suppl/n052p129_supp.pdf to illustrate between-year variation). The summed grid cell values (all years) were then ranked from highest to lowest and cells encompassing the top 95, 75, 50 and 25% of the cumulative frequency distribution were then determined as described by Soanes et al. (2013). This is akin to the concept of utilisation distribution as the minimum area in which the animal has 95, 75, 50 and 25% probability of being found (Worton 1989), as previously applied to determine distribution and core areas for adult turtles (Ferreira et al. 2021, Fossette et al. 2021b). The 50% cumulative frequency distribution of virtual hatchlings during each dispersal phase were used to infer the potential respective core areas of use for actual turtle hatchlings.

Finally, all valid virtual hatchling locations (excluding duplicate locations when particles beached or met the modelling boundary), every 5 d from the day they were released up until Day 30, were used to identify potential hatchling pathways over time. We overlaid rare wild sightings of flatback post-hatchlings up to 15 cm in size (curved carapace length) to validate our approach. Hatchlings of this size are likely to be less than 1 yr old (Turner Tomaszewicz et al. 2022) as captively reared post hatchlings can reach 9.4 and 10.9 cm straight carapace length by 7 and 19 wk, respectively (Salmon et al. 2010, Salmon et al. 2016). Field records (n = 18, Table S1 in the Supplement) were gathered from the Western Australia Department of Biodiversity, Conservation and Attractions and include post hatchlings found while foraging (n = 2) and carcasses found in either (1) sea eagle nests (n = 4), (2) inside fish stomach contents (n = 1), or (3) washed up on shore (n = 11); Young et al. (2020).

2.4.2. Calculating overlap with potential threats

Artificial light and predation around in-water artificial infrastructure represent 2 anthropogenic threats that can influence the movements and survival of flatback turtle hatchlings at sea (Wilson et al. 2018, 2019). We gathered data on the location of these 2 threats on the NW Shelf (Table 2). For in-water artificial infrastructure, we considered oil and gas platforms, petroleum wells, shipwrecks, and coastal infrastructure as sources of threats, as they can act as fish attracting devices (Stephan & Lindquist 1989, Rilov & Benayahu 2000, Schroeder &

Table 2. Threat layers used to determine exposure of virtual flatback turtle hatchlings to potential anthropogenic threats

Threat layer	Impact	Spatial layer	Description	Year	Source	Post-processing
Artificial light	Attraction to artificial light	2015 World Atlas of Artificial Night Sky Brightness	Artificial light at night obtained from the Visible Infrared Imaging Radiometer Suite (VIIRS) Day/Night Band (DNB) and propagated using mapping software and field observations to quantify sky brightness. DNB sensitive to wave-length 500–900 nm and resolution 742 m	DNB data from May–Dec 2014	Falchi et al. (2016). Additional data available for Falchi et al. (2016) at https://doi.org/10.5880/GFZ.1.4.2016.001	Thresholds applied to layer to create areas of high (50% above natural light; >87 µcd m^{-2}), medium (8 to 50% above natural light; 14–87 µcd m^{-2}), low (1 to 8% above natural light; 1.7–14 µcd m^{-2}) and no (up to 1% above natural light; 0–1.7 µcd m^{-2}) pollution defined by Falchi et al. (2016)
Petroleum wells	Increased predation	WA onshore Petroleum Wells Department of Mines, Industry, Regulation and Safety (DMIRS-025)	Exploration and development wells	Last updated in May 2021	Fisheries Research and Development Corporation Marine Infrastructure data-base (FRDC Marine Infrastructure data-base v0.2 (www.arcgis.com)). Data sourced from: https://catalogue.data.wa.gov.au/dataset/wa-onshore-petroleum-wells-dmirs-025	Extracted wells that were present in surface waters only (0–15 m depth) as hatchlings are expected to remain near surface and conduct relatively shallow dives (Salmon et al. 2010)
Oil and gas platforms	Increased predation	Australian Government Geoscience Australia	Oil and gas platforms	2015	FRDC Marine Infrastructure database (www.arcgis.com). Data sourced from: http://services.ga.gov.au/	None
Shipwrecks	Increased predation	Western Australian Museum	Locations of Western Australian shipwrecks	Last updated in Jan 2018	FRDC Marine Infra-structure database. https://catalogue.data.wa.gov.au/tr/dataset/shipwrecks	All shipwrecks were ≤20 m depth, so all were included
Coastal infra-structure	Increased predation	Western Australian Department of Biodiversity, Conservation and Attractions	Infrastructure that modifies the coastline (e.g. jetties, break-water, boat ramp)	2020	Western Australia Department of Biodiversity, Conservation and Attractions	Structures that did not extend into the water and boat ramps without any substantial structure (e.g. an unsealed ramp) were not included

Love 2004, Claisse et al. 2014, McLean et al. 2018), and thus could increase predation on hatchlings (Wilson et al. 2019). For each threat layer, we overlaid the defined core hatchling areas (50% cumulative frequency distribution) and scored each grid cell in relation to

(1) the presence of in-water artificial infrastructure (score 0 or 1); and
(2) presence of artificial light (score 1 to 3).

We assumed all in-water artificial infrastructure were associated with the same threat intensity, as there is no data available showing that the intensity of predation is directly correlated with the size of the infrastructure or the number of structures. Hence the score for in-water artificial infrastructure was therefore either 1 = presence or 0 = absence. In contrast, attraction to artificial lights increases with light intensity (Pendoley & Kamrowski 2015), therefore light pollution was associated with different intensities and the scores used reflected the increasing intensity levels (high = 3, medium = 2, low = 1) based on thresholds defined by Falchi et al. (2016).

