



# A participatory spatial risk assessment of green turtles (*Chelonia mydas*) with indigenous rangers in northern Australia

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## Abstract

Coastal marine species and ecosystems face increasing pressure from anthropogenic threats. Green turtles (*Chelonia mydas*), listed as Vulnerable in Australia, are ecologically important and culturally significant for Indigenous Traditional Owners. This study co-developed a spatial risk assessment with eight Indigenous ranger groups to assess threats to green turtles in waters of Australia's Northern Territory. Six anthropogenic hazards (comprising 11 threats) were mapped and combined with turtle occupancy, derived from the satellite tracks of 45 green turtles, to quantify threat exposure. Expert knowledge from Indigenous rangers on the impact and occurrence of 24 threats was combined to assess turtle vulnerability, generating a spatially explicit map of relative risk. Darwin Harbour had the highest concentration of overlapping threats, including artificial light, recreational vessels, oil infrastructure and shipping. Turtle vulnerability varied by region, reflecting local knowledge. Nest predation (West Arnhem, Tiwi Islands), sea-level rise, traditional hunting and industrial pollution had the highest threat scores. Foraging turtles were concentrated in eight areas, and Channel Island (Darwin Harbour) posed the highest relative risk for foraging turtles. Migration routes near Darwin Harbour and Bynoe Harbour were risk hotspots. Mixed-effects analyses showed that perceived vulnerability was structured primarily by threat type, with ranger experience contributing to variation in threat perceptions, highlighting the importance of retaining experienced Indigenous rangers for effective place-based conservation. Integrating Indigenous knowledge with spatial data, the study identifies high-risk areas for a culturally and ecologically important species and supports targeted management and sustained investment in Indigenous ranger programs amid increasing climate and industrial pressures.

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## Introduction

The health of coastal marine environments is declining due to changes in ecosystem structure and function resulting from multiple anthropogenic hazards, including climate change, habitat loss, pollution and commercial fishing (Kennish 2022). These hazards often have cumulative effects, where their combined impact is greater than the sum of their individual effects (Smit and Spaling 1995; Halpern et al. 2007; Ashford et al. 2022; Ferreira et al. 2023; Adams et al. 2023). For example, overfishing can reduce biodiversity, making ecosystems more vulnerable to other hazards, such as pollution or climate change. Assessing these cumulative effects is challenging due to the complex interactions among various hazards and the difficulty in isolating individual impacts, which complicate the development of effective management strategies (Grech et al. 2011; Ferreira et al. 2023; Adams et al. 2023).

Analysing the combined impact of multiple environmental hazards supports the prioritisation of conservation efforts. However, for conservation investments to be truly effective, it is essential to go beyond identifying vulnerable areas and establish clear links between the dominant hazards affecting ecosystems and the most suitable management actions (Tulloch et al. 2024). This involves understanding the root causes of environmental degradation and implementing targeted strategies that directly mitigate these impacts and enhance ecosystem resilience.

One of the key challenges in applying these approaches is evaluating environmental risk in data-poor areas, where limited scientific information makes it difficult to accurately assess threats and conservation priorities. Without sufficient data, it becomes challenging to determine which hazards may be having impacts – this is a crucial first step in determining prioritisation and potential mitigation. This is especially relevant in remote marine environments, and particularly coastal environments, where human use overlaps with vulnerable species such as marine turtles, which reside in coastal environments and seasonally come onto beaches to lay their eggs.

Six out of the seven species of marine turtles (DEE 2017) are currently listed on the IUCN Red List of Threatened Species (Seminoff 2004, 2023), although green turtles (*Chelonia mydas*) were recently downgraded to ‘Least Concern’ (Hays et al. 2025; Wallace and Broderick 2025). Historically, the most significant human-induced threat to marine turtles was the intensive international harvest of eggs, nesting adults, and foraging juveniles and adults (Seminoff 2004). However, harvest pressure has declined substantially in many regions, and contemporary global assessments now identify climate-change-related impacts, fisheries bycatch, pollution, and coastal development as the most widespread and pressing threats to turtle populations (Seminoff et al. 2023; Hays et al. 2025). Marine turtles have a spatial and temporal separation of tens to thousands of kilometres between their breeding and foraging grounds, and breeding only occurs every two to five years (Lanyon et al. 1989; Witherington 2002; Bell et al. 2012; Shimada et al. 2016; DEE 2017). The use of different habitats and geographic regions over their lifecycle makes turtles more exposed to a broad range of anthropogenic activities and threats than other species (Klein et al. 2017). Several global strategies guide marine turtle conservation (IUCN/SSC Marine Turtle

Specialist Group 1995). These are complimented by population-based regional management frameworks such as Marine Turtle Regional Management Unit (RMUs) that explicitly account for connectivity and shared threat exposure across jurisdiction (Wallace et al. 2023), alongside regional conservation plans (IOSEA 2009) for marine turtles, as well as national recovery plans (National Marine Fisheries Service and U.S. Fish and Wildlife Service 1998; DEE 2017).

Green turtles are listed as ‘Vulnerable’ under Australia’s *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) (DEE 2017). Along with other threatened turtle species in Australia, there is a recovery plan for green turtles, which identifies their main threats in the Northern Territory, Australia, as marine debris, climate change, chemical and terrestrial discharge, international take (turtles taken outside Australian waters) and Indigenous take (DEE 2017).

In this study, the term Indigenous Australians is used as an inclusive descriptor for the Aboriginal and Torres Strait Islander Peoples of Australia. The term Indigenous Traditional Owners refers specifically to Aboriginal and Torres Strait Islander peoples who hold cultural authority and responsibilities for particular areas of land and sea under customary law (Australian Indigenous HealthInfoNet 2024).

Green turtles are a species of high cultural importance to Indigenous Traditional Owners across northern Australia (DEE 2017; Tucker et al. 2021). They appear as totems and in Dreamtime stories (cultural creation narratives that explain the origins of people, animals, landscapes, and law), and are often represented in Aboriginal art (Butler et al. 2012; DEE 2017). The meat and eggs from all turtle species are also important food sources (Kennett et al. 2004b; DEE 2017; Delisle et al. 2018).

The term ‘Sea Country’ is used by Indigenous Australians to refer to any environment within their broader traditional estate that is associated with the sea or saltwater, including coastal areas, estuaries, beaches, marine areas and islands (Ens et al. 2012; Dam Lam et al. 2019). Many Indigenous Traditional Owners of northern Australia are custodians of extensive and often remote Sea Country (Kennett et al. 2004a; Rist et al. 2019). Since 2008, Indigenous Traditional Owners in the Northern Territory have reclaimed legal rights to the intertidal zone of Aboriginal Land under the *Aboriginal Land Rights Act 1976*. Additional protection and management of Sea Country exists through Indigenous Protected Areas, which are areas of land and sea that Traditional Owners have agreed to manage for biodiversity conservation (Rist et al. 2019; DCCEE 2024). As a result, Indigenous natural and cultural resource management organisations and ranger groups are increasingly responsible for the management of northern Australia’s globally significant populations of tropical marine megafauna (Ens et al. 2012; Grech et al. 2014).

Indigenous rangers’ deep relationship with their Country and their complex ways of knowing, being and doing provide profound insights into species such as green turtles. Indigenous knowledge extends beyond raw data or expertise, embodying a unique epistemology rooted in cultural, spiritual and ecological relationships that risk losing meaning if reduced to raw information (Martin and Miraboopa 2003). Effective conservation and environmental management requires genuine co-design with Indigenous ranger groups. This includes recognising their leadership, deep ecological knowledge and governance systems, and acknowledging them as not just as ‘data sources’ but as equal partners (Martin and Miraboopa 2003; Parsons et al. 2016; McLean et al. 2023).

The goal of this project was to use a participatory approach involving scientists and Indigenous ranger groups across the Northern Territory to conduct a spatial risk assessment and identify priority actions for managing green turtles in Indigenous Sea Country. This assessment involved four phases (Furlan et al. 2018):

1. Identification and mapping of anthropogenic hazards that pose threats to green turtles (e.g. commercial fishing, light pollution, oil and gas development).
2. Assessment of the exposure of turtles to these hazards, based on satellite-tracking data and habitat use.
3. Evaluation of turtle vulnerability to each hazard, using a structured expert-elicitation process with Indigenous rangers.
4. Spatial mapping of relative risk, combining exposure and vulnerability to identify hotspots where turtles are most at risk.

By incorporating Indigenous knowledge through co-design of the vulnerability assessment, this project enhances the effectiveness of green turtle conservation and strengthens Indigenous leadership in marine management, ensuring that conservation strategies are culturally appropriate, informed by local knowledge and ecologically sound.

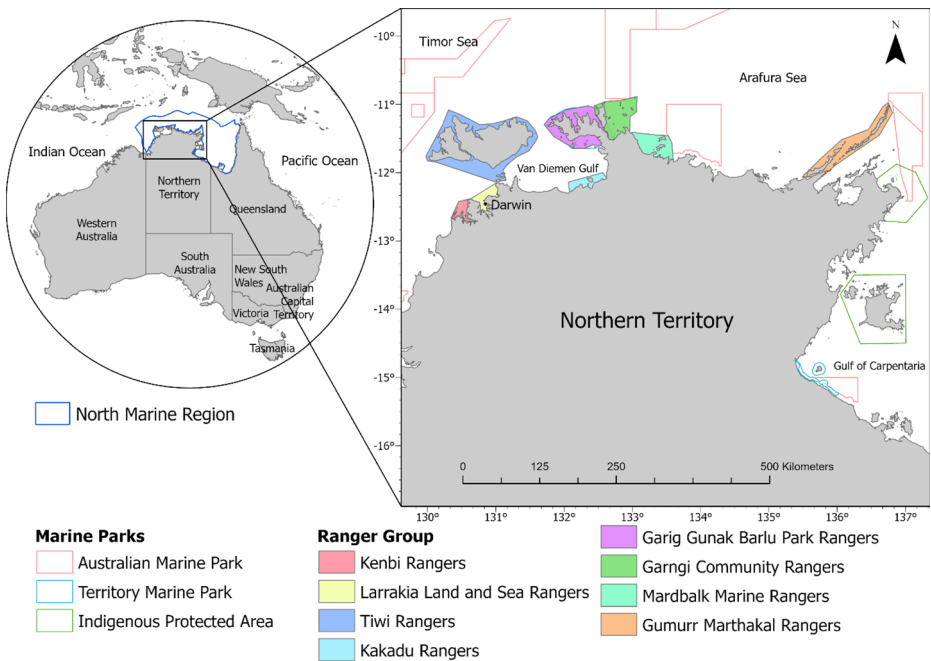
## Methods

### Study area

Australia's North Marine Region, including the Northern Territory (Fig. 1), is characterised by a tropical monsoonal climate with high temperatures (mean daily maximum temperature in Darwin is 32.3 °C; BoM 2025). Heavy seasonal rainfall and cyclones (November–April) alternate with extended rain-free periods (May–October). The region experiences complex tidal regimes. Some areas undergo two daily tidal cycles and other areas have a single daily tidal cycle. Some areas have very large tidal ranges and others have almost no tidal range (DSEWPC 2012). The Northern Territory has an average sea-surface temperature of 30.6 °C in the wet season and 24.5 °C in the dry season (URS Australia Pty Ltd 2008). The area has three levels of marine protected areas: Australian Marine Parks (Australian Government), Territory Marine Parks (Northern Territory Government) and Indigenous Protected Areas (Traditional Owners). Australian Marine Parks such as Joseph Bonaparte, Oceanic Shoals, Arafura, Arnhem, and Wessel include a mix of multiple-use (commercial fishing allowed with a permit), habitat protection, and no-take (sanctuary) zones, while Territory parks like Cobourg Marine Park and Limmen are co-managed with Traditional Owners and allow regulated fishing and customary use. Indigenous Protected Areas (Anindilyakwa and Dhimurru) provide additional culturally led conservation across Sea Country.

