Recreational fishery discard practices influence use of tidal estuary by a large marine mesopredator

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ABSTRACT

Context. It is common for recreational anglers to discard waste produced from filleting catches back into the water, which results in a highly spatio-temporally predictable food subsidy for wildlife to scavenge. However, the behavioural responses of these scavengers has received little attention. **Aims.** We aimed to assess the visitation of a common mesopredatory scavenger in relation to temporal patterns in waste discarding at a boat ramp in south-eastern Australia. **Methods.** Using passive acoustic telemetry, the movements of 13 adult female smooth stingrays (*Bathytoshia brevicaudata*) were tracked, and patterns in their acoustic detections and duration of time spent in different sections within the study area were compared. **Key results.** Use of the study area was strongly focused around the boat ramp, and peaked during periods of increased provisioning activity (i.e. afternoons and weekends). Environmental variables had limited influence on visitation, suggesting that the use of the area was not likely to be linked to natural behaviours. **Conclusions.** The observed patterns indicated that the movements of smooth stingrays were linked to waste-discard practices by recreational anglers. **Implications.** This study has implications for the management of discard practices for recreational fishing.

Keywords: batoidea, behavioural ecology, elasmobranchs, fishing discards, food provisioning, human–wildlife interactions, movement ecology, recreational fishing.

Introduction

The more predictable resources are in time and space, the faster and more strongly animals can build associations that maximise their access to them (Reebs 1993; Mulder *et al.* 2013; Heinrich *et al.* 2020). Due to the stochastic nature of environmental conditions, resources are rarely highly predictable in both time and space, and if conditions do support high predictability, it is typically short-lived. Human activities such as agriculture, hunting and fishing can result in food subsidies being provisioned to wildlife (Oro *et al.* 2013). Many of these activities have inherent temporal cycles (Margalef 1997; Oro *et al.* 2013), such as the 9–5 working-day or 7-day week, and typically occur in specific locations, resulting in highly predictable food subsidies. This, in turn, can cause significant changes to animal distribution and behaviour through their consumption of these provisioned resources (Oro *et al.* 2013). For example, in the Mediterranean, there is a well-studied seabird community that forages on discards (i.e. by-catch) from a trawl fishery that operates during set hours on weekdays and in fishing grounds that are generally consistent in space (Oro *et al.* 2013). The resulting high spatio-temporal predictability of discards from this fishery has led to a significant reduction in foraging times and foraging areas by seabirds that have synchronised their movement with the operating schedule of the fishery (e.g. Bartumeus *et al.* 2010; García-Tarrasón *et al.* 2015; Matos *et al.* 2018).

In marine systems, fisheries generate large quantities of discards, either as by-catch in the form of undersized or non-target species or waste from processing. For commercial fisheries, it is estimated at ~10% of global catches are discarded annually (~7 × 10^6 tonnes, Mg; Kelleher 2005; Zeller *et al.* 2018). Annual catches for

recreational fisheries amount to almost 1×10^6 Mg (Freire *et al.* 2020), and it has been estimated that 30–75% of catches are discarded as by-catch or non-target species (Huddart 2019). For recreational catches that are retained for consumption, it is also widely accepted to discard waste produced from the cleaning and filleting process (i.e. offal, carcasses) back into the water. However, by-catch and waste discards from recreational fisheries are rarely quantified and not currently considered in global fishery discard estimates (Kelleher 2005; Zeller *et al.* 2018; Freire *et al.* 2020). In addition, although the direct impacts of fishing are well documented (e.g. impacts to fish stocks, habitat destruction; Dayton *et al.* 1995; Ortuño Crespo and Dunn 2017; Huddart 2019; Lewin *et al.* 2019), the potential influence of associated discards has received little attention.

There is a considerable body of research characterising the consumers of commercial fishery discards, such as invertebrates, teleost fishes, elasmobranchs, marine mammals, and seabirds (Oro *et al.* 2013). Changes to reproduction, spatial distribution, population sizes, and dispersal has been documented in many of these consumers, particularly seabirds, and to a lesser extent marine mammals (reviewed in Oro *et al.* 2013). However, there is a paucity of research into the impacts on mid-water and benthic species, such as teleost fishes and elasmobranchs, despite a considerable portion of discards sinking below the surface. Likewise, a range of species have been documented foraging on recreational fishing discards, including invertebrates, teleost fishes, marine mammals (Donaldson *et al.* 2010; Christiansen *et al.* 2016; Voohris 2016), elasmobranchs (Newsome *et al.* 2004; Pini-Fitzsimmons *et al.* 2018; Martin *et al.* 2019), sea birds, and even terrestrial predators, such as dingoes (Behrendorff *et al.* 2016; Déaux *et al.* 2018), but few studies have assessed the potential impacts on these animals. The few existing studies suggest that species alter their behaviour and space use to access these resources. For example, bottlenose dolphins (*Tursiops* sp.) learned to associate recreational fishing boats with food and began depredating on non-target fishes discarded by recreational anglers (Powell and Wells 2011; Christiansen *et al.* 2016). Similarly, a repeated-exposure experiment of carcharhinid shark species to fishing boats and food (representing hook and line fishing) resulted in reduced time to arrival and feeding, suggesting that depredation can lead to behavioural modifications (Mitchell *et al.* 2020).

Furthermore, although fishing activity typically occurs over wide areas, discards tend to be concentrated into smaller areas. This is perhaps truer for recreational fisheries, where anglers return to shore-based fish-cleaning facilities associated with boat ramps to process their catches for consumption and discard waste. This high concentration of food in specific locations in conjunction with repetitive temporal patterns in the activity result in conditions where animals can quickly develop strong associations. Given high participation rates and the widespread prevalence of

recreational fishing (Cisneros-Montemayor and Sumaila 2010; Freire *et al.* 2020; Arlinghaus *et al.* 2021), and the potentially significant behavioural modifications identified for species that consume fishery discards, the role of these discards as a food subsidy to marine wildlife and their behavioural adaptations for accessing these resources needs to be further examined.

Smooth stingrays (*Bathytoshia brevicaudata*) are a large demersal ray species found in coastal waters of Australia, New Zealand, southern Africa, Japan, and eastern Russia (Rigby *et al.* 2021). Throughout their range, they are common scavengers of recreational fishing discards (Australia: J. Pini-Fitzsimmons, pers. obs.; New Zealand: H. Cadwallader, pers. obs.; South Africa: C. Elston, pers. obs.) and are known to take advantage of other anthropogenically provisioned food sources, such as baits used for white shark (*Carcharodon carcharias*) cage-diving operations (Rizzari *et al.* 2017; Meyer *et al.* 2020) and commercial fishery discards (Svane *et al.* 2008). In Hamelin Bay, Western Australia, smooth stingrays, along with black stingrays (*Bathytoshia lata,* formerly *Dasyatis thetidis*) and southern eagle rays (*Myliobatis tenuicaudatus*) are hand-fed bait and fish carcasses as part of an unmanaged tourist attraction (Newsome *et al.* 2004). This attraction developed from the rays becoming attracted to commercial anglers cleaning their catches at this location, followed by the installation of fish-cleaning facilities for recreational anglers who discard scraps into the waters (Newsome *et al.* 2004). Their predilection for utilising provisioned resources makes them a useful study species for determining potential impacts of fishing discards, particularly for large mesopredatory species that play central roles in coastal food webs.