If a grid cell in the core hatchling area did not overlap the light or in-water artificial infrastructure layers, it was given a score of 0. The cumulative threat score per grid cell was calculated by summing the value of all overlapping layers. The maximum cumulative threat score was 4, when high artificial light levels (score = 3) and in-water artificial infrastructure were present (score = 1) in a grid cell. Each grid cell was classified as having either high (cumulative threat score = 4; i.e high light level score of 3 + presence [1] of in-water artificial infrastructure), medium (cumulative threat score = 3; i.e. high light level score of 3 + absence [0] of in-water artificial infrastructure or medium light level score of 2 + presence [1] of in-water artificial infrastructure), low (cumulative threat score = 2; i.e. medium light level score of 2 and absence [0] of in-water artificial infrastructure or low light level score of 1 + presence [1] of in-water artificial infrastructure), or very low (threat value = 1; i.e. low light level and absence [0] of in-water artificial infrastructure or no light [0] and presence [1] of in-water artificial infrastructure) threat level or no (zero) threats (i.e. no artificial light nor infrastructure). The proportion of the core hatchling area overlapping with the cumulative threat grid was then calculated. To determine the nesting sites at the highest threat level, we calculated the total number of individual virtual hatchlings within areas with a threat score of 4 (independently of the time spent by each particle in the threat area). From that, we then determined what proportion of the total number of virtual hatchlings in this area came from each of the rookeries by dividing the number of individuals from each rookery by the total. We also calculated the proportion of the total number of virtual hatchlings released from each rookery that ended up in these areas. If grid cells with a value of 4 were next to, or geographically close to, other grid cells that also had a value of 4 (i.e. groups separated by up to 2 grid cells), data from these grid cells were combined.

3. RESULTS

3.1. Overall distribution of virtual hatchlings during their 30 day drift

The distribution of virtual hatchlings from each rookery and for each of the 3 rookery classifications (mainland, coastal islands, and offshore islands) are shown in Figs. S1–S3 in the Supplement. Combining data from all sites indicated that 5 d old virtual hatchlings were largely restricted to shelf waters (<200 m depth contour) whereas virtual hatchlings older than 5 d were distributed further offshore and to the north

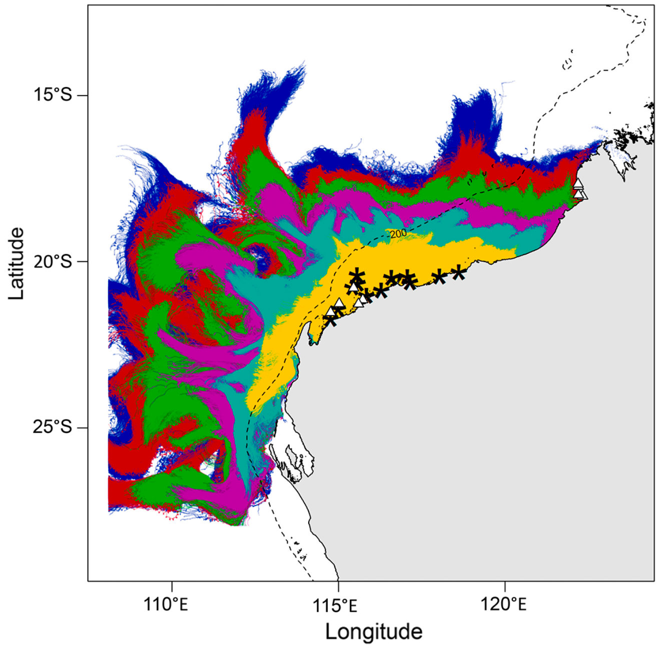

Fig. 2. Distribution of virtual hatchlings released into the model domain in January and February, 2007–2009 during Days 1–5 (yellow), 6–10 (cyan), 11–15 (purple), 16–20 (green), 21–25 (red), and 26–30 (dark blue) for all sites combined. Asterisks: release locations; dashed line: 200 m depth contour; white triangles: wild sightings of post-hatchling flatback turtles

and south (Fig. 2). By Day 25, they began hitting the boundary of the modelling domain in the south and west (108° E and 28° S). Virtual hatchlings from offshore islands did not move as far north as virtual hatchlings from coastal islands and mainland sites; virtual hatchlings from mainland rookeries dispersed further to the north than virtual hatchlings from coastal-island rookeries, reaching Dampier Peninsula and King Sound (Fig. 2, Fig. S1a–c). Also, virtual hatchlings from mainland rookeries were not found as far south as those from coastal islands and offshore rookeries and remained east of NW Cape (Fig. S1c). Field records of wild sightings of flatback turtle *Natator depressus* post-hatchlings were all within the predicted distribution of virtual hatchlings (white triangles, Fig. 2).

3.2. Virtual hatchling distribution during the 4 day frenzy period

All virtual hatchlings remained on the continental shelf during this period (Fig. 3a–b, Fig. S4a–c in the Supplement). The highest density of virtual hatchlings (25% distribution) occurred close to the high-density nesting sites of Barrow, Delambre, Rosemary and Thevenard Islands, and also Mundabullangana Station on the mainland, covering an area of 1647 km^2 (Fig. 3a–b). The core hatchling area (50% distribution, total area 5495 km^2) encompassed 7 discrete locations: waters around Thevenard, Long, Barrow, Trimouille and Rosemary Islands, plus a large area to the east of Rosemary Island that extended to Port Hedland and a small area west of Bells Beach on the mainland (Fig. 3a–b, Fig. S5a in the Supplement). The 95% distribution (total area 33 570 km^2) ranged from Locker Island to Port Hedland and extended out past Trimouille Island (Fig. 3b). Virtual hatchling distribution (95, 50, 25%) for each year are shown in Fig. S4a–c.