### Hazard assessment

A hazard is a condition or an object with the potential to cause or contribute to environmental harm. A hazard is not an event but is a prerequisite for the occurrence of a hazardous event (Furlan et al. 2018; Roberson et al. 2022). A threat is anything that could cause harm



**Fig. 1** Map of the study area. The map on the left shows the regional geographic context, and the inset on the right shows the detailed study area, the different levels of marine protection, and the management areas of the ranger groups that participated in the study

when a species, habitat or ecosystem is exposed to a hazard. For example, if the hazard is commercial fishing, then the threat might be the bycatch of threatened species. Under the Commonwealth’s EPBC Act, a threat can be identified and listed as a ‘threatening process’ if it threatens the survival, abundance or evolutionary development of a native species or ecological community (DEE 2017). Vulnerability is the impact of a hazardous event on individual animals or populations, and risk represents the potential for harm, based on whether turtles are exposed to a hazard (exposure) and how severely they are affected if exposed (vulnerability) (Korpinen and Andersen 2016; Pennino et al. 2017; Furlan et al. 2018; Roberson et al. 2022; Ma et al. 2023).

The first step of this risk assessment was to identify the hazards, the threats associated with the hazards, and the metrics for characterising each hazard for green turtles in the Northern Territory. This study focused specifically on in-water behaviours, including foraging (characterised by slow, localised movements and prolonged use of feeding areas) and migratory movements (long-distance directional travel between foraging and breeding areas) undertaken by juvenile, subadult, and adult turtles, and therefore did not explicitly assess terrestrial or nesting-stage risks. However, selected nesting-related threat data were included to provide contextual information and support broader interpretation of risk. The key anthropogenic activities that threaten green turtles in the Northern Territory, and the behaviour or life stages they impact, were identified from the *Recovery Plan for Marine Turtles in Australia* (DEE 2017), discussions with rangers and published literature (Donlan et al. 2010; Grech et al. 2011; Roelfsema et al. 2016; Klein et al. 2017; Hart et al. 2018;

Williams et al. 2019; Petursson 2021; Ashford et al. 2022; Ferreira et al. 2023; Fuentes et al. 2023). The anthropogenic hazards identified were climate change, commercial fisheries, industrial development, coastal development, commercial shipping and nest predation (Table 1) (Gunn et al. 2010; Donlan et al. 2010; Fuentes and Cinner 2010; DEE 2017; Hart et al. 2018; Hardesty et al. 2021; Ashford et al. 2022).

**Table 1** The hazards and their associated threats (11 spatial layers) and the data sets used to delineate the spatial distribution of these threats

Hazard category	Threats	Spatial layers	Behaviour or life cycle impacted	Data source
Climate change	Heating causing habitat loss (coral bleaching)	Sea surface temperature	Foraging (juveniles, sub-adults, adults)	United States National Oceanic and Atmospheric Administration
	High rainfall increases turbidity, reducing light availability to habitats	Resuspended particles	Foraging (juveniles, sub-adults, adults)	Australian Ocean Data Network (Roelfsema et al. 2016)
Commercial fisheries	Bycatch in net	Commercial fisheries – density	Foraging (juveniles, sub-adults, adults), migrating (sub-adults, adults)	Australian Maritime Safety Authority
Industrial development	Mining, agriculture and sewage run-off	Industrial pollution	Foraging (juveniles, sub-adults, adults)	Australian Ocean Data Network
	Dredging, smothering habitats	Ports/dredging	Foraging (juveniles, sub-adults, adults)	Australian Ocean Data Network (Roelfsema et al. 2016)
	Oil spill or gas leak – from shore	Oil and gas spill	Foraging (juveniles, sub-adults, adults), migrating (sub-adults, adults)	Australian Ocean Data Network (Roelfsema et al. 2016)
	Gas leak – at sea	Oil and gas spill (pipeline)	Foraging (juveniles, sub-adults, adults), migrating (sub-adults, adults)	Marine Biodiversity Hub
Coastal development	Noise, vessel strikes	Recreational vessel density	Foraging (sub-adults, adults), migrating, (sub-adults, adults)	Road Safety NT, Bureau of Statistics
	Illumination/light pollution impacting navigation	Artificial light	Foraging (juveniles, sub-adults, adults), migrating (sub-adults, adults), nesting (adults)	The New World Atlas of Artificial Sky Brightness (Falchi et al. 2016)
Commercial shipping	Vessel strike, oil/fuel spill	Commercial shipping – density	Foraging (juveniles, sub-adults, adults), migrating (sub-adults, adults)	Australian Maritime Safety Authority
Nest predation	Digging up and eating turtle eggs	Invasive predators	Nesting (adults)	Department of Agriculture Fisheries and Forestry – National Feral Pig Current Distribution in Australia (ABARES and CSIRO 2024)

## Cumulative hazards

A cumulative-hazard map is a spatial tool that visualises the combined weights (occurrence and intensity) of multiple anthropogenic hazards on ecosystems. These maps help identify areas experiencing the greatest relative intensity of occurrence of threats, guiding sustainable management and conservation efforts, particularly when combined with turtle-movement data (Roberson et al. 2022; Ashford et al. 2022; Ferreira et al. 2023). Each of the 11 threats associated with the hazards (Table 1), and the occurrence and intensity of each threat (e.g. fishing density, sea-surface temperature anomalies), were mapped using a cell size of  $2 \text{ km} \times 2 \text{ km}$ .

The choice of a  $2 \text{ km} \times 2 \text{ km}$  grid for all hazard layers reflects a balance between ecological relevance, data resolution, and consistency with previous large-scale marine risk assessments. This grid size is fine relative to the spatial extent of the Northern Territory coastline (Fig. 1) and comparable to, or finer than, resolutions used in similar cumulative-hazard and exposure analyses for marine turtles and other marine megafauna (Grech et al. 2011; Thums et al. 2021; Ferreira et al. 2023). In gridded spatial analyses, results can vary with the size and placement of grid cells, and artificial boundaries may affect how highly localised hazards or turtle use are represented near cell edges. Accordingly, the cumulative-hazard and exposure maps are interpreted as indicators of relative spatial risk rather than precise cell-level predictions. The fine spatial resolution used here reduces boundary effects relative to coarser grids and supports identification of persistent areas of overlap between turtle use and anthropogenic pressures.

For each hazard layer, raw values were normalised to a unitless scale between 0 and 1 using min–max normalisation across the full spatial extent of the Northern Territory, where 0 represents the lowest observed intensity and 1 represents the highest observed intensity for that hazard (Grech et al. 2011). Using the ‘Raster’ package in R (Hijmans 2023), the spatial hazard layers were stacked together, and the relative intensity scores were summed for each potential turtle behaviour impacted (foraging and migrating), each layer was given the same weighting (assumed that each hazard has the same impact on turtles) (Table 1). While hazards affecting nesting behaviour were identified and spatially mapped, they were excluded from the cumulative-hazard assessment owing to insufficient recent data on nesting activity in the Northern Territory. The most comprehensive survey remains Chatto and Baker (2008) – no recent updates are available to support a robust risk assessment for nesting turtles. The final raster was normalised to calculate the relative cumulative-hazard score between 0 and 1. This cumulative-hazard score accounts for the number of hazards in a grid cell as well as the relative intensity for each of these hazards.

For some hazards, including commercial fisheries and industrial development, available spatial datasets did not consistently distinguish among specific activity or gear types at a resolution appropriate for this study. Fisheries data represented aggregated fishing activity (vessel density/effort), as gear-specific datasets were only available at much broader spatial scales and were therefore unsuitable for fine-scale exposure mapping. Similarly, industrial development encompasses multiple activities (e.g. mining runoff, dredging, oil and gas infrastructure), which were represented using separate spatial layers where available, but grouped under a common hazard category to reflect shared origins and overlapping spatial footprints. This aggregation reflects data availability rather than an assumption of equiva-

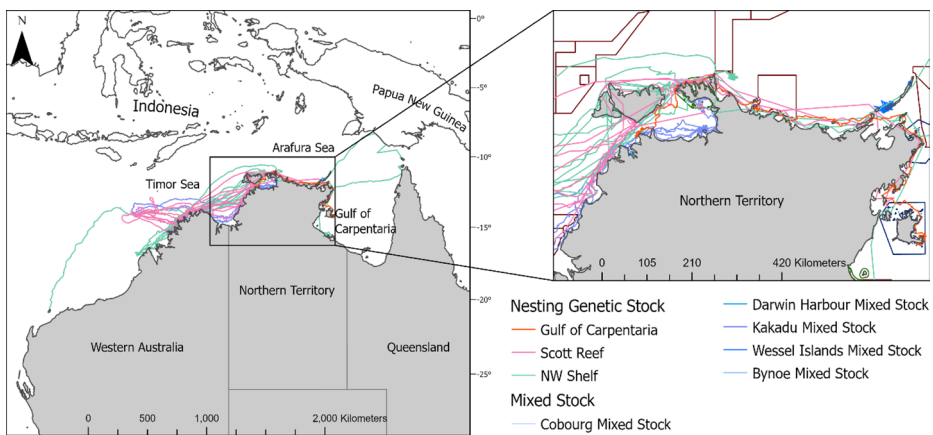
lent impacts; differentiation among specific threat mechanisms was addressed explicitly through the vulnerability assessment using expert elicitation.

The count of hazards per grid cell was calculated by summing the presence (1) and absence (0) of each hazard across the Northern Territory (Ferreira et al. 2023).

## Exposure assessment

The exposure assessment aims to identify areas where the turtles are most likely to be exposed to cumulative hazards during each behaviour (foraging and migrating). The core exposure areas were identified by using satellite-tracking data from satellite tags deployed on green turtles in Northern Territory foraging grounds and from nesting green turtles satellite-tagged in other states that migrated through or foraged in the Northern Territory (Fig. 2, Supplementary Material: Table S1). Eighteen adult foraging green turtles (primarily males) were satellite-tagged at Cobourg, Kakadu, Bynoe Harbour and the Wessel Islands by Indigenous ranger groups in collaboration with Charles Darwin University from 2021 to 2024. Other turtle satellite-tagging data, spanning around 20 years, was sourced from adult female nesting turtles at Scott Reef (Scott Reef genetic stock), the Maret Islands, the Lacepede Islands, Barrow Island (North West Shelf genetic stock), Groote Eylandt (Gulf of Carpentaria genetic stock) and foraging turtles in Darwin Harbour (mixed genetic stock) (Pendoley 2005; Waayers et al. 2011; Ferreira et al. 2020, 2023; Thums et al. 2021). A total of 45 turtle satellite tracks were used for the exposure assessment (Supplementary Material: Table S1).

Both Argos and Fastloc-GPS location data were used in the exposure assessment. Fastloc-GPS tags provided higher-accuracy positions, while Argos tags provided longer but lower-resolution tracks. All locations were first filtered in R using the package ‘SDLfilter’ (Shimada et al. 2016, 2021). A state-space model from the ‘aniMotum’ R Package (Jonsen et al. 2023) was used to account for location error and to standardise to four positions every 24 h. It included a movement-persistence model, which provided an objective behavioural index (move persistence) along the tracks.