In the Jervis Bay Marine Park, on the southern coast of New South Wales (NSW), Australia, smooth stingrays have scavenged discards from the cleaning of recreational fishing catches at the Woollamia Regional Boat Ramp in Currambene Creek since the 1980s. Previous research has indicated that the stingray' use of the boat ramp is strongly linked to the timing and intensity of fish-cleaning activity and associated to discarding of fish waste from the shore-based fish-cleaning facilities (i.e. increased presence with increased fish cleaning, particularly in afternoons when fish cleaning is more common; Pini-Fitzsimmons *et al.* 2018). However, the previous study relied on visual observations and was limited in duration (22 days). How smooth stingrays use the wider creek system within which the fish-cleaning facilities are located in relation to the provisioning of recreational fishing discards remains unknown.

Here we built on our previous study by using passive acoustic telemetry to assess the visitation of smooth stingrays within Currambene Creek, specifically in relation to temporal patterns in discarding at the boat ramp and environmental conditions. If provisioning of fishing discards is the primary driver of smooth stingray use of the creek, we expected (1) smooth stingray visitation to be higher at the Woollamia

Regional Boat Ramp than in other areas within the study site where provisioning is not occurring, and (2) for visitation at the boat ramp to match temporal patterns in food provisioning (i.e. higher visitation in afternoons and on weekends) with no such patterns being observed at other areas where provisioning is not occurring. In contrast, if smooth stingray use of the creek system was related to natural behaviours, during which they utilised provisioned resources if and when they were available, we expected visitation to be linked to the physical environment (i.e. water temperature, tides, rainfall, etc.), and for these variables to be of greater influence than patterns in provisioning activity.

Materials and methods

Study site and acoustic-array design

Currambene Creek in the Jervis Bay Marine Park is a mature barrier estuary (Fig. 1*a*) and the main tributary of Jervis Bay, NSW, Australia (Owers *et al.* 2016). It is dominated by soft sandy substrata and lined by small areas of *Zostera* sp. (NSW Department of Primary Industries 2013; Lucieer *et al.* 2017), and supports an extensive temperate saline wetland of mangroves and saltmarsh (Owers *et al.* 2016). The creek is ~15 km long, has a waterway area of 1.2 km², and drains a catchment of 165 km² (Ricardo *et al.* 2014). It is influenced by the semi-diurnal tidal range of ~2 m experienced in the neighbouring Jervis Bay (Owers *et al.* 2016).

The study area for this research was restricted to the lower reaches around the Woollamia Regional Boat Ramp, with the total study area spanning from 250 m inside the mouth to 2.75 km upstream (Fig. 1*b*). The Woollamia Regional Boat Ramp is a popular public boat ramp with fish-cleaning facilities that, at the time of the study, featured running water and a four-station metal fish-cleaning table with an open pipe in the centre that drained into the creek for disposing of fish discards from cleaning and filleting. The boat ramp and fish-cleaning facilities are used daily, and smooth stingrays have been observed foraging discards here since the 1980s and are seen in the vicinity daily (R. Simpson, Simo's Afloat Fishing Charts, pers. obs.).

Four acoustic receivers (VR2W 69 kHz; Innovasea Systems, Nova Scotia, Canada) were deployed in the study area, namely, 0.5 km ('Creek Mouth'), 1.2 km ('Downstream'), 1.85 km, ('Woollamia Boat Ramp') and 2.65 km ('Upstream') upstream from the mouth of the creek (Fig. 1). The Woollamia Boat Ramp receiver detection range encompassed the provisioning area at the Woollamia Regional Boat Ramp. Receivers were affixed to moorings ~1–2 m from the benthos, with the hydrophone facing up. The detection range was estimated as 200–300 m and was determined through deployment of transmitters anchored at 50, 100, 200 and 300 m from the Woollamia Boat Ramp receiver. All detections were captured at 200 m and ~50% of detections were captured at 300 m. The widest point of the creek within the study area was ~220 m at the mean high-water mark and therefore the vast majority of detections from tagged
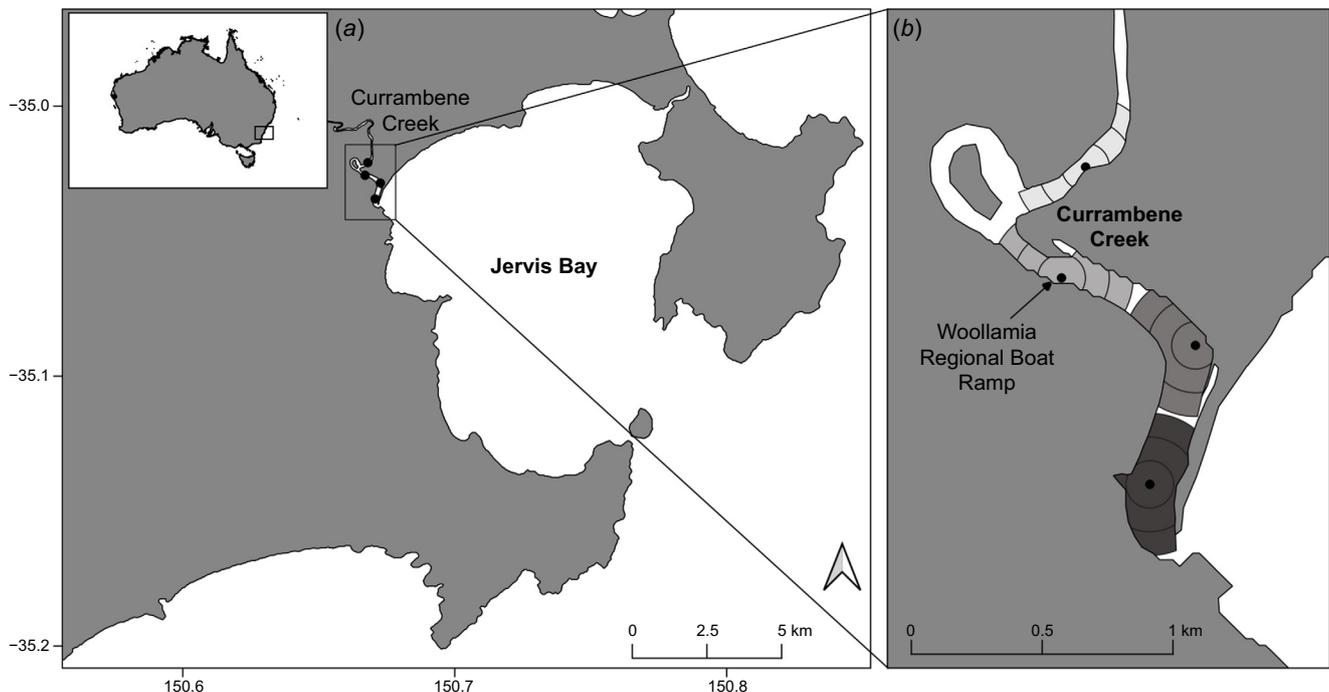

Fig. 1. (*a*) Location of Currambene Creek within Jervis Bay, NSW, and Australia (inset). (*b*) Positioning of VR2W passive acoustic receivers (points) and detection ranges (contours = 100 m; 300-m total detection range) relative to the Woollamia Regional Boat Ramp.

animals were expected to be captured by the receivers in the array as they passed. Acoustic coverage of the study area (250 m from mouth to 2.75 km upstream) was estimated to be 55–87% (200–300-m detection range; Fig. 1*b*). No receiver was placed in the loop in the north-west of the study site, between the Woollamia Boat Ramp and the Upstream receiver (Fig. 1), because this area of the creek is too shallow to deploy a receiver and stingrays are rarely observed (local residents, pers. comm.).