3.3. Virtual hatchling distribution during Days 10 to 15

Highest density of virtual hatchling (25% distribution, total area 5917 km^2) was found along the coast between the Dampier Archipelago and Pardoo, and on the coast near Onslow (Fig. 3c–d). The 50% distribution (total area 29 677 km^2) was almost entirely restricted to the shelf, extending from east of NW Cape to Eighty Mile Beach. The 50% distribution included 3 semi-discrete areas: along the coast west of South West Regnard Island, a large area north of Rosemary Island, and a section east of Dampier Archipelago that was also identified as a part of the core area for the frenzy period which extended further east to Eighty Mile Beach (Fig. 3c–d, Fig. S5b). The 95% distribution (total area 181 345 km^2) ranged from south of Shark Bay to the northern end of Eighty Mile Beach and further west to the 2000 m depth contour. Virtual hatchling distribution (95, 50, 25%) for each year are shown in Fig. S4d–f.

3.4. Virtual hatchling distribution during Days 25 to 30

Virtual hatchling density was highest (25% distribution, total area 17 889 km^2) along the coast between the Dampier Archipelago and Pardoo, and offshore from these areas near the 200 m depth contour (Fig. 3e–f, Fig. S4g–i). The 50% distribution (total area 83 852 km^2) was largely restricted to the continental shelf. It did not form discrete areas but highlighted similar coastal areas as the 25% distribution, in addition to a few areas north of Pardoo and Eighty Mile Beach (Fig. 3e–f, Fig. S5c). It also highlighted coastal areas east of the Dampier Archipelago which were part of the core hatchling areas during the other dispersal phases (Fig. 3, Fig. S5). The 95% distribution (total area 546 432 km^2) ranged from south of Shark Bay to Dampier Peninsula and further west to water depths exceeding 2000 m (Fig. 3e–f). Virtual hatchling distribution (95, 50, 25%) for each year are shown in Fig. S4g–i.

3.5. Overlap between core areas and threats during the 4 day frenzy period

All 7 discrete areas that made up the core hatchling area in the frenzy period (50% distribution, n = 367 grid cells) overlapped with threats (Fig. 4a). A total of 84.5% of the core area overlapped with artificial light (Fig. S6a in the Supplement; 13.9, 42.0 and 28.6% overlapped with high, medium and low levels of artificial light, respectively). The highest levels of artificial light occurred around Cape Lambert, Barrow Island and Port Hedland (Fig. S6a). One grid cell near Thevenard Island and the Burrup Peninsula also had high light levels (Fig. S6a). A total of 6.5% of the core area contained in-water artificial infrastructure (Fig. S7a in the Supplement); 8 grid cells contained oil and gas platforms (n = 1 or 2 platforms per grid cell), 15 contained petroleum wells (maximum number of wells per grid cell was 22), 7 grid cells contained other types of in-water infrastructure (e.g. jetty, port infrastructure, retaining wall), and one grid cell contained a shipwreck.

Over 80% of grid cells within the core area overlapped with one or more threat (Fig. 4a, Table 3). Grid cells with the highest cumulative threat score (n = 4) were found in 3 of the 7 discrete core areas (red grid cells in areas A1, B, and C1 in Fig. 4a). Approximately 94 % of the virtual hatchlings found in area 'A1' (Fig. 4a) were from Thevenard Island (Table 4) and this represents 33% of the total number of virtual hatchlings released from this rookery (Table S2 in the Supplement). Similarly, virtual hatchlings in area 'B' originated mostly (98.9%) from Barrow and Varanus Island rookeries (equivalent to 99.6 and 100% of the total number of virtual hatchlings released from each rookery, respectively; Table S2); the remaining 1.1% were mainly from Thevenard and Trimouille Islands (Table 4). Virtual hatchlings from 4 nesting sites were found in area 'C1': 77.5% came from Delambre, 19.2% from Bells Beach and 1.6% from both Rosemary Island and Mundabullangana (Table 4). More than 89 and 19.5% of the total number of virtual hatchlings re-