**Fig. 2** A summary of the recent and historical green turtle satellite-tracking data sourced for this project. The left map shows all the tracks collected for this project, and the inset shows a closer view of the Northern Territory data

Move persistence ranges between 0 (decrease in speed and directionality=low move persistence) and 1 (increase in speed and directionality=high move persistence). Segments of relatively low move persistence generally indicate foraging, but low move persistence is also observed by turtles on nesting grounds (associated with breeding and resting behaviour) (Bailey et al. 2010). Segments of high move persistence are related to migration or transit behaviour (Jonsen et al. 2020). Turtle tracks were split into either foraging, nesting or migrating behaviour based on their movement persistence (ranging from 0 to 1). An initial threshold of  $\gamma=0.5$  was explored, consistent with common practice; however, this cut-off did not reliably distinguish migratory and foraging behaviours when evaluated against tagging location and known behavioural context. A more conservative threshold ( $\gamma>0.75$  for migration;  $\gamma\leq 0.75$  for foraging or nesting) was therefore adopted to reduce behavioural misclassification. Foraging or nesting behaviour was determined by the turtles' behaviour when tagged and distance from nesting grounds.

To map the relative distribution of green turtles in the Northern Territory, the study area was gridded into 2 km  $\times$  2 km grids (to match the cumulative-hazard map). Time spent foraging in each grid cell was calculated using the R package 'Trip' (Sumner et al. 2021) from the tracks for each turtle when it was displaying foraging behaviour.

The relative proportion of time spent per cell was calculated for each turtle that displayed foraging behaviour by dividing the time spent foraging or resting in each grid cell by the total track time (the total time that the satellite tag transmitted data). This per-individual normalisation ensured that turtles contributed equally to the occupancy index regardless of deployment duration, preventing longer tracks from disproportionately influencing spatial patterns. For each turtle, the resulting per-cell proportion rasters were stacked, and the values in each grid cell were summed. The values were normalised to range between 0 and 1 to provide a foraging occupancy index (Ferreira et al. 2023).

Because migrating turtles do not spend much time in individual grid cells, time spent is not a useful metric for mapping relative distribution (Ferreira et al. 2020). As such, the turtle tracks that displayed migrating behaviour were analysed based on the number of turtles passing through each grid cell using the same methods outlined above for time spent. This number was then transformed into a percentage of migrating turtles per cell.

Exposure intensity was then calculated using the cumulative-hazard map and the occupancy index for foraging turtles or the percentage of tagged migrating turtles per grid cell using the following formula (Ferreira et al. 2023):

$$\text{Exposure intensity} = \text{cumulative hazards} \\ \times \text{occupancy index (for aging) or percentage of turtles (migrating)}$$

Although satellite tracking sample sizes are inherently limited for large marine vertebrates, previous studies demonstrate that for highly mobile marine megafauna, including marine turtles, relatively small telemetry sample sizes (often 20–40 individuals) are sufficient to reliably characterise spatial use, migration corridors, and relative exposure patterns, with additional tracks potentially yielding diminishing returns (Sequeira et al. 2019; Ferreira et al. 2020). The dataset used here provides broad spatial and behavioural coverage of green turtle use of Northern Territory waters. The 45 satellite tracks span approximately two decades and include turtles from multiple genetic stocks and life-history contexts, encompassing adult foraging turtles tagged at key Northern Territory foraging grounds, as well as

adult nesting females from major rookeries whose migratory routes and foraging behaviour overlap Northern Territory waters. Given the long life span and strong site fidelity of green turtles, migratory corridors and core foraging areas are generally stable over decadal timescales. Accordingly, these data are used to identify persistent areas of turtle use and relative risk hotspots, rather than to infer fine-scale or time-specific exposure. While not all foraging grounds or demographic groups are represented, the dataset captures most known foraging areas and migratory pathways in the study area and provides a representative basis for mapping relative exposure rather than population size or density.

## Vulnerability assessment

The exposure-intensity maps enabled an assessment of where green turtles are exposed to multiple threats; however, they did not provide information on the likelihood or potential impacts of that exposure. For this reason, and because spatial-density layers were not available for all threats, a vulnerability-assessment process using expert elicitation was used to evaluate the degree to which hazards and their threats impact green turtles. Structured expert-elicitation surveys have previously been used to inform sea-turtle conservation and aid in setting priorities in Australia and internationally (Donlan et al. 2010; Fuentes and Cinner 2010; Williams et al. 2019).

These expert-elicitation surveys were conducted in accordance with the principle of free, prior and informed consent (ISE 2006; Rumler 2011). The notion of 'free' implies freedom from coercion and manipulation and freedom from conduct deemed inappropriate because of unequal power dynamics. This was achieved through the development of research partnerships between scientists and ranger groups and the conduction of workshops to discuss research priorities. 'Prior' consent was obtained by early research-partnership agreements and human-ethics approvals (Charles Darwin University Human Research Ethics Committee). 'Informed' consent was obtained by conducting an information briefing at a workshop with all ranger groups, following which rangers were asked if they were interested in participating in the survey. A follow-up plain-language information sheet was provided to all participants. Each individual participant was asked to sign a consent form immediately prior to taking part in the survey. The right to withhold or withdraw consent at any time was explained to all participants before signing the consent form. The surveys were voluntary and conducted in person and on Country, during visits to the ranger stations or during fieldwork. All rangers and Traditional Owners who were currently working in the region or had participated in other aspects of the project were interviewed. All surveys were audio-recorded to ensure an accurate capture and transcription of participants' responses.

Interviews were conducted with 39 Indigenous rangers and Traditional Owners from eight Sea Ranger groups across the Northern Territory. These groups were selected using purposeful sampling because they were active partners in the broader research project (Early-Capistrán et al. 2020) and have custodial responsibility for Sea Country (Ens et al. 2012; Dam Lam et al. 2019) where green turtles occur (Wedemeyer-Strombel et al. 2019). Participant numbers per ranger group ranged from three to 15 individuals, reflecting differences in ranger group size and availability.

The expert-elicitation survey included a series of background questions to gauge the participants' experience as rangers working with turtles on Sea Country, and their experience in marine environments outside of work (i.e. how much time spent out on sea country

fishing/hunting outside of work hours) (Ens et al. 2012; Dam Lam et al. 2019). Self-reported confidence, reflecting participants perceived overall knowledge of marine turtles, was collected as a background descriptor to characterise participant experience and to test the sensitivity of vulnerability scores to perceived certainty; it was not used to define expertise or to weight individual participants relative to one another. While many of these threats could be represented spatially in the cumulative-hazard map (Table 1), spatial density data were not available for others, including such as direct take (e.g. traditional hunting or illegal poaching) and plastic pollution. For these threats, vulnerability was assessed exclusively through expert elicitation, allowing ranger knowledge and experience to account for impacts that could not be spatially quantified. The vulnerability assessment included eight hazards: climate change, commercial fisheries, industrial development, direct take, coastal development, plastic pollution, commercial shipping and nest predation (Roelfsema et al. 2016; DEE 2017; Ashford et al. 2022; DCCEEW 2022a; Ferreira et al. 2023; Kvamsdal et al. 2023). The threats within these hazards were based on the literature (Donlan et al. 2010; Roelfsema et al. 2016; DEE 2017; Klein et al. 2017; Hart et al. 2018; Williams et al. 2019; Ashford et al. 2022; DCCEEW 2022a; Ferreira et al. 2023), and input was received from all ranger groups across several successive workshops (attended by at least two rangers from all eight ranger groups) from 2022 to 2024. Twenty-four threats were identified: sea-level rise and erosion; sea surface temperature/habitat destruction; sand temperature; fisheries bycatch; trawling/habitat destruction; aquaculture; agriculture, mining and sewage runoff; oil and gas development; dredging; traditional harvest (foraging turtles); traditional harvest (eggs and nesting turtles); unauthorised take; illegal take; beach armouring; recreational fishing; artificial light; changes to coastal processes; plastic entanglement (water); plastic ingestion; plastic entanglement (beach); commercial vessel strike; oil spill; native predation and invasive predation (see results Table 4). Participants scored the threats to green turtles in their geographic region with respect to the level of impact of the threat to turtles (no comment [NA], none [0], low [1 – only impacts a small number of turtles every year], moderate [2 – impacts a large number of turtles a year], or high [3 – impacts most/all of the turtles in the area]) and occurrence (scale of 1 [low] to 4 [high]) of the threats (Donlan et al. 2010; Fuentes and Cinner 2010; Williams et al. 2019; Kvamsdal et al. 2023). In addition, consequences and specific examples of observed impacts were often given during the surveys through storytelling and were accounted for in the impact scoring. Occurrence was considered as the timing of the threats; for example, if a threat was observed daily (high occurrence) or every few years (low occurrence) (scale of 1 [low] to 4 [high]). Respondents were also asked to rank their confidence in their knowledge of each threat (scale of 1 [low] to 4 [high]). The survey information pack is available in S2 Supplementary Material.

The vulnerability score per threat was calculated in two ways to test the sensitivity of vulnerability rankings to inclusion of self-reported confidence as a modifier of perceived certainty, rather than as a core component of vulnerability:

1.  $Vulnerability = impact \times occurrence \times confidence.$
2.  $Vulnerability = impact \times occurrence.$

This vulnerability formulation was selected for its simplicity and alignment with the spatial risk-mapping framework used in other sections of this study (e.g. exposure intensity calculated as the product of hazard density and turtle occurrence; Ferreira et al. 2023). Similar

multiplicative scoring frameworks are widely used in semi-quantitative risk prioritisation across disciplines (e.g. severity  $\times$  likelihood  $\times$  modifier terms), providing a transparent structure for comparing relative risk when mechanistic data are unavailable. Although more complex expert-elicitation models exist, the objective here was to spatially represent expert perceptions of relative vulnerability rather than to model causal processes; a simple multiplicative formulation was therefore appropriate.

To assess the sensitivity of vulnerability scores to inclusion of confidence, vulnerability estimates were pooled across all threat categories and analysed using generalised linear models (GLMs) with a Gaussian error distribution and identity link function. These analyses were conducted as sensitivity tests rather than inferential hypothesis testing, reflecting the intentional, non-random sampling design inherent to structured expert elicitation.

Vulnerability was modelled as a function of treatment (confidence-included vs. confidence-excluded), with threat category included as a blocking factor to account for baseline differences among threats. Candidate models derived from a global model were compared using the dredge () function in the MuMIn R package (Barton 2025), which evaluates all supported model combinations using the small-sample corrected Akaike Information Criterion (AICc) and associated model weights. Comparisons focused on contrasts among an intercept-only null model, a threat-only model, and models including treatment, to assess whether inclusion of confidence improved model fit (Burnham and Anderson 2002). The assumptions of residual normality, homogeneity of variance, and zero-mean residuals were evaluated using standard diagnostic plots (residuals versus fitted values and Q-Q plots), and no violations were detected.

A set of mixed-effects models were used to assess the influence of social predictors and threat type on perceived vulnerability scores (Donlan et al. 2010), while accounting for repeated scoring by individual participants. The analysis of these social predictors was included to test whether perceived vulnerability scores varied systematically with participant experience or role, rather than to define or weight expertise, which was established a priori through custodial responsibility and long-term engagement with Sea Country. Vulnerability scores (continuous) were modelled using linear mixed-effects models (LMMs) fitted with restricted maximum likelihood (REML) in R using the package “lme4” (Bates et al. 2015), with Satterthwaite’s approximation for degrees of freedom used for inference on fixed effects using the R package “lmerTest” (Kuznetsova et al. 2026).

The primary model took the form:

*vulnerability* ~ *threat* + *ranger\_group* + *turtle\_knowledge* + *experience\_outside\_of\_work* + *traditional\_owner* + (*I* | *id*). Threat category, ranger group, self-reported turtle knowledge, experience outside of work, and Traditional Owner status were included as categorical fixed effects, the variable ‘ranger institution’ was not included as it could not be treated as independent of ‘ranger group’. Participant identity (*id*) was included as a random intercept (*I*|*id*) to account for non-independence among observations from the same respondent (i.e., each participant scored multiple threat categories) The overall contribution of fixed effects was assessed using Type III F-tests (Donlan et al. 2010). Model diagnostics were evaluated using residual plots and histograms of residuals, and the random-effects structure was checked for singularity; no major violations were detected.