Acoustic tagging

Smooth stingrays were tagged at the Woollamia Regional Boat Ramp. Stingrays were enticed onto the boat ramp by using a bait tube filled with locally sourced fish frames creating a chum trail. When a ray entered the tagging area, a 3- × 2-m sling made from shade cloth with wooden dowels as handles and weights at the base, was walked behind the ray and used to beach it on the boat ramp. The ray was orientated such that most of the body was out of the water, but the mouth, gills and spiracles remained fully submerged, allowing unrestricted respiration. Heavy wet towels were used to disable the tail and barb.

Smooth stingrays were then tagged externally with Vemco V9-2H 69 kHz coded acoustic transmitters (400-mm total length, 2.9 g in water) with a random repeat interval of 30–90 s and estimated battery life of 476 days (Innovasea Systems, Nova Scotia, Canada). Stingrays were tagged using a novel pelvic fin transmitter attachment method that was based on a similar method used by Hunter *et al.* (2005) on thornback rays (*Raja clavata*). However, we opted for pelvic fin over pectoral wing attachment because of wing undulation potentially causing necrosis around transmitter attachment wounds (Ward *et al.* 2019), and the potential for transmitter loss from males biting and scraping the wings of females during mating (Kajiura *et al.* 2000; Chapman *et al.* 2003; Le Port *et al.* 2008). The tagging procedure is described below.

The transmitters were affixed to plastic Petersen discs (250-mm diameter; Fig. 2) by using Shellys Aqua Fix waterproof epoxy adhesive, with a length of 200-lb (~90.7-kg) monofilament fishing line threaded through the disc.
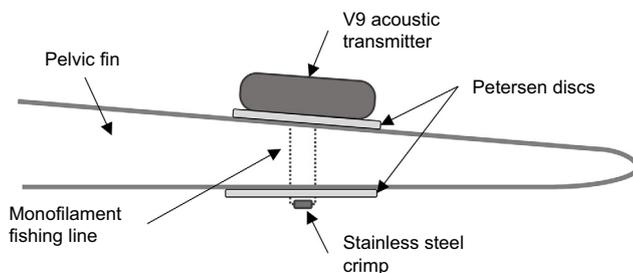

Fig. 2. Cross-sectional view of acoustic-transmitter attachment on smooth stingray pelvic fin. Figure not to scale.

A sterile stainless-steel needle (2.5-mm diameter) was used to make a guide hole through the middle of one of the stingrays' pelvic fins, through which a sterile stainless-steel hypodermic needle (3.5-mm internal diameter) was then passed. The monofilament from the Petersen disc was then threaded through the pelvic fin via the hypodermic needle and the needle was removed through the ventral side. Another Petersen disc was then threaded onto the monofilament on the ventral side of the pelvic fin and crimped in place with a 150-lb (~68-kg) stainless steel fishing crimp (Fig. 2).

During the tagging procedure, disc width and disc length were measured, sex was determined and any distinguishing features on the ray were noted and photographed for individual identification. Following tagging, the sling was lowered, allowing the ray to swim freely out of the tagging area. The tagging procedure took ~5 min per individual and most stingrays returned to the tagging area within an hour of tagging, indicating limited negative effects from the tagging procedure.

Tagging and tracking were approved by the Macquarie University Animal Ethics Committee under ARA 2014/015 and NSW DPI Scientific Collection Permit Number P08/0010.

Food-provisioning variables

Previous research at this site highlighted that fish-cleaning intensity at the Woollamia Regional Boat Ramp is higher in the afternoons (Pini-Fitzsimmons *et al.* 2018). This matches patterns in recreational fishing effort documented in the literature; specifically, effort is skewed to daylight hours, with peaks in fishing effort at approximately midday (Askey *et al.* 2018) and returns to fish-cleaning facilities in the afternoon (Pini-Fitzsimmons *et al.* 2018; Lynch *et al.* 2020). Similarly, recreational fishing effort is increased on non-business days (i.e. weekends and holidays; Parnell *et al.* 2010; van Poorten *et al.* 2015; Flynn *et al.* 2018; Kendall *et al.* 2021). Therefore, *hour of the day* and *day of the week* served as temporal variables for investigating the influence of provisioning activity. *Receiver* location allowed investigation of the spatial influence of provisioning activity (e.g. differences in visitation at the Woollamia Boat Ramp receiver vs other receivers).

Environmental variables

Environmental data were collected to determine the potential influence of the physical environment on smooth stingray use of lower Currambene Creek. Variables used were *water temperature, daily rainfall, previous-day rainfall* (i.e. to examine delayed effects of rain events)*, tidal phase,* and *lunar phase* (Table 1). These variables were chosen because they are commonly associated with or examined when assessing drivers of elasmobranch movements in nearshore environments (e.g. Heupel *et al.* 2003; Smoothey *et al.* 2019;

Table 1. Environmental variables used to determine the influence of the physical environment on smooth stingray space use in lower Currambene Creek.

Variable used	Raw data (units)	Source
Tidal phase - Incoming - Outgoing	Hourly sea level (m)	Australian Baseline Sea Level Monitoring Project Port Kembla Station (34°28′24″S, 150°54′42″E; Bureau of Meteorology 2019)
Lunar phase - Full - Waning - New - Waxing	Daily moon illumination data (%)	United States Naval Observatory (2019)
Water temperature (°C)	Temperature (°C) recorded every 15 min	HOBO Pendant Temperature Data Logger (Hobo Data Loggers, Australia) affixed to the base of the acoustic receiver at the Woollamia Boat Ramp
Daily rainfall - No rainfall - 1–20 mm - 20–40 mm - >40 mm	Total rainfall recorded in the 24 h previous to 09:00 AEST daily	Australian Data Archive for Meteorology for the Point Perpendicular Weather Station (35°5′37″S, 150°48′18″E; Bureau of Meteorology 2020)
Previous-day rainfall - No rainfall - 1–20 mm - 20–40 mm - >40 mm	Total rainfall recorded in the 24 h previous to 0900 hours AEST of the previous day	Australian Data Archive for Meteorology for the Point Perpendicular Weather Station (35°5′37″S, 150°48′18″E; Bureau of Meteorology 2020)

Niella *et al.* 2020; Spaet *et al.* 2020). These data, their treatments, and the sources are summarised in Table 1. It should be noted that *water temperature* was collected by a single data logger deployed at the provisioning site and used as a proxy for water temperature within the study area generally. *Water temperature* was included as a continuous variable. *Tidal phase, lunar phase, daily rainfall* and *previous-day rainfall* were included as categorical variables to simplify analyses and account for sparseness in some datasets (e.g. rainfall).

Data analysis

Pre-processing

Passive acoustic detection data gathered in the 12 h following tagging were excluded to account for potential changes in behaviour from the tagging procedure. Similarly, the first 3 h of water-temperature data were removed to ensure that the data logger was acclimated after deployment.