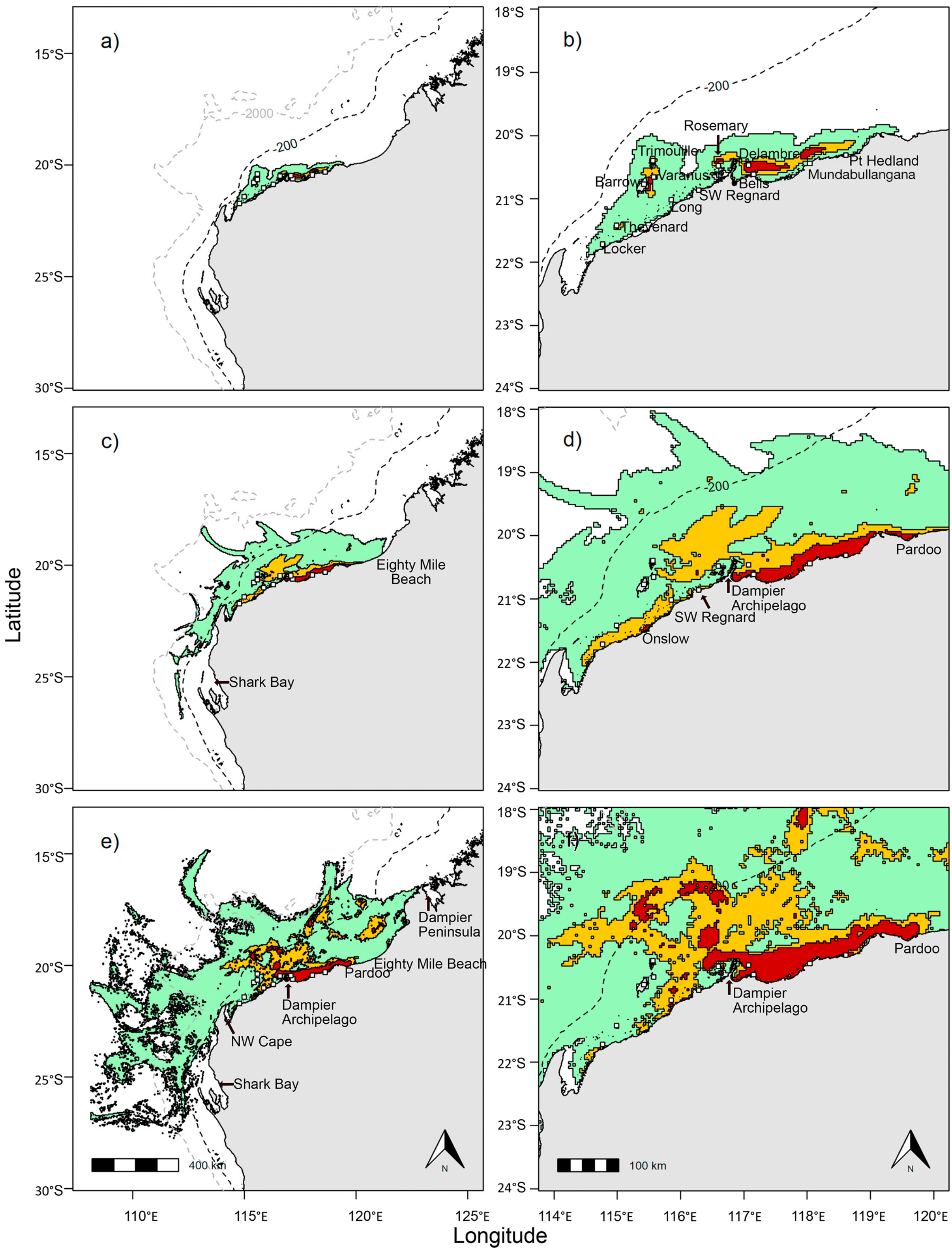

Fig. 3. Distribution of virtual flatback turtles during their first 4 d (a,b), Days 10–15 (c,d) and Days 25–30 (e,f) after entering the sea, calculated by summing the number of particles per 4 × 4 km grid cell. White squares: release locations; colored areas represent cumulative frequency distribution—red: 25%, orange: 50%, green: 95%; dashed lines represent depth contours—black: 200 m, grey: 2000 m. Left panels are the entire distribution, right panels are zoomed to highlight core areas. The 50% distribution is also shown in Fig. S5 in the Supplement as some of these areas are too small to view here

Table 3. Percentage of grid cells within the core hatchling area (50% distribution) allocated to each cumulative threat score (0 = zero, 1 = very low, 2 = low, 3 = medium, 4 = high) during each phase of dispersal (the 4 d frenzy period, Days 10–15 and Days 25–30). The total number of grid cells within the 50% distribution during Days 1 to 4, 10 to 15, and 25 to 30 was 367, 1981 and 5565, respectively

Period	Cumulative threat score (%)				
	0	1	2	3	4
Days 1 to 4	15.5	28.1	40.3	12.3	3.8
Days 10 to 15	28.4	51.9	13.8	5.1	0.8
Days 25 to 30	58.6	28.1	9.7	3.4	0.3

leased from Bells Beach and Delambre Island, respectively, were found in area 'C1' (Table S2). Virtual hatchlings from Port Hedland were not found in area 'A1', 'B' or 'C1' (Table 4).

3.6. Overlap between core areas and threats during Days 10 to 15

A total of 1981 grid cells (total area 29 677 km^2) constituted the core hatchling area. Approximately 28% of the core area had no artificial light (Fig. S6b) whereas 5.4, 12.5 and 53.6% of the core area overlapped with high, medium and low light levels, respectively. Around 3% of grid cells contained in-water artificial infrastructure (Fig. S7b): 7 grid cells had shipwrecks (maximum number of shipwrecks per grid cell was 9), 14 overlapped with coastal infrastructure, 11 had oil and gas platforms (n = 1 or 2 platforms per grid cell) and 42 contained petroleum wells, with some grid cells containing up to 12 wells.

When artificial light and in-water artificial infrastructure were combined, 16 grid cells had the maximum threat score of 4 (Table 3) and were dispersed over 7 general areas (Fig. 4b). One of these areas was associated with an offshore oil and gas platform (E2), another contained port infrastructure and shipwrecks (C2), and the remaining 5 areas were associated with coastal infrastructure areas, including developments near Onslow (D), Thevenard Island (A2), the Burrup Peninsula (F), Karratha (G) and Port Hedland port and its associated facilities (H2, Fig. 4b). Area 'D' also contained a petroleum well. Areas 'D', 'A2', and 'E2' contained virtual hatchlings from most nesting sites, but those hatchlings in these 3 areas were predominantly from Delambre, Rosemary, Thevenard and Barrow Island, although only a small proportion of the hatchlings released from each of these rookeries ended up there (Table 4, Table S2). Virtual hatchlings in areas 'F', 'G', 'C2', and 'H2' originated predominately (~90%) from Delambre Island and Mundabullangana (Table 4).