To examine whether the pattern of perceived vulnerability among ranger groups differed across threat categories, an interaction model including a threat  $\times$  ranger group term was fitted and compared with the additive model using a likelihood ratio test after refit-

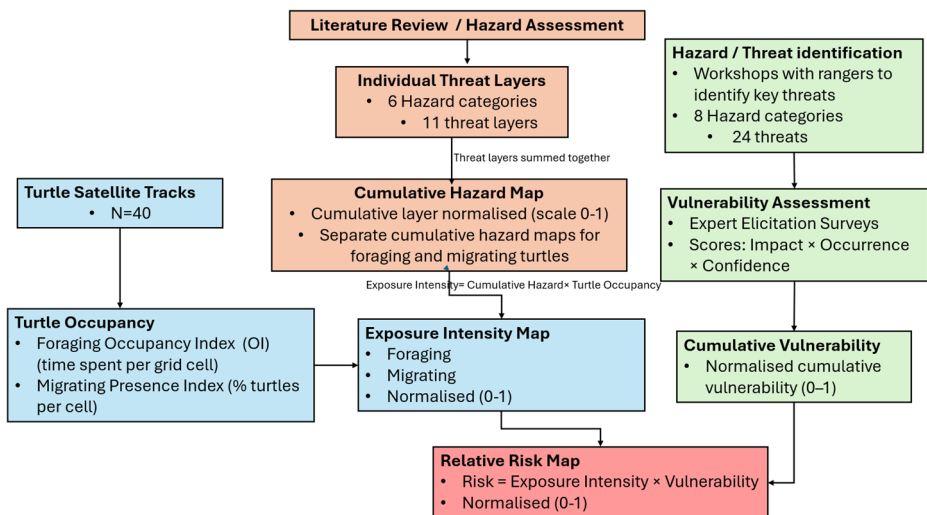
ting models with maximum likelihood (ML). Adjusted marginal means (estimated marginal means; EMMs) and 95% confidence intervals for threat categories and ranger groups were computed using the emmeans R package (Lenth et al. 2025) to support interpretation and visualisation of modelled differences.

To balance any bias not accounted for in the background and confidence questions, the vulnerability score for each threat across all eight ranger groups was calculated using the mean score from each ranger group. The average vulnerability was normalised to obtain a relative vulnerability score between 0 and 1. The relative vulnerability score for each threat was multiplied by the hazard maps, where available. Some of the threats in the vulnerability assessment, such as native predation, sand temperature, plastic entanglement and traditional harvest, did not have any spatial density data available. These vulnerability scores were retained in the cumulative vulnerability calculation but were not multiplied by individual hazard layers.

A cumulative vulnerability score was calculated by summing the vulnerability for each threat (including those without corresponding hazard layers). This was normalised and mapped for each ranger group (Fig. 3).

### Relative risk mapping

A risk map was developed to visualise the spatial distribution of the risk to marine turtles, allowing for regional and site-specific conservation planning and more targeted management interventions based on geographic risk variation. In this context, risk represents the potential for harm to turtles arising from the combination of how exposed they are to human activities and how vulnerable they are to those threats (Grech et al. 2011; Furlan et al. 2018). To create the final risk map, the vulnerability map was rasterised and stacked with the exposure intensity in R using the ‘Raster’ package (Hijmans 2023). The risk was calculated by (Furlan et al. 2018):



**Fig. 3** A flowchart summarising the methods and how each spatial layer was incorporated into the relative risk assessment

$$Risk = exposure\ intensity \times vulnerability.$$

Relative risk ranged from 0 to 1, where 0 represents areas with no risk to turtles, and 1 represents areas where the risk to turtles is the highest relative to other areas in the Northern Territory (Grech et al. 2011; Ma et al. 2023). This relative risk score includes the occurrence and intensity of hazards (cumulative hazards), the potential for a turtle to interact with those hazards (exposure intensity), and the vulnerability of turtles to the hazards in each ranger-management area (cumulative vulnerability assigned by expert elicitation surveys) (Furlan et al. 2018) (Fig. 3).

## Results

### Hazard assessment

The hazards of artificial light, recreational vessels, oil and gas pipelines, commercial fishing and commercial shipping all had the highest relative intensity in Darwin Harbour (Fig. 4). The highest probability of ports/dredging was near Gove and Groote Eylandt, while the hazard of industrial pollution had the highest relative intensity nearby at Gove. The highest relative intensity of sea-surface temperature anomalies (anomalies above the average temperature) was in the Joseph Bonaparte Gulf. The highest relative intensity of feral pigs was around Kakadu National Park and Bathurst Island (Tiwi Islands) (Fig. 4).

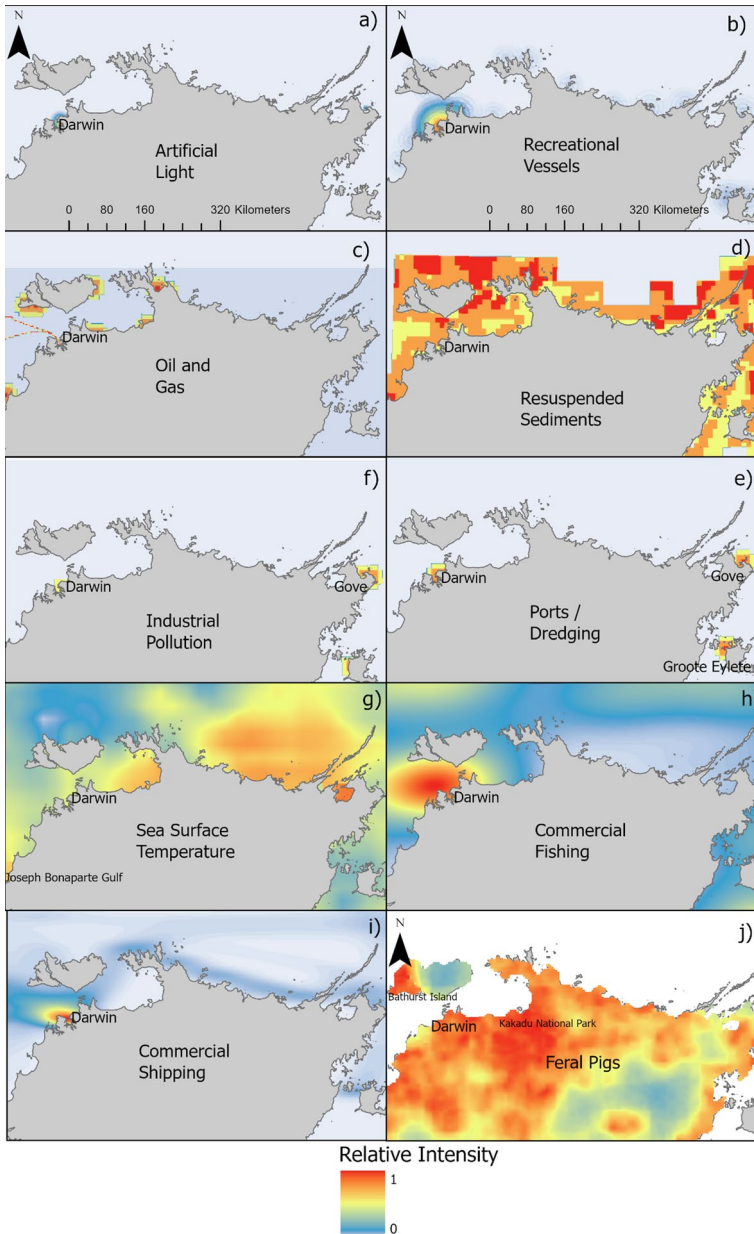
The highest cumulative-hazard score for foraging turtles was in Darwin Harbour (Larrakia Country), where there was a mean score of 0.67 and a maximum score of 0.96 (Table 2). The number of hazards for foraging turtles in Larrakia Country was also the highest, having a mean of 7.00 and a maximum of 9 hazards in a grid cell.

While the cumulative-hazard scores for migrating turtles in Larrakia Country were similar to those for foraging turtles (mean of 0.61 and maximum of 1.00), the mean and maximum scores for migrating turtles were lower than for foraging turtles across all other management areas (Table 2). The maximum number of hazards per grid cell (5) was also lower for migrating turtles.

### Exposure intensity

Foraging-occupancy index scores ranged from 0 to 1, where 1 is high occupancy. High-occupancy foraging areas were the Peron Islands (Daly River), Bare Sand Island (Bynoe Harbour), Channel Island (Darwin Harbour), East Tinganoo Bay (Melville Island, Tiwi Islands), Field Island (Kakadu National Park), Morse Island (Cobourg Marine Park), Cape Don (Cobourg Marine Park) and McCluer Island (West Arnhem) (Fig. 5). The cells with high foraging occupancy had a depth range of 1–11 m (GEBCO Compilation Group 2021), aligning with previous studies showing that adult green turtles typically forage in shallow coastal waters where seagrass and algal habitats are most available (Ferreira et al. 2020; Thums et al. 2021).

The foraging-turtle exposure intensity had a maximum score of 0.64 (out of a possible maximum of 1). The highest exposure intensities were at Bare Sand Island, Bynoe Harbour (managed by the Kenbi Rangers) and Channel Island, Darwin Harbour (managed by Lar-



**Fig. 4** The relative intensity of each hazard across the Northern Territory: (a) artificial light, (b) recreational vessels, (c) oil and gas, (d) resuspended sediments, (e) ports or dredging, (f) industrial pollution, (g) sea-surface temperature, (h) commercial fishing, (i) commercial shipping and (j) feral pigs

**Table 2** The mean and maximum cumulative hazards and the number of hazards that could impact foraging or migrating turtles, per management area. For = foraging, Mig = migrating

Management area		Mean cumulative hazards		Maximum cumulative hazards		Mean number of hazards		Maximum number of hazards	
		For	Mig	For	Mig	For	Mig	For	Mig
Ranger groups involved in this project	Kenbi	0.34	0.35	0.50	0.57	4.00	2.67	5	3
	Larrakia	<b>0.67</b>	<b>0.61</b>	<b>0.96</b>	<b>1.00</b>	<b>7.00</b>	<b>3.93</b>	<b>9</b>	<b>5</b>
	Tiwi Islands	0.27	0.22	0.41	0.41	4.41	3.08	6	4
	Kakadu	0.26	0.11	0.31	0.21	3.86	1.86	5	3
	Garngi	0.23	0.16	0.33	0.28	4.32	2.32	6	4
	Mardbalk	0.17	0.08	0.25	0.22	3.36	1.67	5	3
	Gumurr Marthakal	0.21	0.07	0.27	0.02	3.50	1.63	5	3
Australian Marine Parks	Cobourg Marine Park	0.19	0.12	0.33	0.28	4.32	2.35	6	4
	Joseph Bonaparte Marine Park	<b>0.36</b>	<b>0.19</b>	<b>0.52</b>	<b>0.41</b>	3.33	1.65	5	3
	Oceanic Shoals Marine Park	0.10	0.06	0.20	0.11	2.43	1.50	4	2
	Arafura Marine Park	0.14	0.02	0.23	0.02	3.90	2.13	5	3
	Arnhem Marine Park	0.18	0.01	0.23	0.02	2.65	0.93	4	2
	Wessel Marine Park	0.19	0.02	0.38	0.03	4.08	1.78	6	3
Indigenous Protected Areas	Limmen Marine Park	0.17	0.05	0.22	0.11	3.54	1.60	4	2
	Anindilyakwa Indigenous Protected Area	0.17	0.04	0.38	0.07	<b>4.85</b>	<b>2.38</b>	<b>8</b>	<b>4</b>
	Dhimurru Indigenous Protected Area	0.30	0.03	0.50	0.14	4.83	2.06	7	3