Periodicity of detections

To identify whether periodicity existed within the acoustic detection data, Rao's spacing tests were used to determine whether the mean number of detections (for all individuals combined) varied across (1) *hour of the day* and (2) *day of the week* for each *receiver*. Polar plots were then used to visualise these differences. Rao's spacing tests and polar plots were conducted with the *circular* package (ver. 0.4-95, C. Agostinelli and U. Lund, see https://CRAN.R-project.org/package=circular) in R (ver. 4.0.0, R Foundation for Statistical Computing, Vienna, Austria, see https://www.r-project.org/). If food provisioning was a major driver of visitation by smooth stingrays, we expected to see detections (1) peak in the afternoon at the Woollamia Boat Ramp receiver but not at other receivers and (2) peak on weekend days at the Woollamia Boat Ramp receiver but not at other receivers.

Visitation patterns

To capture how often tagged stingrays used areas of Currambene Creek, a *detection index* was estimated for (1) each stingray overall and (2) each stingray at each receiver, on the basis of the number of days detected divided by the total number of days an individual was tracked for the study (Udyawer *et al.* 2018). Values ranged from 0 (never detected) to 1 (detected every day). The total number of days tracked was calculated as the number of days from 12 h post-release until the last recorded detection. A Kruskal–Wallis test followed by a Dunn's multiple comparisons *post hoc* test was used to determine whether *detection indices* were significantly different across receivers.

The proportion of acoustic detections recorded on each receiver by each individual was calculated to identify site preferences by tagged stingrays. If food provisioning from the Woollamia Regional Boat Ramp was driving the distribution of stingrays within the creek system, it was expected that the highest proportion of detections would be recorded on the receiver closest to the boat ramp.

To assess the time spent by stingrays within each section (defined by receiver location) of Currambene Creek,

visitation events were extracted from the acoustic detection data. *Visitation events* were defined as the continuous periods of time a tagged stingray was within the range of a given receiver. They were initiated when a transmitter was detected by a receiver and terminated either when the transmitter was detected at a different receiver or if no further detections were made within 15 min. The 15-min timeout was selected because this is ample time for a smooth stingray to move through the detection range of a receiver (up to ~600 m) (Campbell *et al.* 2012). Visitation events less than 5 min in length were not considered to represent meaningful site occupancy and were therefore removed from further analyses.

A generalised additive mixed-effects model (GAMM) was used to assess how food provisioning at the Woollamia Regional Boat Ramp and aspects of the physical environment at the initiation of visitation events influenced the duration of visitation events. In other words, to test what conditions influenced the arrival of smooth stingrays and resulted in longer stays at each acoustic receiver. This model considered *hour of day* and *day of week* that visitation events were initiated on in interaction with *receiver* location, with cyclic cubic regression splines being applied to *hour of the day* and *day of the week* to account for their cyclical nature. Categorical (*lunar phase, tidal phase, daily rainfall, previous-day rainfall*) and continuous (*water temperature*) environmental variables occurring at the initiation of visitation events were also included additively. No regression spline was applied to *water temperature* because the relationship in the model was determined to be linear. *Transmitter number* was included as a random effect to account for the unequal number of visitation events recorded for each individual and lack of independence of individual ray behaviour. The duration of visitation-event data were transformed using Ordered Quantile normalisation (Peterson and Cavanaugh 2020) prior to modelling, and the model used a Gaussian error structure.

The GAMM was run using the *mgcv* package (ver. 1.8-41, S. Wood, see https://cran.r-project.org/package=mgcv/; Wood 2017) in R (R Foundation for Statistical Computing). Model selection was conducted using the double-penalty approach by setting 'select = TRUE' within the *bam*() function in *mgcv*. This method penalises variables of limited influence out of the global model, without the need to compare candidate models with all possible combinations of variables. An autocorrelation plot was used to assess whether there was serial correlation among residuals within the model. Temporal autocorrelation was indeed evident and so a first-order auto-regressive structure was included. The final model was validated by inspecting diagnostic plots (Q–Q plots, histograms of residuals, response vs fitted values and linear predictors vs residuals). Predictor variables were visually checked for outliers using Cleveland dot plots and collinearity was checked using variance inflation factors (VIFs) prior to modelling. No outliers or collinearity (VIF < 3; Zuur *et al.* 2010) were detected.

It should be noted that *water-temperature* data were available only for 129 days of the 210-day study period. For completeness during data exploration, a GAMM was run using the full *visitation event dataset* without *water temperature* as a variable (9001 *visitation events*) and compared with the GAMM with *water temperature* included as a variable (8160 *visitation events*); the former was found to perform substantially worse than the latter model. Therefore, the model with *water temperature* was retained and the results for this model are presented here.

Results

Acoustic monitoring

The study spanned August 2017 until April 2018. Acoustic transmitters were deployed on 13 smooth stingrays during August and September 2017 at the Woollamia Regional Boat Ramp (Table 2). Disc widths averaged 158.9 cm (±6.4 cm s.e.) and disc lengths averaged 126.2 cm (±3.3 cm s.e.; Table 2), and all tagged rays were adult females (disc width ≥100 cm; Le Port *et al.* 2012). All 13 tagged rays were detected within the array post-release. Following the removal of detections recorded within 12 h post-release for each individual, 196 393 detections remained (Fig. 3). Tracking periods for the rays ranged between 33 and 153 days (mean ± s.e. = 99 ± 10 days; Table 2). Owing to the external tagging methodology, tracking periods ended following premature loss of tags rather than by stingrays leaving the system. This was confirmed through resighting of all individuals at the boat ramp in the following months (August–September 2018). Therefore, tracking periods were considerably shorter than expected (tag battery life of ~476 days), but no stingrays appeared to leave the broader study area.

The highest proportion of detections (averaged across individuals) were recorded at the Woollamia Boat Ramp receiver (mean ± s.e. = 48 ± 4.569%), followed by the Downstream (mean ± s.e. = 31 ± 2.870%), Creek Mouth (mean ± s.e. = 11 ± 1.438%), and Upstream (mean ± s.e. = 11% ± 3.270%) receivers. *Detection indices* were high for all stingrays in Currambene Creek (mean ± s.e. = 0.817 ± 0.036; Table 2). By receiver, mean *detection indices* were high at the Woollamia Boat Ramp, Downstream and Creek Mouth receivers (mean ± s.e. = 0.763 ± 0.039, 0.794 ± 0.035 and 0.763 ± 0.033 respectively), and low at the Upstream receiver (mean ± s.e. = 0.381 ± 0.077). *Detection indices* varied by receiver (Kruskal–Wallis test: d.f. = 3, χ^2 = 16.148, P = 0.001), driven by the significantly lower indices at the Upstream receiver (Dunn's multiple-comparisons test: Upstream compared with all other receivers, $P < 0.01$; see Supplementary Table S1).

Table 2. Summary of acoustic-transmitter deployments.