Virtual hatchlings originating from Delambre and Rosemary Islands were present in all areas with the highest threat score, and the largest proportion of

Table 4. Percentage of virtual hatchlings from each nesting site that were present in areas with the maximum threat score of 4 (red grid cells in Fig. 4, labelled A1-L) during each dispersal period (Days 1–4, 10–15, and 25–30). The table is shaded by the percentage contribution (warmer colours represent greater contributions of nesting site to areas with threat score 4), calculated by summing the total number of virtual hatchlings from each nesting site that were present in an area with 4 threats and dividing it by the total number of individual virtual hatchlings found in that area. Each letter uniquely identifies a location with a threat score of 4 and the number identifies the period (1 = Days 1–4, 2 = Days 10–15, 3 = Days 25–30) for areas identified as having a threat score of 4 across 1 or more dispersal phases

Nesting site	Group	Days 1 to 4 (Frenzy)			Days 10 to 15							Days 25 to 30						
		A1	B	C1	D	A2	E2	F	G	C2	H2	I	J	C3	H3	E3	K	L
Delambre	Coastal Is.	0.27	0.001	77.54	19.71	32.10	17.36	57.69	82.41	55.33	49.92	45.33	67.82	55.14	39.46	22.11	8.50	2.94
SW Regnard	Coastal Is.	0.22			2.30	2.04	0.29			0.03						2.11		
Locker	Coastal Is.	4.12	0.003		3.26	0.29	3.30									2.11		0.74
Long	Coastal Is.	0.36	0.001		1.15	2.33	8.90	2.20		0.10	0.08	2.67	2.30	0.07	0.54	7.37	1.96	0.74
Rosemary	Coastal Is.	0.02		1.59	33.33	12.51	17.22	4.95	2.50	5.75	5.88	22.67	1.15	2.08	6.49	16.84	13.73	4.41
Thevenard	Coastal Is.	93.65	0.616		19.45	8.83	16.93	0.55		0.04		6.67				7.37	7.84	7.35
Bells	Mainland			19.23	0.38	0.19		1.10	6.97	4.11	1.26		8.05	1.65	0.54	4.21	1.96	0.74
Mundabullangana	Mainland			1.64			3.59	33.52	8.11	34.57	40.43	14.67	18.39	38.53	50.00	16.84	39.87	55.88
Port Hedland	Mainland									0.08	2.43			1.87	2.97			
Barrow	Offshore Is.	1.12	90.175		15.29	36.08	24.82					5.33	2.30	0.65		20.00	19.61	21.32
Trimouille	Offshore Is.	0.17	0.517		4.54	2.72	2.87					1.33					3.27	4.41
Varanus	Offshore Is.	0.06	8.688		0.58	2.91	4.73					1.33				1.05	3.27	1.47

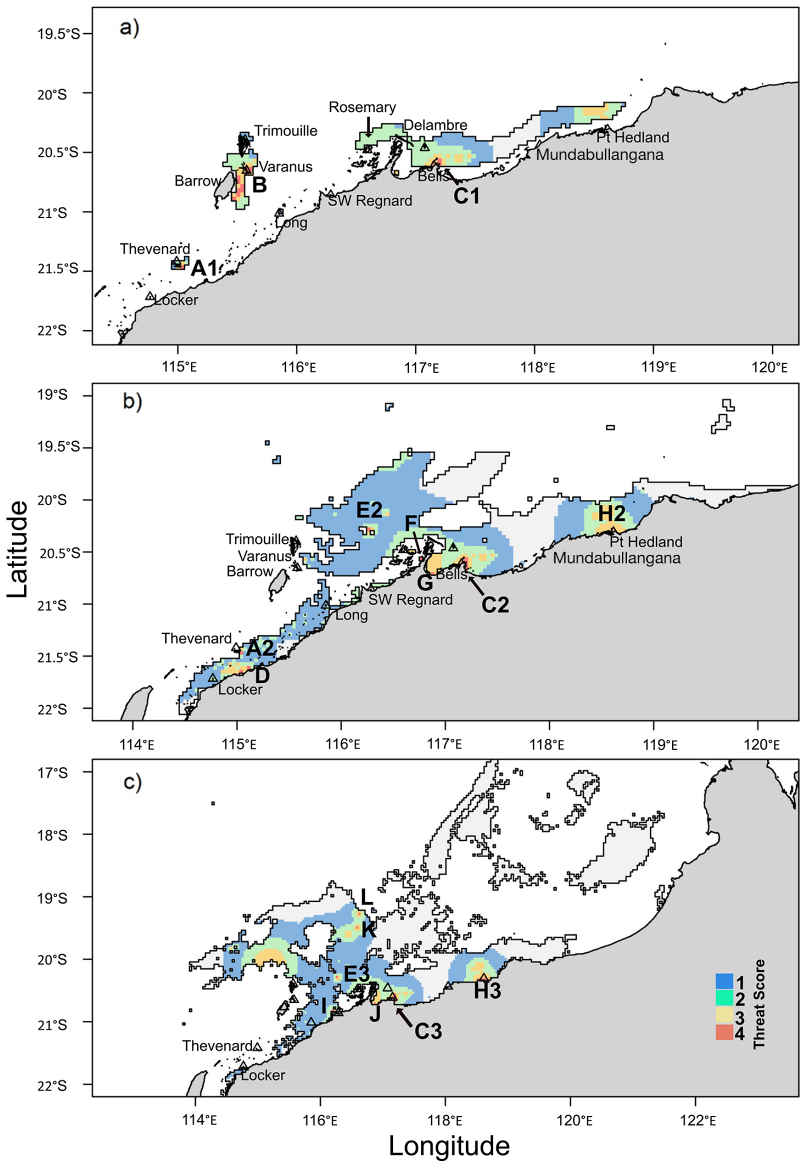

Fig. 4. The cumulative threat score per 4 × 4 km grid cell in the core hatchling area (50% cumulative frequency distribution) calculated for (a) the first 4 d at sea (frenzy), (b) Days 10–15 and (c) Days 25–30. Letters A–L are used to label areas with a value of 4 threats (the maximum). Each letter uniquely identifies a location and the number identifies the period (1 = frenzy, 2 = Days 10–15, 3 = Days 25–30) for areas identified as having a threat score of 4 across 1 or more dispersal phases. Release locations are marked with an open triangle

hatchlings released from these rookeries ended up in areas ‘C2’ and ‘D’, respectively (Table 4, Table S2). Virtual hatchlings from Port Hedland were only found in areas ‘C2’ and ‘H2’, although only a small proportion of the hatchlings released from this rookery ended up there (0.16 and 3.12%, respectively) (Table S2). The largest proportion of virtual hatchlings released from a nesting site that ended up in areas with the highest cumulative threat score was from Bells Beach (12.5 and 16.3% dispersed to areas ‘G’ and ‘C2’, respectively) (Table S2).