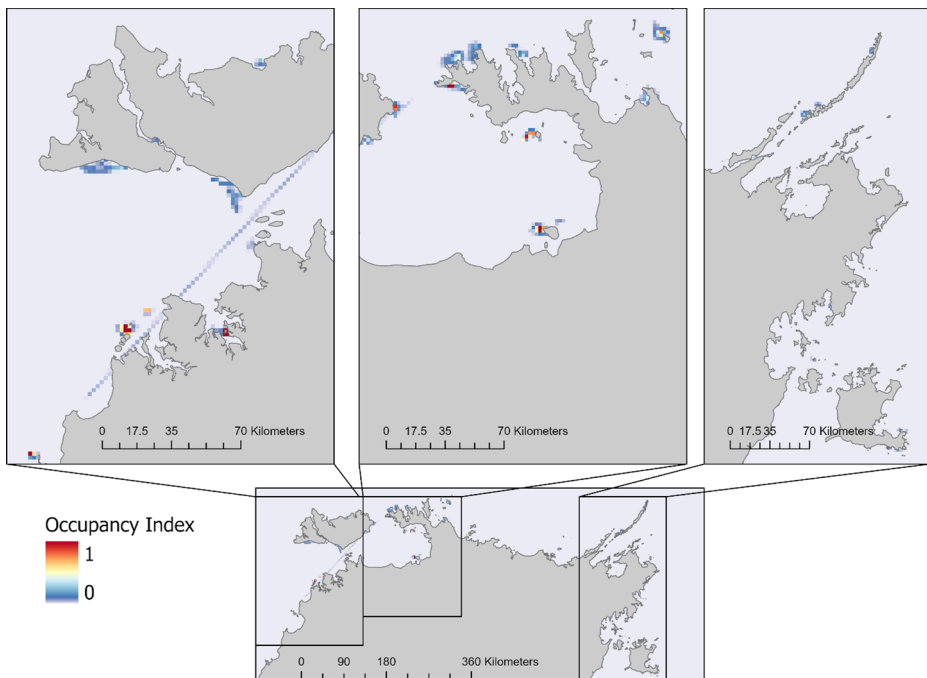
rakia Rangers), indicating that adult turtles in these foraging areas had the highest chance of exposure to the highest density of hazards (Fig. 6).

The highest percentage of adult migrating turtles in a grid cell was in Cobourg Marine Park, – a maximum score of 40.74% was located around 700 m north of Smith Point (Fig. 7.). This indicates that Cobourg Marine Park (within Garig Gunak Barlu National Park) is not only an important area for foraging green turtles (Fig. 5) but also an important migratory corridor (Fig. 7). Migrating turtles generally followed the coast, moving past Darwin and through the inside of the Tiwi Islands (Van Diemen Gulf) before funnelling through the top of Cobourg Marine Park. The waters outside Fog Bay and Bynoe Harbour (managed by the Kenbi Rangers) and between the Vernon Islands and Melville Island (Managed by the Tiwi Rangers) also had a moderate proportion of migrating turtles per cell (7.40% to 29.63%).

The migrating-turtle exposure intensity had a maximum score of 0.12 (out of a possible maximum of 1). The highest exposure intensity was around the entrance to Bynoe Harbour and around the top of Charles Point (north-west of Darwin Harbour) (Managed by the Kenbi Rangers) (Fig. 8). This indicates that migrating turtles in these regions have the highest probability of exposure to the highest density of hazards.

### Vulnerability assessment

Out of the 39 interview participants, from the eight sea-ranger groups, 51.28% are Traditional Owners for the area in which they work. Most rangers had a medium (51.28%) level of confidence in their knowledge of marine turtles. The 10.25% of rangers who were not confident in their knowledge of turtles all came from the Larrakia Land and Sea Rangers

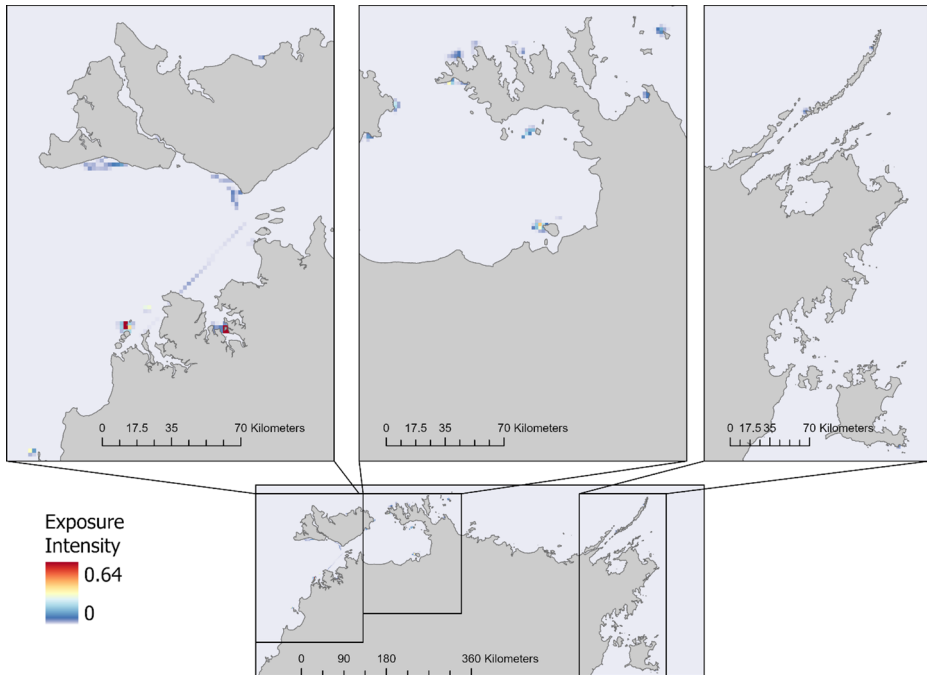


**Fig. 5** Maps displaying the occupancy index for green turtle foraging areas. One track (dotted blue line) appears spatially distinct from other foraging tracks. Although classified as foraging based on movement-state criteria, its relatively linear trajectory suggests it may represent a slowly migrating individual that did not exceed the velocity threshold used to distinguish migratory behaviour

and were predominantly new staff or junior rangers. The more senior rangers generally considered themselves to have a high (28.20%) or an expert (10.25%) level of knowledge of marine turtles.

The pooled GLM sensitivity analysis across all threat categories provided no evidence that inclusion of self-reported ranger confidence improved model fit relative to a null model. Model selection based on AICc provided strongest support for the threat-only model ( $AICc = -20.6$ ,  $weight = 0.699$ ), indicating that variation in pooled vulnerability scores was primarily explained by differences among threat categories (Table 3). A model including both threat and confidence received moderate but lower support ( $\Delta AICc = 1.69$ ,  $weight = 0.301$ ), while models excluding threat—including the intercept-only null model and the confidence-only model—received negligible support ( $\Delta AICc > 168$ ). However, due to its practical relevance in participatory conservation assessments and its moderate statistical support, the threat and confidence model was selected for the risk mapping (Table 4).

Vulnerability scores varied across each ranger group and threat (Table 4). Turtles are particularly vulnerable to nesting predation across West Arnhem and the Tiwi Islands. Vulnerability was consistently scored as very high by the Garig Gunak Barlu Park Rangers (0.92), Tiwi Rangers (0.86), Mardbalk Marine Rangers (1.00), Garngi Community Rangers (0.95) and Gumurr Marthakal Rangers (0.80) (Table 4). Sea-level rise, erosion and sand temperature were also concerns for many of these same ranger groups (Table 4). Turtles are vulnerable to agriculture, mining and sewage run-off in the Darwin region – vulnerability



**Fig. 6** Maps displaying the exposure intensity for green turtle foraging areas. One track (dotted blue line) appears spatially distinct from other foraging tracks. Although classified as foraging based on movement-state criteria, its relatively linear trajectory suggests it may represent a slowly migrating individual that did not exceed the velocity threshold used to distinguish migratory behaviour

scored as very high from the Kenbi Rangers (0.94), high from the Larrakia Land and Sea Rangers (0.64) and medium for the Tiwi Rangers (0.33) (Table 4). The vulnerability of foraging turtles to traditional hunting was highest at the Goulburn Islands (score of 1.00 by Mardbalk Marine Rangers), followed by the Tiwi Islands (score of 0.67 by Tiwi Rangers), Darwin Harbour (score of 0.45 by Larrakia Land and Sea Rangers), Croker Island (score of 0.37 by Garngi Community Rangers), Wessel Islands (score of 0.35 by Gumurr Marthakal Rangers) and Cobourg Marine Park (score of 0.29 by Garig Gunak Barlu Park Rangers). Other threats that caused very high vulnerability in turtles were recreational fishing (score of 0.75 by Kenbi Rangers) and plastic entanglement (water) (score of 0.94 by Tiwi Rangers and score of 0.78 by Larrakia Land and Sea Rangers) (Table 4).

Multiplying these vulnerability scores (Table 4) by the relative intensity of the hazards (Fig. 4) revealed the highest vulnerability was from invasive predation on the mainland of West Arnhem (near the Goulburn Islands – Mardbalk Marine Rangers), which scored 0.90. This was followed by Bathurst Island (Tiwi Islands), which scored 0.84 (Supplementary Material: Figure S2). Turtles were most vulnerable to eight of the 10 threats in the Darwin Harbour region, a populated and industrialised area (Supplementary Material: Figure S2).

Linear mixed-effects models revealed that threat category was the dominant predictor of perceived vulnerability, explaining substantial variation in vulnerability scores across the 24 assessed threats ( $F=12.70$ ,  $p<2e-16$ ) (Table 5). After accounting for threat type, ranger group explained a modest but detectable proportion of variation in vulnerability