Transmitter number	Sex	Disc width (cm)	Disc length (cm)	Time tagged (local)	Tracking period (days from time tagged + 12 h)	Total number of detections (from time tagged + 12 h)	Detection index
47272	Female	133	115	2017-09-10 17:22:00	83	6910	0.72
47273	Female	172	139	2017-09-04 14:54:00	100	32 616	1.00
47274	Female	164	138	2017-09-09 17:17:00	119	6979	0.56
47275	Female	179	131	2017-09-04 16:24:00	109	11 626	0.74
47280	Female	200	148	2017-09-16 15:55:00	116	17 514	0.66
47282	Female	173	122	2017-10-25 15:40:00	153	15 575	0.77
47283	Female	162	127	2017-10-25 15:15:00	49	9831	0.98
2424	Female	187	134	2017-08-30 14:41:00	118	14 126	0.80
2425	Female	147	114	2017-09-02 17:55:00	141	23 325	0.82
2426	Female	121	106	2017-08-31 15:06:00	33	4377	0.94
2427	Female	141	119	2017-09-01 16:53:00	45	5776	0.80
2428	Female	146	119	2017-08-31 14:05:00	110	22 544	0.93
2429	Female	140	129	2017-08-29 13:59:00	111	25 194	0.90

Note that the first 12 h of detection data for each tagged individual was removed before statistical analyses. Time at liberty and total number of detections are calculated from 12 h post-tagging time. Tracking period is until date of last detection. *Detection index* is the proportion of days detected of total days tracked.
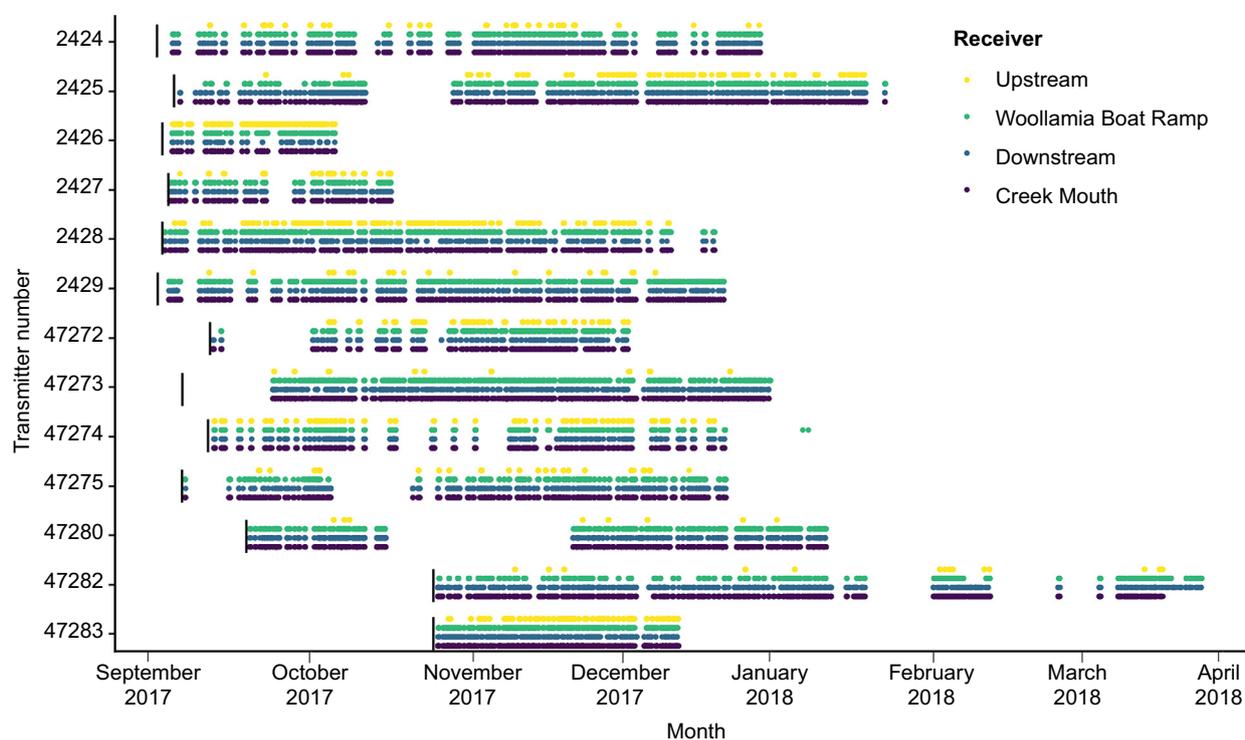

Fig. 3. Timeline of detections (local time) of tagged smooth stingrays at the four acoustic receivers in the array. Each point represents that the tagged smooth stingray was detected on the respective receiver on a given day.

Periodicity of detections

Mean hourly detections were significantly non-homogeneous across *hour of the day* at all receivers (Rao's spacing tests: Upstream: $t = 323.578$, $P < 0.001$; Woollamia Boat Ramp: $t = 355.211$, $P < 0.001$; Downstream: $t = 350.512$, $P < 0.001$; Creek Mouth: $t = 333.119$, $P < 0.001$). Diurnal patterns were present in the mean hourly detections at the Woollamia Boat Ramp and the Downstream receivers
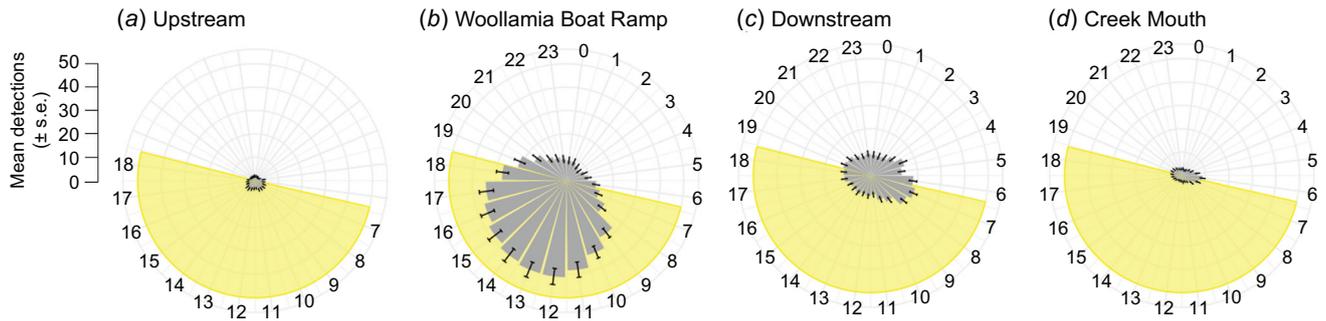
Fig. 4. Mean acoustic detections (±s.e.) for smooth stingrays by hour of the day at each acoustic receiver (*a*, Upstream; *b*, Woollamia Boat Ramp; *c*, Downstream; and *d*, Creek Mouth). Average daylight hours for the study period (0622 to 1827 hours local time) are highlighted yellow.
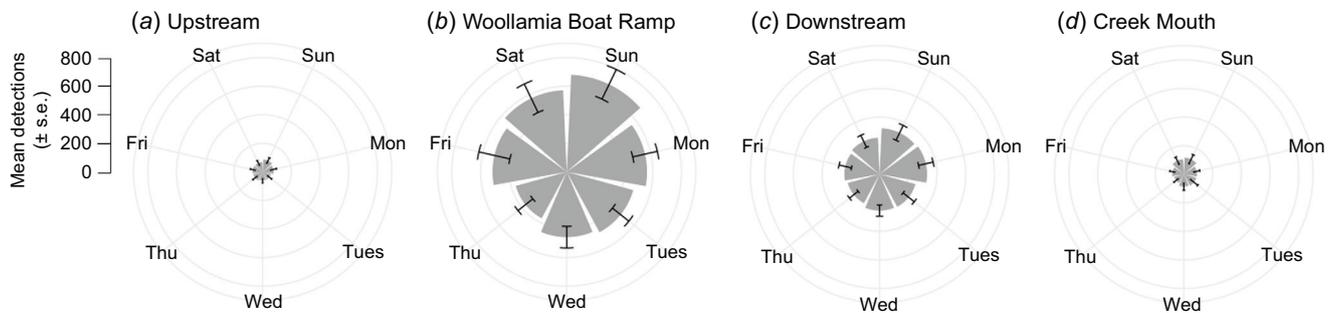

Fig. 5. Mean acoustic detections (±s.e.) for smooth stingrays by day of the week at each acoustic receiver (*a*, Upstream; *b*, Woollamia Boat Ramp; *c*, Downstream; and *d*, Creek Mouth).