3.7. Overlap between core areas and threats during Days 25 to 30

A total of 5565 grid cells (total area 83 852 km^2) covered the core hatching area. More than half of these grid cells had no artificial light (58.6%) (Fig. S6c); 3.6, 9.5 and 28.3% of grid cells experienced high, medium, and low levels of light, respectively. Less than 1% of grid cells contained in-water artificial infrastructure (n = 34) (Fig. S7c); 7 grid cells had shipwrecks (maximum number of shipwrecks per grid cell was 9), 13 overlapped with coastal infrastructure, 5 had oil and gas platforms (n = 1 or 2 platforms per grid cell) and 11 contained petroleum wells.

When in-water artificial infrastructure and artificial light were combined, 16 grid cells had the maximum threat score of 4 and were located in 7 general areas (identified in Fig. 4c). Three of these areas were associated with offshore oil and gas platforms (E3, K, L) and the remainder were associated with areas that have been modified along the coastline, including the Cape Preston wharf (I), a boat ramp near Karratha (J), the Cape Lambert port facility, Point Samson Harbour and Cossack wharf (C3) and Port Hedland port and its associated facilities (H3, Fig. 4c). Virtual hatchlings in areas ‘J’, ‘C3’, and ‘H3’ (Fig. 4c) originated predominantly from Mundabullangana and Delambre Island (>80%) (Table 4). Virtual hatchlings in area ‘I’ mostly originated from Rosemary and Delambre Islands (Table 4). Virtual hatchlings in areas ‘K’ and ‘L’ originated mostly from Barrow Island (~20%) and Mundabullangana (40–56%), whereas area ‘E3’ contained virtual hatchlings that predominately came from Mundabullangana, Rosemary, Delambre and Barrow Islands (Table 4).

Virtual hatchlings from the majority (9 or 10) of nesting sites were found in offshore areas ‘E3’, ‘K’, and ‘L’ (Fig. 4c, Table 4). Virtual hatchlings from South West Regnard Island were only found in area

'E3', whereas virtual hatchlings from Delambre, Long and Rosemary Islands and Mundabullangana were found in all areas (Table 4). More than 5% of the total number of virtual hatchlings released from Delambre and Mundabullangana and 4.3% of the virtual hatchlings released from Bells Beach were found in area 'C3' (Table S2).

4. DISCUSSION

Oceanographic models have been widely used to study the dispersal of organisms where actual measurement is difficult or impossible. Here, we used such a model to quantify the distribution of virtual flatback turtle *Natator depressus* hatchlings in Western Australia during 3 phases of dispersal: Days 1–4 (the frenzy), 10–15 and 25–30. The results support the hypothesis that flatback turtles can remain in neritic waters, at least for their early life history. In addition, our calculation of the core area of these distributions allowed for the inference of the most likely area of use for actual hatchlings up to 30 d post hatching, and the overlap with 2 acknowledged threats. Our results can be used to guide future management and conservation of this age class (up to 30 d) of this threatened species. Given the absence of empirical data to assess impact, any management of this age class has been overlooked. Our results identify areas where post-hatchlings may be present and potentially exposed to threats and areas which should be prioritised to conduct in-water surveys to start collecting baseline monitoring data for this age class.

Our model did not account for hatchling swimming and orientation as data on their movement behaviour once they leave coastal waters is unavailable due to a lack of suitable telemetry technology. However, observations suggest that hatchling flatback turtles spend a large proportion of time floating after 2 h of entering the water (Bell & Pendoley 2014). Given the lack of hatchling behavioural data to parametrise the model, our approach of predicting hatchling movement by surface currents is a reasonable starting point, and similar approaches on other species have led to accurate predictions. For example, the first predicted pathways for loggerhead *Caretta caretta* hatchlings in the North Atlantic, identified using ocean currents (Hays & Marsh 1997), were similar to pathways from satellite tracked neonates (Mansfield et al. 2009, Mansfield et al. 2014). Moreover, the predominant surface currents in the study area are very similar to hatchling speeds recorded in the field (0.25 and 0.34 m s^{-1}; Thums et al. 2013) so it is not unreasonable to assume the actual hatchlings would move at similar speeds as that of the virtual hatchlings simulated in the model. We restricted the model to 30 d, as the longer the model runs, the more uncertain the results become based on many factors, one of them being hatchling behaviour. It is expected that as hatchlings age, they become stronger and increase their ability to influence their position relative to the coast to maintain preferred habitat (Gatto & Reina 2020). In-water surveys of core areas could be conducted to ground-truth our results, which will provide empirical data to support this model.