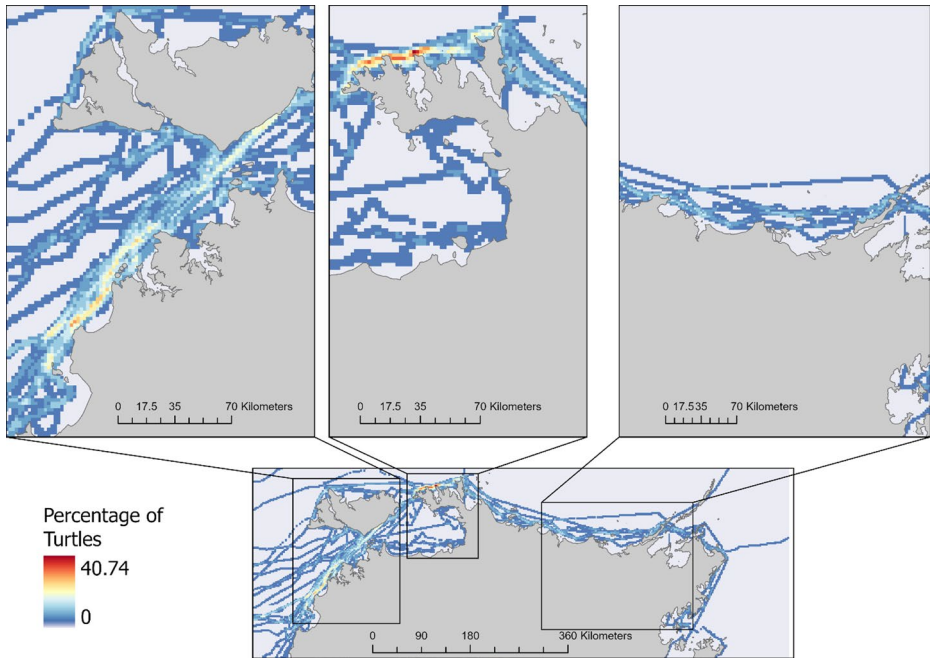


Fig. 7 Maps displaying green turtle migration routes by percentage of turtles

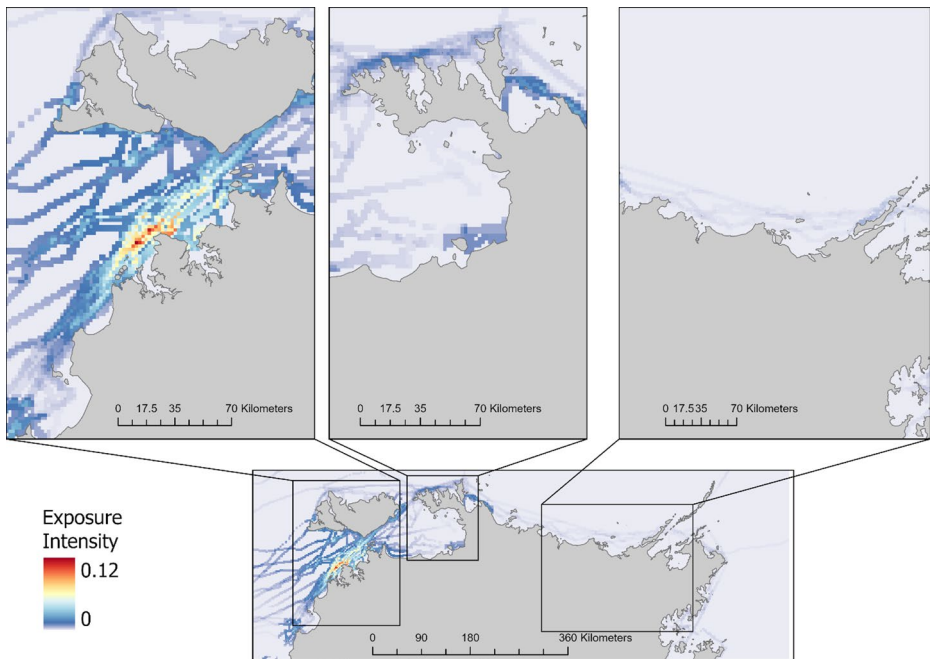


Fig. 8 Maps displaying green turtle migration routes by exposure intensity

**Table 3** Model selection results from pooled GLM sensitivity analysis assessing the influence of confidence weighting on vulnerability scores across all threat categories

Model	df	logLik	AICc	$\Delta$ AICc	weight
Threat	25	37.118	-20.6	0	0.699
Threat + Treatment (Confidence)	26	37.424	-18.9	1.69	0.301
Null	2	-71.795	147.6	168.23	0
Treatment (Confidence) only	3	-71.621	149.3	169.91	0

Models were ranked using AICc;  $\Delta$ AICc values are relative to the best-supported model. Model weights indicate relative support among candidate models

scores ( $F=2.11$ ,  $p=0.07$ ), although differences among groups were not statistically significant (Table 5). Estimated marginal means suggested higher overall vulnerability scores for Larrakia and Tiwi Island ranger groups, and lower scores for Kakadu and Gargi ranger groups, but with substantial overlap in confidence intervals, particularly for groups with smaller sample sizes (Fig. 9a). Self-reported turtle knowledge was associated with vulnerability scores, with respondents self-reporting lower levels of turtle knowledge assigning significantly lower vulnerability scores relative to those reporting the highest knowledge level. In particular, vulnerability scores were significantly lower for respondents who rated their turtle knowledge as “Medium” ( $p=0.04$ ) or “Not confident” ( $p=0.02$ ). In contrast, experience outside of work and Traditional Owner status did not significantly influence perceived vulnerability scores after accounting for threat type and other social predictors.

Random effects indicated meaningful among-participant variation in baseline vulnerability scoring (random intercept  $SD=7.32$ ), supporting the inclusion of participant identity as a random effect. Residual diagnostics showed no major deviations from model assumptions, and the model was not singular. Adjusted marginal means indicated consistently high vulnerability scores for threats related to plastic entanglement (particularly in water), native predation, sea-level rise and erosion, sand temperature, and fisheries bycatch, whereas threats such as aquaculture, beach armouring, and changes to coastal processes were perceived as relatively low vulnerability on average (Fig. 9b).

Although individual vulnerability scores exhibited substantial variability and floor–ceiling effects, model diagnostics indicated that this variability was primarily within individuals rather than between ranger groups (Supplementary Material: Figure S6). Rank-based comparisons showed good concordance between observed and predicted vulnerability, and group-level mean predictions closely matched observed values. These results indicate that the model reliably captured relative differences among threats and ranger groups, despite unavoidable heterogeneity in individual expert judgements.

When summed together, the highest cumulative vulnerability score was at the Tiwi Islands (a score of 11.03 out of a maximum of 24 threats), followed by Larrakia Country (a score of 10.18) (Fig. 10). Kakadu had the lowest cumulative vulnerability score of 4.14, and turtles foraging in Kakadu most vulnerable to climate change and commercial fisheries. All ranger groups consistently ranked climate change as the highest-scoring hazard (Fig. 10).

### Relative risk mapping

Channel Island in Darwin Harbour, managed by the Larrakia Land and Sea Rangers, posed the highest relative risk (exposure intensity (hazards  $\times$  turtle occupancy)  $\times$  cumulative vulnerability) to foraging turtles, scoring 1.00 (Fig. 11). Bare Sand Island in Bynoe Harbour,

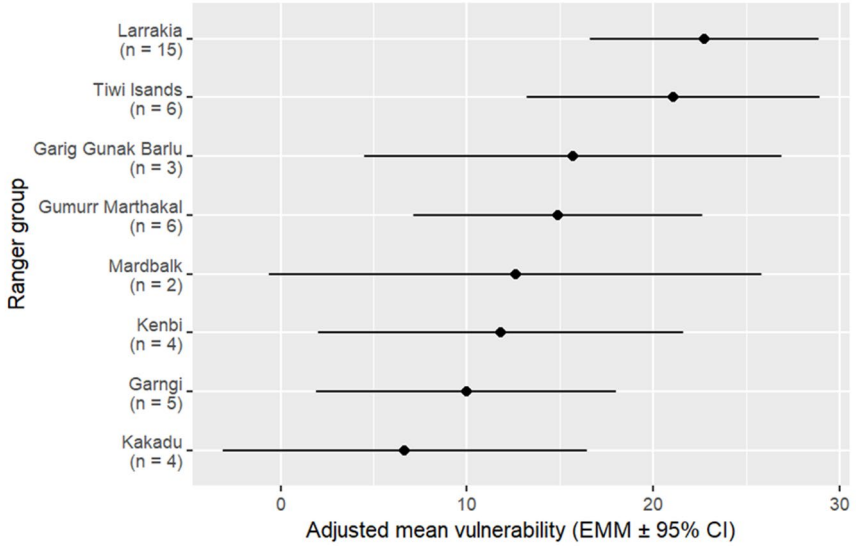
**Table 4** The vulnerability scores from the expert-elicitation surveys. The scores indicate the vulnerability of turtles to different hazards and threats in the management area of each ranger group. The colours display the category of vulnerability: low (white: 0–0.25), medium (yellow: 0.25–0.5), high (orange: 0.5–0.75) and very high (red: 0.7–1).

Hazards and threats	Larrakia	Kenbi	Kakadu	Garig Gunak Barlu	Tiwi Islands	Mardbalk	Gamji	Gumurr Marthakal
<b>Hazard: Climate change</b>								
Sea-level rise and erosion	0.48	0.79	0.42	0.59	0.67	0.83	0.72	0.62
Sea surface temperature, habitat destruction	0.29	0.15	0.42	0.33	0.61	0.67	0.12	0.24
Sand temperature	0.53	0.47	0.52	0.61	0.74	1.00	0.73	0.53
<b>Hazard: Commercial fisheries</b>								
Fisheries bycatch	0.53	0.05	1.00	0.77	0.58	0.00	0.30	0.36
Trawling, habitat destruction	0.29	0.00	0.29	0.46	0.58	0.00	0.17	0.28
Aquaculture	0.03	0.17	0.00	0.12	0.40	0.00	0.03	0.04
<b>Hazard: Industrial development</b>								
Agriculture, mining, sewage runoff	0.68	0.94	0.01	0.00	0.33	0.00	0.00	0.09
Oil and gas development	0.71	0.38	0.00	0.08	0.29	0.00	0.10	0.16
Dredging	0.41	0.25	0.00	0.00	0.28	0.00	0.00	0.09
<b>Hazard: Direct take</b>								
Traditional harvest (foraging turtles)	0.45	0.08	0.15	0.29	0.67	1.00	0.37	0.35
Traditional harvest (eggs and nesting turtles)	0.36	0.10	0.15	0.24	0.61	1.00	0.20	0.27
Unauthorised take	0.41	0.00	0.04	0.22	0.42	0.00	0.09	0.25
Illegal take	0.22	0.00	0.04	0.15	0.42	0.00	0.15	0.32
<b>Hazard: Coastal development</b>								
Beach armouring	0.23	0.21	0.00	0.00	0.01	0.00	0.00	0.00
Recreational fishing	0.61	0.75	0.31	0.31	0.56	0.00	0.17	0.11
Artificial light	0.24	0.08	0.04	0.00	0.14	0.00	0.01	0.01
Changes to coastal Processes	0.16	0.10	0.10	0.00	0.04	0.00	0.01	0.04
<b>Hazard: Plastic pollution</b>								
Plastic entanglement (water)	0.78	0.56	0.10	0.67	0.94	0.00	0.50	0.64
Plastic ingestion	0.73	0.59	0.04	0.28	0.29	0.04	0.13	0.37
Plastic entanglement (beach)	0.54	0.31	0.04	0.69	0.35	0.00	0.32	0.38
<b>Hazard: Commercial vessels</b>								
Commercial vessel strike	0.54	0.25	0.00	0.44	0.29	0.00	0.15	0.14
Oil spill	0.34	0.02	0.00	0.00	0.08	0.00	0.08	0.09
<b>Hazard: Predation</b>								
Native predation	0.29	0.69	0.24	0.92	0.86	1.00	0.95	0.80
Invasive predation	0.33	0.06	0.22	0.50	0.86	1.00	0.68	0.56

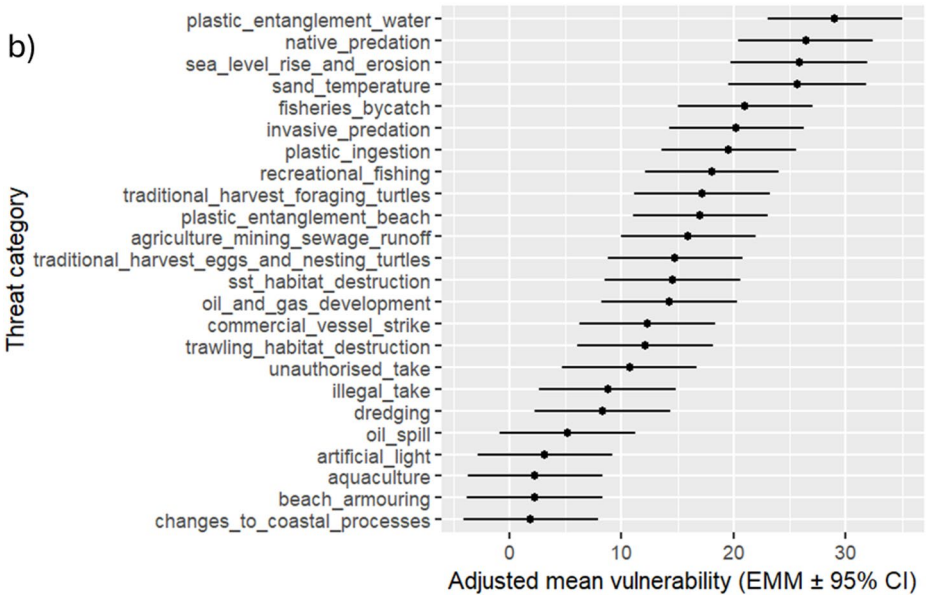
**Table 5** Table of results for the Type III ANOVA Table with Satterthwaite’s method