(Fig. 4*b*, *c*, *d*). At the Woollamia Boat Ramp, mean hourly detections increased from 0900 hours, peaked at 1200–1500 hours, followed by a substantial drop at 1800 hours (Fig. 4*b*). At the Downstream receiver, a matutinal pattern was seen, with higher detections between 0600 and 0800 hours (Fig. 4*c*). Mean hourly detections were too low at the Creek Mouth and Upstream receivers (<10 detections at peaks) to discern any clear patterns (Fig. 4*a*, *d*).

Detections by *day of the week* were significantly non-homogeneous at all receivers (Rao's spacing tests: Upstream: $t = 359.823$, $P < 0.001$; Woollamia Boat Ramp: $t = 359.977$, $P < 0.001$; Downstream: $t = 359.954$, $P < 0.001$; Creek Mouth: $t = 359.869$, $P < 0.001$). At the Woollamia Boat Ramp, mean daily detections peaked on Sundays, with generally higher mean daily detections seen Friday to Monday (Fig. 5*b*). A similar trend was seen at the Creek Mouth receiver, although mean daily detections were substantially lower than at the boat ramp (Fig. 5*d*). Mean daily detections peaked on Sunday and Monday at the Downstream receiver (Fig. 5*c*) and the Upstream receiver (Fig. 5*a*), although mean daily detections were substantially lower at the Upstream receiver.

Visitation patterns

In total, 9001 *visitation events* were recorded throughout the study period, lasting between 5 min and 13 h 47 min

(mean ± s.e. = 36 min ± 35 s). *Visitation events* were, on average, longer at the Woollamia Boat Ramp (mean ± s.e. = 53 ± 1.3 min) than at the Downstream (mean ± s.e. = 28 min ± 36 s), Upstream (mean ± s.e. = 24 ± 1.6 min), and Creek Mouth (mean ± s.e. = 23 min ± 41 s) receivers.

The GAMM considered 8160 of the total 9001 *visitation events* and explained 11.3% of the deviance observed (summarised in Table S2). Overall, *visitation events* were significantly longer at the Woollamia Boat Ramp than at the Upstream ($\beta = -0.545$, $t = -13.217$, $P < 0.001$), Downstream ($\beta = -0.299$, $t = -11.586$, $P < 0.001$), and Creek Mouth ($\beta = -0.524$, $t = -16.746$, $P < 0.001$) receivers (Fig. 6*i*), indicating that stingrays spent more time in the vicinity of the Woollamia Regional Boat Ramp than in other parts of the study area. There was a significant effect of *day of the week* on the duration of *visitation events* at the Woollamia Boat Ramp (d.f.$_e$ = 1.660, $F = 0.998$, $P = 0.039$), with *visitation events* being longest when initiated on Saturday and Sunday and shortest on Wednesday–Thursday (Fig. 6*b*). No patterns were observed at the other three receivers (Fig. 6*a*, *c*, *d*). There was a significant effect of *hour of the day* at all receivers except the Creek Mouth (Upstream: d.f.$_e$ = 1.932, $F = 0.335$, $P = 0.010$; Woollamia Boat Ramp: d.f.$_e$ = 5.218, $F = 3.997$, $P < 0.001$; Downstream: d.f.$_e$ = 3.460, $F = 2.602$, $P < 0.001$; Fig. 6*e–h*). At the Woollamia Boat Ramp, *visitation events* were longest when initiated between 1000 and 1200 hours (Fig. 6*f*). That is, stingrays that arrived at the boat ramp
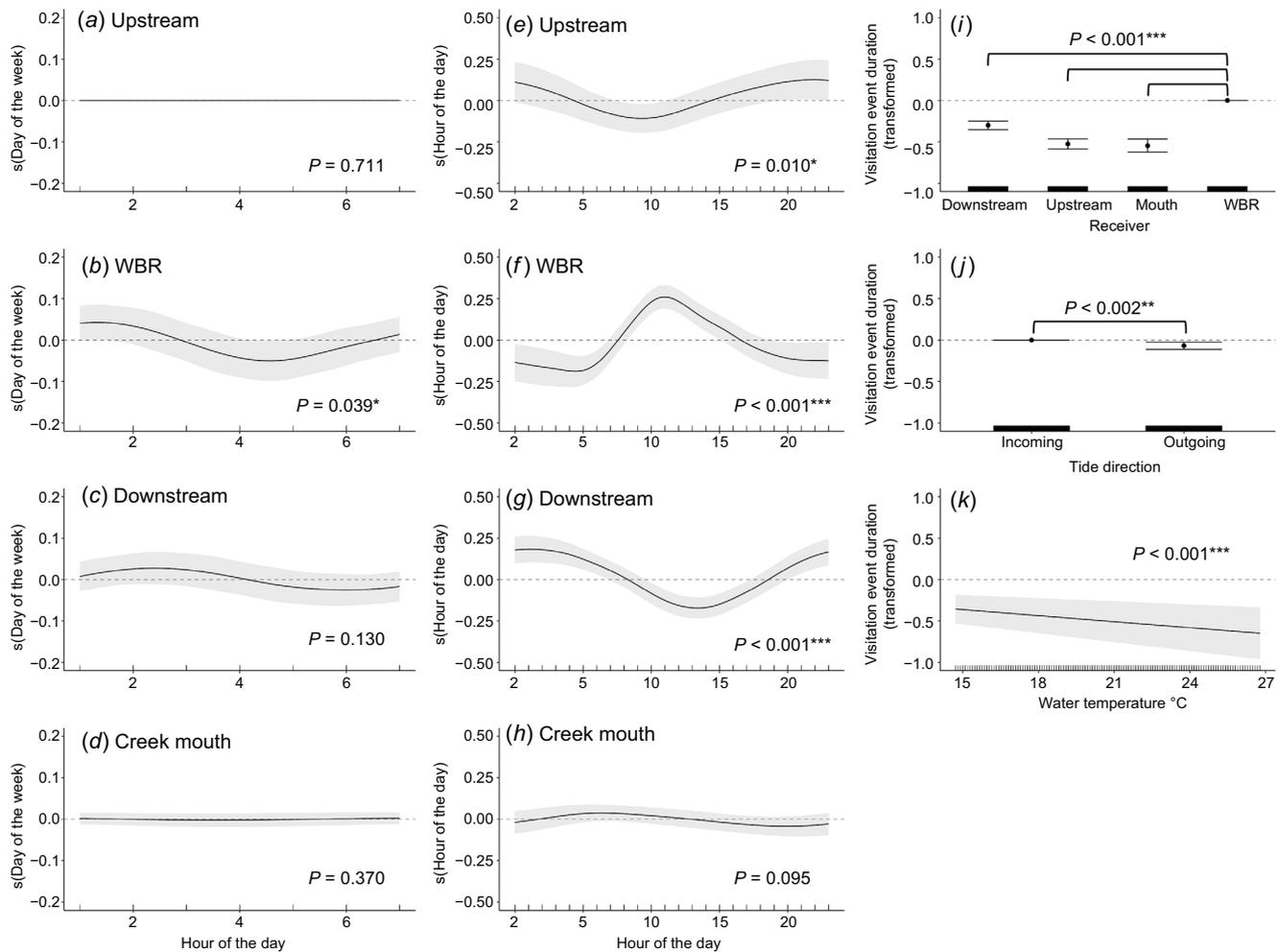
Fig. 6. Effect plots from the generalised additive mixed-effects model evaluating the duration of smooth stingray visitation events in lower Currambene Creek against temporal and environmental variables. The model estimated the effects of (*a–d*) the interaction between day of the week (1–7 = Sunday–Saturday) and receiver, (*e–h*) the interaction between hour of the day and receiver, (*i*) receiver, (*j*) tide direction, and (*k*) water temperature (°C) at the initiation of visitation events. The model contained a first-order auto-regression structure to account for temporal autocorrelation. The effect of cyclic smooths are given in *a–h*, denoted by s(x) on the y-axis. P-values are provided and significant effects are denoted by: *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$. Grey-shaded areas indicate 95% confidence intervals. Note y-axis values differ among plots.