The results indicate that the passive model retains flatback hatchlings on the continental shelf as the core areas of use (50% distribution) were predominately located within the 200 m depth contour during all 3 phases of dispersal. This shows that flatback turtle hatchlings do not need to swim to stay on the continental shelf, at least during their first 5 d at sea, and that even after 30 d a large proportion of virtual hatchlings remain on the shelf (Fig. 3). This provides some support for our decision to not include hatchling swimming and orientation in the model given previous shelf observations and hypotheses of the absence of an oceanic dispersal phase (Walker & Parmenter 1990, Walker 1991, Bolten 2003). Similar results were reported on the east coast of Australia where particle tracking was used to predict flatback hatchling dispersal, and most of the simulated hatchlings remained in shallow waters during their first 2 wk at sea, also without swimming (Hamann et al. 2011). In addition, our predicted distribution also encompasses areas where post-hatchlings have been observed in the wild. Although these field observations mostly stem from records where carcasses have been found, they provide some support for this model.

Nesting site selection by adult females has been shown to influence hatchling distribution, with turtles nesting in areas that facilitate dispersal to favourable habitats, such as to profitable and/or predictable foraging grounds or areas that support their life history patterns (i.e. oceanic or neritic development) (Hays et al. 2010b, Putman et al. 2010, Hamann et al. 2011, Wildermann et al. 2017). The fact that virtual flatback turtles were retained on the shelf may explain flatback rookery locations, and many of these rookeries are exclusively used by flatback turtles (e.g. most mainland rookeries east of longitude 117° in Fig. 1). A future test of this hypothesis would be to model dispersal from non-nesting areas to determine if they result in dispersal to less favourable habitats.

A combination of tides and wind driven currents constrain them to the coast in this area, particularly within the 50 m depth contour (Fig. 1). Outside this depth contour, they are still transported parallel to the coast but with an offshore component that eventually takes particles to offshore waters, particularly beyond the 200 m depth contour. In contrast, loggerhead and green turtles *Chelonia mydas* require an oceanic dispersal phase (Bolten 2003). These species nest in high numbers at mainland sites further south, at locations such as NW Cape, where hatchlings would be transported offshore past the nearby 200 m depth contour due to offshore winds and upwelling (Woo et al. 2006a,b), likely facilitating their dispersal to oceanic waters. Indeed, particle tracking to predict turtle dispersal pathways has confirmed this (Robson et al. 2017). Furthermore, green turtles nest on the west coast of Barrow Island whereas flatback turtles nest on the east coast. Nesting on the west coast would also aid offshore dispersal whereas nesting on the east coast would transport hatchlings parallel to the coast (Fig. 1). This suggests that they may be nesting in areas that support their life history strategy and this could be explored further using a similar particle tracking approach. Although the majority of virtual hatchlings were retained within the 200 m depth contour, some dispersed further offshore, and releases from some of the rookeries resulted in a high level of beaching (up to 96.5% at Port Hedland, Table 1), particularly sites that were close to or on the mainland (Mundabullangana, Bells Beach, South West Regnard and Port Hedland), where we released the particles up to 20 km from shore to reduce the amount of particles beaching. But of course, actual hatchlings are not seen beaching along these coastlines, as they use active swimming to avoid this. In areas of high tidal range like these, the model needs to be refined potentially by having the oceanographic circulation outputs at finer spatial scales and by incorporating swimming behaviour of the virtual hatchlings.

Our particle tracking simulations indicate that hatchlings from the same genetic stock are likely to disperse to different areas during their early dispersal due to local topography and surface circulation patterns along the NW Shelf. For instance, virtual hatchlings released from nesting sites on the eastern side of the Dampier Archipelago (Delambre, Bells Beach, Mundabullangana and Port Hedland) were likely to be transported further to the east than virtual hatchlings released from offshore islands and coastal islands west of the Dampier Archipelago, which dispersed further offshore and south (Fig. 1, Figs. S2–S3). This was due to the direction of surface currents that transported virtual hatchlings in different directions. The irregular topography around Barrow Island forms a topographic barrier between Barrow Island and the mainland which causes cooler water from the Ningaloo Current to be deflected north, separating the coastal current east of Barrow Island from the offshore current (Bui 2021). Furthermore, the >40 islands that make up the Dampier Archipelago interact with water transport and that, along with the westerly winds, causes water to be pushed eastward and northward near Rosemary Island (Pearce et al. 2003). This suggests that management of the NW Shelf flatback turtle stock should be considered within the context of these findings.

There is evidence in other species that the foraging areas used by adults are areas that hatchlings encountered during their dispersal from the nesting beach (Hays et al. 2010b, Hoenner et al. 2016). While we recorded broad dispersion across the NW Shelf (Fig. 3), a large proportion of the hatchling core areas during all 3 time periods (Days 1–4, 10–15 and 25–30) were concentrated close to the coast. Female flatbacks turtles from the NW Shelf genetic stock have been found to forage along coastal areas, from NW Cape to Broome, largely within the 50 m depth contour (Pendoley et al. 2014b, Whittock et al. 2016, Thums et al. 2018, L. R. Peel et al. unpubl.) and our results show there is overlap between these foraging areas and hatchling core areas, particularly during their early dispersal (Days 1–4 and 10–15; Fig. S8 in the Supplement). Although speculative, these results provide some support for this hypothesis. Interestingly, virtual hatchlings from mainland rookeries had a tendency to disperse towards the northeast (Fig. S2) and post-nesting females from Port Hedland and Mundabullangana also forage in areas northeast of their nesting locations near Eighty Mile Beach and the Lacepede Islands (Whittock et al. 2016).