Predictor	Sum Sq	Mean Sq	NumDF	DenDF	F value	Pr(>F)
Threat	66060.00	2872.17	23.00	986.95	12.70	<2e-16
Ranger group	3333.00	476.11	7.00	30.55	2.11	0.07
Turtle knowledge	1461.00	487.06	3.00	30.94	2.15	0.11
Experience outside of work	431.00	215.34	2.00	30.86	0.95	0.40
Traditional owner	1.00	0.90	1.00	30.87	0.00	0.95

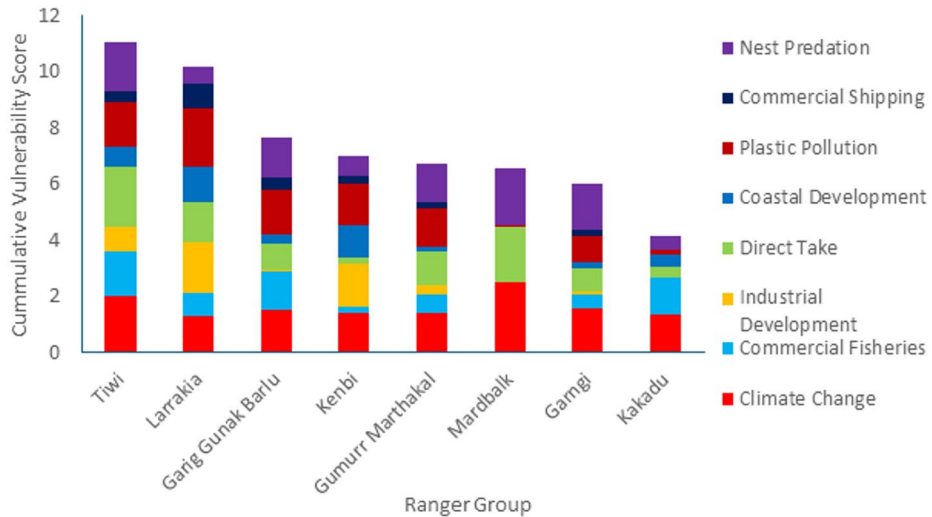
a)



b)



**Fig. 9** A plot of the adjusted mean vulnerability (across all ranger groups) for each threat-level predictor on perceived turtle vulnerability scores



**Fig. 10** Bar plot displaying the cumulative vulnerability score for each ranger group. Colours indicate the contribution of each hazard

managed by the Kenbi Rangers, posed the second-highest relative risk to foraging turtles, scoring 0.35.

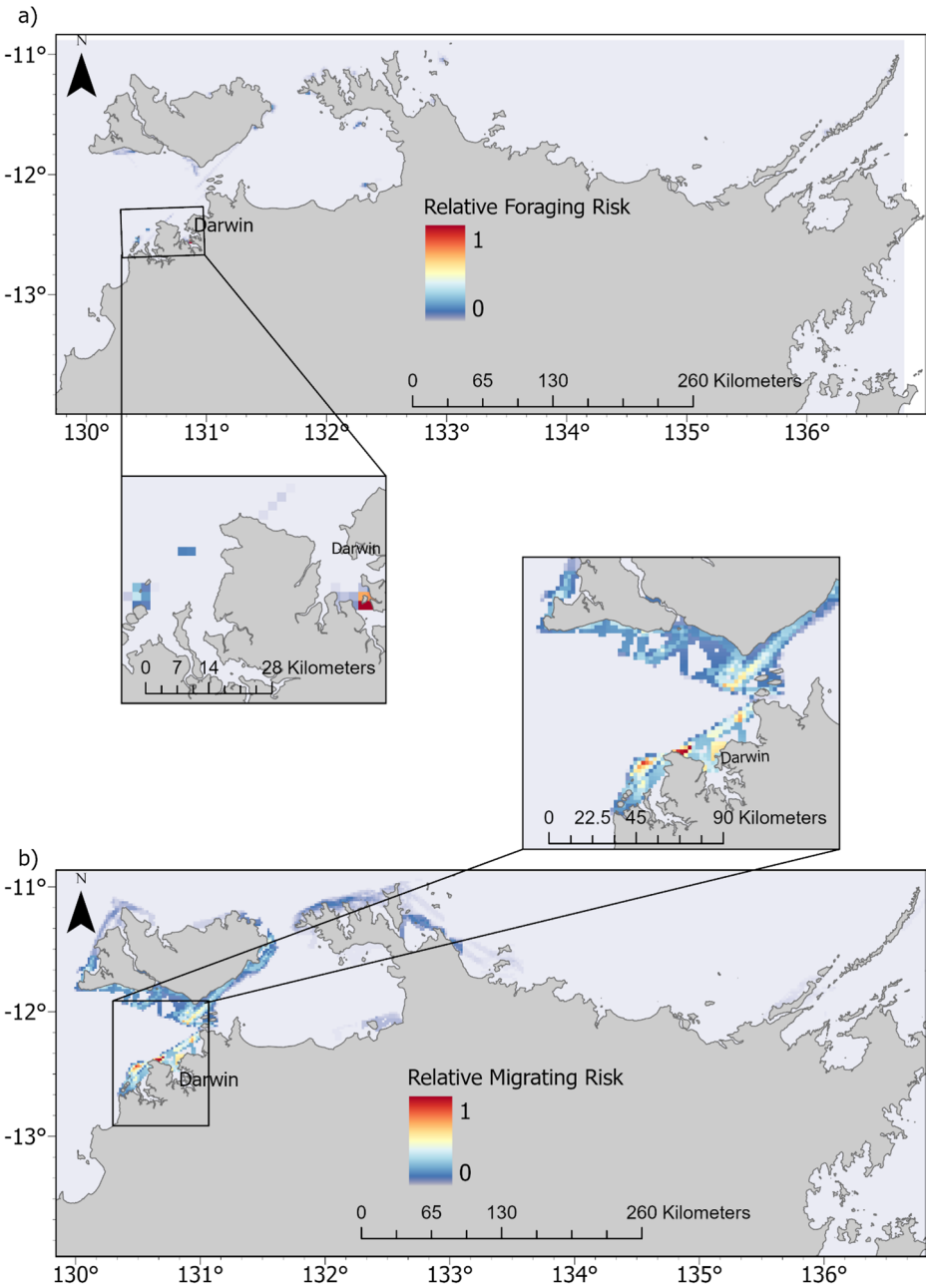
Migrating turtles in the Northern Territory are most at risk from the anthropogenic threats assessed near the entrance of Darwin Harbour and Bynoe Harbour (relative risk ranging between 0.30 and 1.00). The highest relative risk score (1.00) was on the east side of the Cox Peninsula (entrance to Darwin Harbour) (Fig. 11).

## Discussion

There are gaps in empirical data for many species and ecosystems across much of remote northern Australia. However, Indigenous ranger groups across the region provide local capability for environmental monitoring and management as well as traditional knowledge of Sea Country (Kennett et al. 2004a, b; Rist et al. 2019). This study illustrates the use of structured expert-elicitation surveys to incorporate Indigenous ranger knowledge when assessing the vulnerability of marine species, specifically green turtles, and mapping the spatial distribution of anthropogenic risks across the Northern Territory.

### Hazards and vulnerability of green turtles in the Northern Territory

The distribution of environmental hazards and anthropogenic threats across the study area varied significantly. Darwin Harbour (Larrakia Country) emerged as a high-risk area for foraging turtles. The high cumulative-hazard scores in this region indicate multiple overlapping hazards, including artificial light, recreational vessels, oil and gas pipelines, commercial fishing and shipping. Foraging adult turtles faced greater localised exposure within grid cells to hazards than migrating individuals, in part because they spend more time in



**Fig. 11** Turtle risk maps: (a) foraging behaviour and (b) migrating behaviour. The inset shows the location of the highest risk score

specific areas, increasing the likelihood of encountering threats. This exposure is further compounded by their use of shallow coastal habitats, which typically are subject to more anthropogenic pressures than deeper offshore areas (Shimada et al. 2017; Ferreira et al. 2023) – at the grid-cell level, up to nine hazards overlapped in some areas. The grid cells used during the migratory movements of adult turtles experienced lower cumulative hazards overall and contained fewer overlapping threats than foraging turtle grid cells (maximum of five per grid cell), although Darwin Harbour remained a hotspot. High-hazard zones, such as Darwin Harbour, could benefit from targeted interventions, including vessel regulation, light-pollution mitigation and habitat protection. Other regions, such as Nhulunbuy and Groote Eylandt (in the Gulf of Carpentaria), would benefit from strategies addressing industrial pollution and climate-induced impacts.

Perceptions of turtle vulnerability varied across ranger groups and was shaped by local environmental conditions and management practices. For example, calculated vulnerability of turtles to traditional hunting was high at the Goulburn Islands (1.00) (Mardbalk Rangers) and Tiwi Islands (0.67) (Tiwi Rangers), while calculated vulnerability of turtles to pollution and plastic entanglement was high in Larrakia and Tiwi Island waters. Climate-related threats, including sea-level rise and sand-temperature changes, affected all regions. Mixed-effects analyses indicated that perceived vulnerability was structured primarily by threat type, with ranger group explaining additional but more modest variation once threat category was accounted for. Some ranger groups, including Gumurr Marthakal, Kakadu and Larrakia, reported consistently lower vulnerability scores across threats, reflecting differences in local exposure, management histories, and lived experience on Sea Country. In addition to ranger group, other social variables also influenced threat perception. Self-reported turtle knowledge was also strongly associated with perceived vulnerability – more knowledgeable rangers rated threats as more severe. This suggests that long-term ecological experience and engagement with Sea Country enhances the capacity to detect and evaluate risk. Retention of experienced Indigenous rangers is therefore not only a workforce consideration but a conservation priority. High staff turnover could erode locally accumulated ecological knowledge and weaken the ability to identify emerging threats or subtle changes in turtle populations. Sustained investment in ranger retention supports continuity of knowledge, strengthens threat detection, and improves the effectiveness of place-based management interventions. Certain threats, particularly plastic entanglement (water), native predation, and sea-level rise and erosion, were perceived as more severe overall, while others, such as oil spills, beach armouring and aquaculture, were rated as less severe. Certain threats, particularly plastic entanglement (water), native predation, and sea-level rise and erosion, were perceived as more severe overall, while others, such as oil spills, beach armouring and aquaculture, were rated as less severe.