between 1000 and 1200 hours stayed the longest, with these events spanning the afternoon. This pattern is also supported by peaking detections during this period shown above (Fig. 4b). A somewhat opposing relationship was observed at the Downstream (i.e. shortest when initiated 1000 to 1700 hours; Fig. 6g) and Upstream (i.e. shortest when initiated 0800 to 1100 hours; Fig. 6e) receivers. *Visitation events* were also significantly shorter when initiated during an outgoing tide compared with an incoming tide, but the effect was small ($\beta = -0.069$, $t = -3.101$, $P = 0.002$; Fig. 6j). Similarly, *visitation events* were significantly shorter with increasing water temperatures, but the effect was also small ($\beta = -0.024$, $t = -4.048$, $P < 0.001$; Fig. 6k). There was a significant effect of *transmitter number* as the random effect (d.f.$_e$ = 11.382, $F = 21.696$, $P < 0.001$), suggesting that

individual rays varied in their behaviour. There was no effect of *lunar phase*, *daily rainfall* or *previous-day rainfall*. Therefore, the physical environment had little (*tidal phase* and *water temperature*) to no (*lunar phase*, *daily rainfall*, and *previous-day rainfall*) effect on the duration of stingray visits.

Discussion

Previous research has indicated that smooth stingray visitation to the Woollamia Regional Boat Ramp was linked to the intensity of recreational fish cleaning and associated provisioning of discards, with increased presence in the afternoons when fish-cleaning activity peaked (Pini-Fitzsimmons *et al.* 2018). This study has built on this work to show that

smooth stingray use of the broader lower Currambene Creek area is strongly linked to provisioning activity. Specifically, we found that (1) smooth stingrays use Currambene creek frequently (~79% of days tracked) and visited the provisioning site (Woollamia Regional Boat Ramp) with the same frequency (~74% of days tracked), (2) smooth stingray visitation was highest at the provisioning site relative to all other sites, and (3) patterns in their visitation to this site coincided with provisioning activity (i.e. higher mean acoustic detections and longer visitation events during afternoons and weekends). Importantly, these patterns were not observed at the other areas within the creek. In addition, (4) environmental variables had little (*tidal phase* and *water temperature*) to no (*lunar phase, daily rainfall*, and *previous-day rainfall*) effect on the length of time stingrays spent in areas of the creek, as might have been expected if their use of the creek was predominantly related to natural behaviours based on environmental cues. These spatial and temporal patterns are consistent with our hypothesis that the use of Currambene Creek by smooth stingrays is linked to the discarding of fish-cleaning waste at the Woollamia Regional Boat Ramp.

Daily patterns

Smooth stingrays tracked in this study appeared to show diel movements whereby they enter Currambene Creek in the morning, travel upstream to the Woollamia Regional Boat Ramp in the afternoon where they remain for extended periods and then leave again over night. Natural diel movement patterns for smooth stingrays are currently unknown, but diel patterns in the use of inshore habitats for other batoid species typically involve use of warmer shallow waters during the night and refuging in cooler, deeper waters while they digest during the day (i.e. diel vertical migration; Wearmouth and Sims 2009; Farrugia *et al.* 2011; Humphries *et al.* 2017; DeGroot *et al.* 2020). Indeed, for several dasyatid ray species, presence in shallow habitats is generally higher at night and nocturnal space use is larger as individuals actively forage for food (Cartamil *et al.* 2003; Farrugia *et al.* 2011; Corcoran *et al.* 2013). Smooth stingrays might, therefore, be expected to show similar natural diel patterns if their use of Currambene Creek was related to natural movements. Instead, here we found that their use of the shallow creek area was higher during the day than at night, particularly in the afternoon and was overwhelmingly focussed on the provisioning site. On the basis of comparatively low night-time detections, it is likely that smooth stingrays leave Currambene Creek overnight. However, diel movements related to thermoregulation can also result in higher use of shallow waters during the day (Schlaff *et al.* 2014). For example, bat rays (*Myliobatis californicus*) travel from cooler deeper waters to forage intertidal sandflats in the middle of the day, using the warmer waters as a means of behavioural thermoregulation (Matern *et al.* 2000).

Although smooth stingrays in this study exhibited longer visitation events from the middle of the day and peaks in detections in the afternoon, visitation events were actually shorter with increased water temperatures, but the effect was negligible compared with temporal and spatial variables related to food-provisioning activity. In addition, if smooth stingrays were using behavioural thermoregulation, the area around the downstream receiver would be preferable to the boat ramp area, at least during high tide, because of the presence of expansive shallow sandflats that are submerged with the high tide; however, this was not the case. It is unlikely, therefore, that the diel patterns in space use observed are related to behavioural thermoregulation. However, it is important to re-iterate that diurnal behaviours of smooth stingrays are unknown, and other elasmobranchs show mixed diurnal behaviours (Hammerschlag *et al.* 2017). In addition, thermal and salinity preferences for smooth stingrays are unknown, preventing detailed discussion of such influences on space use. Therefore, further work is needed to understand baseline behaviour and preferences, to identify potential changes caused by provisioning activity.

Food provisioning has been shown to cause the reversal of diel behaviour in southern stingrays (*Hypanus americanus*, formerly *Dasyatis americana*) fed as part of ecotourism at Stingray City in the Bahamas (Corcoran *et al.* 2013). The diel behaviour of non-provisioned stingrays involved resting in cooler deeper waters at night and larger activity spaces over shallow habitats during the day (Corcoran *et al.* 2013). In comparison, provisioned stingrays were constantly active during the day, particularly during provisioning activity, with high attachment to the provisioning site, and would disperse at night (Corcoran *et al.* 2013). With the normal diel movements of smooth stingrays being currently unknown, we cannot comment on whether such a behaviour switch has occurred in the studies context and further research is needed.