Previous studies have suggested increased predation of hatchlings from attraction to artificial lights and from in-water infrastructure near turtle rookeries which act as fish attracting devices (Wilson et al. 2019, 2022). However, a lack of understanding of the distribution of hatchlings, whose range overlaps with coastal and offshore activities for hydrocarbon and mineral resource exploitation (Kamrowski et al. 2014a, Pendoley et al. 2014a), has so far precluded assessment of the risk of these threats more broadly. We found 84.5% overlap between the core hatchling area during the early dispersal (Days 1 to 4) and at least one anthropogenic threat. Port Hedland was the only nesting site that was absent in one or more of these high cumulative threat areas during early dispersal, although this was likely the result of releasing hatchlings beyond areas where high light levels and in-water infrastructure overlapped (i.e. hatchlings were released 20 km from the shoreline). Virtual hatchlings released from Delambre Island, Mundabullangana and Rosemary Island were found in all of the high cumulative threat areas during one or more dispersal phase. The potential impact of these threats is therefore greatest at these rookeries, and these nesting locations represent a large proportion of the flatback turtle population from the NW Shelf Stock (Fossette et al. 2021a). Additionally, a considerable proportion of the virtual hatchlings released from Bells Beach ended up in one or more of the high cumulative threat areas during all dispersal phases and essentially all virtual hatchlings released from Barrow and Varanus Island during the frenzy period were found in the high cumulative threat area located near these rookeries. Subsequent validation of our predicted core areas will allow more certainty around the need to address these threats to these rookeries. In addition, finer-scale models should be developed to better resolve hatchling pathways from mainland rookeries and explore overlap with coastal areas having high values of cumulative threats. For example, virtual hatchlings were released at least 5 km from shore at mainland rookeries, and virtual hatchlings were not released inshore of Delambre and Rosemary Islands in the Dampier Archipelago. As such, these areas were not included in the model, and many of these locations contain several lit industrial developments such as port developments that extend far beyond the shoreline (Pilbara Ports Authority 2021).

When hatchlings enter the water, they can be immediately attracted towards light sources (Limpus et al. 2003, Thums et al. 2016, Wilson et al. 2018), and if these lights are associated with infrastructure, they can be at higher risk of predation (Wilson et al. 2019). But our knowledge of attraction to lights is mostly limited to their initial dispersal through nearshore waters in the first 1 to 2 h following their entry in the sea. What is less well known is how long attraction towards lights occurs for (days, weeks or more). Information provided here suggests most exposure may happen during their early dispersal (i.e. the frenzy and Days 10–15). Although we are not able to determine the attraction of virtual hatchlings to lights during these phases, more than 80 % of the core areas identified during the 4 d frenzy and 40–70 % of the areas during settlement (Days 10–15 and 25–30) overlapped with artificial light. If flatback hatchlings and post-hatchlings are drawn towards lights beyond nearshore waters where experiments have occurred, then our results suggest that the potential to increase their mortality occurs over much larger areas than just the coastal fringe, and warrants further study.

National light guidelines were recently developed in Australia to provide guidance for developers to follow on best practice light management principles and to provide information for managing the impacts of artificial light on wildlife (Department of the Environment and Energy 2020). Considering a large proportion of the core areas are already affected by artificial light, any new developments will add to these current levels. Given this, consideration should be given to the cumulative effect that new projects would cause to existing light levels. Additionally, efforts should be focused on improving light regimes for existing infrastructure to lower emissions such as by reducing the number or intensity of light fixtures and, where possible, using light types that marine turtles are less sensitive to (e.g. avoiding lights enriched in short wavelength light) (Department of the Environment and Energy 2020).

Importantly, our analysis has also identified core areas for hatchlings not currently impacted by threats that could be considered for conservation. In particular, the waters adjacent to Mundabullangana and east of Port Hedland currently have no artificial light or increased predation pressures caused by in-water artificial infrastructure. Mundabullangana is a regionally important nesting site and supports a substantial population of nesting flatback turtles (Pendoley et al. 2014a, Fossette et al. 2021a). Similarly, Eighty Mile Beach, which is located to the east of Port Hedland, is an important nesting site for flatback turtles; however, they form a separate genetic stock to the NW Shelf Stock (FitzSimmons et al. 2020). Ensuring these areas remain free from these threats may therefore benefit multiple stocks. As virtual hatchlings were most frequently present in these areas through all phases of dispersal, managers could consider making these waters priority areas for minimising impacts. Some level of protection already exists as this area falls within the boundary of the Eighty Mile Beach Marine Park (Department of Parks and Wildlife 2014).

Biologically Important Areas (BIAs) are areas defined by the Australian government to protect species use for different activities such as foraging, migration, breeding. They are therefore important management zones, as they provide critical habitat for the species survival (Department of the Environment and Energy 2017). For turtles, most of the data used to define BIAs originates from data on adult turtles. However, no data exists to define BIAs for hatchlings. In the absence of empirical data on hatchling distribution, and as a precautionary measure, we suggest the core hatchling areas we delineate (or potentially the 25% distribution) could be defined as 'Potential' BIAs for hatchlings. These areas should however be further validated by field surveys or refined modelling studies.

5. CONCLUSIONS

A passive drifting model was used to predict the distribution and core areas for flatback turtle *Natator depressus* hatchlings in Western Australia over their first 30 d at sea. As more data on their early life history characteristics comes to light, we can re-run this model, potentially adding behaviours such as swim speed and direction and time spent swimming to refine these predictions. Here we show that virtual hatchlings can passively stay on the continental shelf during this dispersal stage, supporting the hypothesis that flatback turtles have a neritic development pattern. We have identified areas, such as along the coast between the Dampier Archipelago and Pardoo (up to ~40 km from shore), where managers and researchers could conduct surveys to look for post-hatchlings dispersing from the NW Shelf Stock during years with typical oceanic conditions. We have also shown that a large proportion of their predicted core areas during their early dispersal are areas where they may encounter a range of threats that may threaten their survival, suggesting mitigations might be necessary for the long-term conservation of this species and life stage.

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