This pattern of vulnerability scores indicates a clear distinction between threats that act persistently over long timescales and those that are spatially localised or episodic. Threats such as sea-level rise, sand temperature, fisheries bycatch, plastic pollution and predation were consistently perceived as highly vulnerable, reflecting their chronic nature and cumulative impacts on turtles and habitats. In contrast, threats such as aquaculture, beach armouring and some coastal modification activities were generally assigned lower vulnerability scores, likely because their effects are more localised or occur intermittently. This distinction highlights how long-term, repeated pressures may pose greater risks to long-lived species like green turtles and underscores the importance of addressing cumulative

impacts in spatial risk assessments and management planning. These findings underscore the importance of integrating ranger perspectives into threat assessments, to not only capture local variation in environmental pressures but also ensure that conservation responses are grounded in place-based knowledge systems and experience. The direct involvement of rangers in land and sea management positions them as leaders in conservation efforts and this is essential for the success of management interventions.

Occupancy indices revealed high-use foraging areas around the Peron Islands (Daly River), Bare Sand Island (Bynoe Harbour) and Cape Don (Cobourg Marine Park). These sites could warrant formal recognition as Biologically Important Areas (BIAs) (Ferreira et al. 2020; Robson et al. 2025). BIAs are regions where protected marine species display key behaviours, such as foraging, breeding or migration, and they are designated under Australia's EPBC Act. Bare Sand Island and Channel Island had the highest foraging-exposure intensity (maximum 0.64), driven by high levels of vessel activity, fishing and habitat degradation.

Migration data reinforced the ecological importance of Cobourg Marine Park, which functions as a high-occupancy foraging area for resident turtles, as well as a migratory corridor – 40.74% of recorded migrating turtles passed through this region. Routes extended past Darwin through Van Diemen Gulf and between the Vernon Islands and Melville Island. Exposure intensity for migrating turtles peaked at the entrances to Bynoe Harbour and Charles Point. Combining vulnerability with hazard occurrence and turtle occupancy revealed hotspots of relative risk, such as West Arnhem (due to nest predation) and Darwin Harbour (vulnerable to eight of 10 threats). Foraging and migratory areas, such as Bare Sand Island, the Peron Islands and Cobourg Marine Park, could be considered priorities for protective measures, including the potential designation of BIAs, reduced vessel-speed zones and targeted ghost-net removal. Migratory routes, particularly through the Vernon Islands and around Bynoe Harbour, may also benefit from monitoring and mitigation strategies, such as the implementation of designated marine corridors to reduce disturbances.

### **From regional and national patterns to policy: implications for Indigenous-led turtle conservation**

The threats identified in this study, such as artificial light, vessel traffic, ghost nets, pollution, climate change and nest predation, are consistent with those documented in other regions of Australia. For example, artificial lighting and vessel traffic in Darwin Harbour mirror similar impacts observed in Moreton Bay and along the Queensland coast, where such hazards disrupt nesting and increase mortality (Kamrowski et al. 2013; Shimada et al. 2017). Ghost-net entanglement and fishing-gear impacts are also widely reported in the Gulf of Carpentaria (Jensen et al. 2013; Phillips 2017), while nest predation and climate-related threats align with findings from turtle nesting grounds across northern and eastern Australia (Doherty 2005; Fuentes and Cinner 2010; Lei et al. 2017; Shimada et al. 2017; Nordberg et al. 2019; King et al. 2023). At a global scale, these results are also consistent with the recent threat reassessment by Wallace et al. (2025), which identified fisheries bycatch, coastal development, and climate change as the most pervasive pressures across marine turtle populations worldwide. However, our spatially explicit risk assessment highlights the fine-scale variation in these threats, particularly nest predation and vessel impacts, that are often underrepresented in global analyses, demonstrating how local Indigenous-led moni-

toring can complement and refine global conservation priorities. This study uniquely applies structured expert-elicitation to incorporate Indigenous ranger knowledge, providing fine-scale spatial assessments of turtle vulnerability. By doing so, it highlights both known and locally specific risks, reinforcing the value of Indigenous-led monitoring and conservation.

This study builds on a growing body of literature highlighting the role of Indigenous knowledge in biodiversity monitoring (Drew 2005; Raymond et al. 2010; Martin et al. 2012; Reid et al. 2020; Wedding et al. 2024) and advances it by applying a structured and spatially explicit methodology in a data-poor marine context. While past conservation policy in Australia has largely relied on Western scientific methods, there is growing recognition of the value of Indigenous ecological knowledge in shaping more effective and culturally relevant management strategies. Examples include Queensland's Indigenous Land and Sea Ranger program and co-management arrangements in Kakadu National Park and Bardi Jawi Sea Country, which have demonstrated improved outcomes for both biodiversity and community engagement (DBCA 2011; Australian Government 2022; DBCA 2022; DCCEEW 2022b; Queensland Government 2025). However, structured and quantitative approaches that meaningfully integrate Indigenous and local knowledge into conservation assessment and decision-making remain rare globally, underscoring the need for broader integration of Indigenous-led monitoring and assessment frameworks into national conservation policy. Recent syntheses highlight persistent structural and methodological barriers to embedding Indigenous knowledge alongside scientific data in wildlife analyses and environmental governance, despite clear benefits for equity, legitimacy, and conservation outcomes (Vierros et al. 2020; Trisos et al. 2021; Stern and Humphries 2022).

Importantly, ranger knowledge also distinguished between locally generated threats and those driven by broader regional processes. With the exception of Darwin Harbour, many ranger-managed areas are sparsely populated or uninhabited, with small resident communities (ABS 2019). Rangers consistently reported that plastic pollution and marine debris are largely transported into northern Australian waters during the wet season by prevailing north-westerly monsoonal currents, likely originating from sources outside the region, including Southeast Asia (Hardesty et al. 2021; Patterson et al. 2023). This distinction has direct management implications, indicating that while local mitigation and clean-up efforts led by Indigenous rangers are essential, effective reduction of plastic impacts will also require coordinated regional, national, and international policy responses.

The management implications of this study are therefore substantial. The results support the expansion and sustained funding of Indigenous ranger programs, enabling them to lead the implementation of the Commonwealth's Threatened Species Action Plan for adult green turtles (DCCEEW 2022a). These findings also align with the IUCN Important Marine Turtle Areas framework, which emphasises the identification of spatially discrete areas of biological and cultural importance using multiple knowledge sources, including Indigenous knowledge (Bandimere et al. 2021). While mitigation strategies were not directly incorporated into the spatial risk assessment, several high-priority actions were consistently identified through the structured expert-elicitation process with Indigenous rangers. For example, based on ranger knowledge, nest-cooling studies and predator control methods are urgent priorities in West Arnhem and the Tiwi Islands. In areas like Cobourg Marine Park and Kakadu National Park, innovations in bycatch mitigation should be prioritised.

## Limitations and future directions

There are several limitations of this study that must be acknowledged. First, satellite-tracking data used to estimate turtle movements and occupancy are subject to spatial, temporal and behavioural bias, as individuals tagged may not be fully representative of the broader population or their movement may be affected by where and when they were caught. There were no turtle tracks between the Northern Territory and Queensland or South-east Asia; however, genetic studies have shown that there is some level of migration between these areas (Dethmers et al. 2010). Second, although the spatial mapping of hazards provided valuable insights, it was constrained by the availability and resolution of input data. Many known threats, such as marine debris and chemical pollution, were either not mapped or lacked spatially explicit datasets, potentially underestimating the true risk in some areas. Third, mitigation strategies were discussed based on expert recommendations but were not incorporated directly into the spatial risk assessment. This presents an opportunity for future work to evaluate the potential effectiveness of different management interventions. Finally, large gaps remain in empirical data for many marine species and ecosystems across northern Australia. Indigenous ranger groups are uniquely positioned to help address these data gaps, given their knowledge, on-ground presence and growing capability in environmental monitoring. This study demonstrates the value of structured expert elicitation as a practical framework for integrating Indigenous knowledge into spatial conservation planning, even in regions with limited empirical data.

## Conclusion

The results of this study highlight the need for future research, monitoring and conservation-management activities. These could include investigating climate resilience and conservation methods for nesting turtles in the West Arnhem and Tiwi Islands regions, particularly predator prevention (Doherty 2005; O'Connor et al. 2017; Nordberg et al. 2019; Phillott 2020; Lovemore et al. 2020), and exploring the impacts of industrial development (artificial light and pollution) on turtles foraging in Darwin Harbour, focusing on the ecotoxicology (of pesticides, hydrocarbons, heavy metals, PFAS [perfluoroalkyl] and polyfluoroalkyl substances) of foraging turtles and other resident marine megafauna.

The participatory approach used in this study not only enhances the accuracy and relevance of spatial risk assessments but also reinforces the importance of Indigenous-led conservation initiatives. This research demonstrated that ranger experience significantly shaped vulnerability assessments, underscoring that retaining experienced Indigenous rangers is critical to maintaining locally grounded ecological knowledge and strengthening long-term conservation outcomes. Similar participatory and knowledge-bridging approaches have been shown to improve cumulative impact assessments by capturing stressors, interactions, and ecological changes that are often missed by conventional scientific datasets alone (Mantyka-Pringle et al. 2017). In marine systems in particular, integrating Indigenous and local knowledge within social–ecological frameworks have been identified as critical for effective governance of “peopled seas,” where human use, cultural values, and ecological processes are tightly intertwined (Bennett 2019). Strengthening partnerships between researchers, policymakers, and Indigenous ranger groups can therefore foster more inclusive and legitimate

decision-making processes, ensuring that conservation strategies align with both scientific evidence and place-based knowledge systems. Moving forward, expanding the integration of Indigenous expert knowledge into environmental assessments across species and ecosystems would support more comprehensive, equitable, and context-appropriate biodiversity conservation in northern Australia and Internationally.

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**Author contributions** All authors contributed to the study conception and design. Natalie Robson developed the study concept, obtained human-ethics approval, led the turtle fieldwork, and conducted all expert-elicitation surveys with Indigenous ranger groups. She also completed all data analysis, mapping and writing of the report and manuscript. Alana Grech contributed to the design of the expert-elicitation surveys and survey methodology and provided critical feedback and revisions to the manuscript. Michele Thums provided advice on survey design, supported data analysis, and critically reviewed the manuscript. Joanna Day and Garnet Hooper contributed to survey design and provided manuscript reviews. Carol Palmer contributed to the grant application, animal-ethics approvals and turtle field surveys, including planning and logistical support, as well as manuscript review. The Indigenous ranger groups (Kakadu Rangers, Garig Gunak Barlu Park Rangers, Larrakia Land and Sea Rangers, Gumurr Marthakal Rangers, Tiwi Rangers, Garngi Community Rangers, and Mardbalk Marine Rangers) contributed to turtle data collection (satellite telemetry), participated in all fieldwork, and co-designed and participated in the expert-elicitation surveys as knowledge holders and experts. Sam Banks contributed to the grant proposal, human-ethics and animal-ethics applications, survey design and manuscript review.

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**Data availability** The data presented in this project have multiple ownerships. Therefore, the data cannot be made publicly available. Data requests can be made to the lead author. A GIS Hub website has been created to display these results to rangers and community members (<https://nt-turtle-data-cduni.hub.arcgis.com/>) (<https://nt-turtle-data-cduni.hub.arcgis.com/>). This includes videos and interactive maps displaying the results of this study. This website can be a tool for ranger groups and natural resource managers.

## Declarations

**Conflict of interest** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

**Ethical approval** The satellite tagging of turtles in the Northern Territory was conducted under Animal Ethics Approval from the Charles Darwin University Ethics Committee: A21008 – Collaborative Science for monitoring Northern Territory marine megafauna. Other satellite-tracking data were collected from previously published studies and were not subject to Animal Ethics for this project. The expert-elicitation surveys were conducted under Human Ethics Approval: H24024 – Collaborative science for monitoring Northern Territory marine megafauna: Integrating expert knowledge into a spatially explicit risk assessment of green turtles

(*Chelonia mydas*) in the Northern Territory. Approved by the Charles Darwin University Human Research Ethics Committee, Research Ethics and Integrity.

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