Weekly patterns

Few, if any, environmental phenomena or combinations of environmental variables function on 7-day cycles. For instance, tides vary in accordance with lunar cycles over short (~11 h) and long (30 day) cycles, and water temperature varies across days and by season. As such, the most likely cue to explain increased detections and longer visitation events on weekends at the Woollamia Regional Boat Ramp is human behaviour, specifically that related to increased recreational fishing effort on weekends (Parnell *et al.* 2010; van Poorten *et al.* 2015; Flynn *et al.* 2018; Kendall *et al.* 2021). These observed patterns are indicative of a 'weekend effect', whereby animals demonstrate differing behavioural patterns on weekends from those on weekdays in areas of increased human recreational activity (Nix *et al.* 2018). However, this phenomenon typically involves animals retreating from areas with increased human use on weekends

(e.g. Stalmaster and Kaiser 1998; Lafferty 2001; Longshore *et al.* 2013; Nix *et al.* 2018), rather than increased attraction to such sites as demonstrated here.

However, human behaviour and environmental conditions are not always mutually exclusive. Environmental conditions may determine when and where people go fishing, both in regard to the spatio-temporal distribution of target species (e.g. fish migrations, prey patches) and the level of enjoyment experienced because of weather conditions (e.g. lower angler number during adverse weather; Cabanellas-Reboredo *et al.* 2014; Lynch *et al.* 2020; Kendall *et al.* 2021). Nevertheless, temporal factors related to provisioning (hour of the day and receiver) had a greater effect on smooth stingray visitation than had environmental variables in the present study. However, it is important to note that the modelling used in this study does not consider the periods between visitation events (i.e. stingray absences), and certain environmental variables may be more closely linked to stingray disuse of an area.

Implications of utilising provisioned recreational fishing discards

Even though recreational fishery discards are likely to drive the use of Currambene Creek by smooth stingrays, the broader implications of this shift in behaviour are currently unknown, although, some insights can be gained from wildlife tourism. Feeding wildlife for tourism is based on animals learning associations with provisioned food that is provided predictably in time and space, and there is a growing body of evidence that feeding wildlife in these contexts can lead to long-term changes in abundance, community structure, behaviour, and movement patterns, in both terrestrial and marine species (reviewed in Orams (2002), Newsome and Rodger (2008), Brena *et al.* (2015), Trave *et al.* (2017), Patroni *et al.* (2018)). It is argued that the extent to which food provisioning affects animals is based on the amount and frequency of provisioning (Abrantes *et al.* 2018; Heinrich *et al.* 2020). For example, southern stingrays provisioned daily by 1 million tourists annually at Stingray City in the Bahamas (Vaudo *et al.* 2018) suffer from long-term behavioural impacts (Corcoran *et al.* 2013), whereas Caribbean reef sharks (*Carcharhinus perezi*) that have been provisioned daily for over 20 years elsewhere in the Bahamas but are fed a restricted amount of food showed no significant changes in movement patterns (Maljković and Côté 2011). The Woollamia Regional Boat Ramp is one of the most popular ramps in the region and used daily (R. Simpson, pers. comm.). Smooth stingrays are long-lived and have been observed foraging discarded recreational fish-cleaning waste at the boat ramp for over 35 years, during which weekly and daily trends have been reinforced, and may therefore be at high risk of longer-term impacts.

Notably, all smooth stingrays tagged in this study were adult females, and a number were observed in breeding condition (J. Pini-Fitzsimmons, pers. obs.). This female bias has been consistent at the site for a number of years (Pini-Fitzsimmons *et al.* 2018, 2021), and has been noted at other sites where this species is provisioned (e.g. cage-diving in the Neptune Islands, South Australia, A. Fox, pers. comm.; Hamelin Bay, Western Australia, Newsome *et al.* 2004). Further, female-bias in provisioned elasmobranch populations is common (e.g. Brunnschweiler and Baensch 2011; Clarke *et al.* 2011; Maljković and Côté 2011; Clarke *et al.* 2013; Corcoran *et al.* 2013; Brunnschweiler *et al.* 2014; Rizzari *et al.* 2017; Vaudo *et al.* 2018). Yet, there has been limited research into the potential implications of this, and the reasons are not yet clear. Adult females in breeding condition may seek to supplement their diets with provisioned foods to assist in meeting the increased energetic demands of reproduction (Wearmouth and Sims 2008). Alternatively, provisioning may simply occur in locations that are already used by these individuals for some purpose (e.g. gestation sites), and the animals make use of the additional resources as they come available (Clarke *et al.* 2011; Hammerschlag *et al.* 2012; Sulikowski *et al.* 2016). Female smooth stingrays are also larger than males and may competitively exclude them from these provisioning sites, as has been suggested for provisioned southern stingrays (*H. americanus*) at Stingray City in the Caymans Islands (Semeniuk and Rothley 2008; Corcoran *et al.* 2013; Vaudo *et al.* 2018). This could induce higher stress or affect energy reserves for females who are exerting extra energy to defend provisioned resources (Pini-Fitzsimmons *et al.* 2021). Nonetheless, any activity that affects only a subset of a population, such as one sex or reproductive stage, has the potential to disrupt population dynamics (Semeniuk *et al.* 2009; Clarke *et al.* 2011). Future research should focus on quantifying the use of provisioning sites by female elasmobranchs, particularly those in breeding condition, compared with non-provisioned populations, to determine how provisioned foods are integrated into and affect their reproductive success and energetic demands (Hammerschlag *et al.* 2012; Mourier *et al.* 2021), with foresight to evaluating impacts to population dynamics more broadly. Specifically for smooth stingrays, there is a need for improved understanding of reproductive behaviour, which remains a significant knowledge gap (Rigby *et al.* 2021).

Given that stingrays in this study were tagged at the provisioning site and no non-provisioned stingrays were tracked for comparison, it is possible that we have sampled only individuals that have a propensity for (1) utilising provisioned resources, (2) using the area around the boat ramp more generally, or (3) being more active in the afternoons. Indeed, elasmobranchs have been shown to form specific individual preferences with provisioning sites. For example, Martin *et al.* (2019) found a surprising level of individual variation in terms of association with piers where fishing waste is discarded by blacktip sharks (*Carcharhinus limbatus*). Without tagging individuals from

non-provisioning sites in the present study, it is difficult to account for such individualistic differences in behaviour or whether the creek is used by other individuals that do not use the provisioning site. However, our long-term monitoring of the smooth stingray population in this region indicates that all individuals sighted in the creek regularly visit the Woollamia Regional Boat Ramp provisioning site and preliminary tracking data in a concurrent study indicate that there is little overlap in the use of Currambene Creek by smooth stingrays tagged at other provisioning and non-provisioning sites nearby (Pini-Fitzsimmons, unpubl. data). Future research should look to expand this work over a broader spatio-temporal context and include the tracking on non-provisioned smooth stingrays to clarify whether individual preferences play a role in accessing provisioned resources.

Although the present study was limited in temporal and spatial scope, we have shown that the tagged smooth stingrays develop strong associations with the location and timing of the provisioning of recreational fishing discards, and therefore it is reasonable to suggest that these stingrays may be experiencing negative impacts (e.g. changes in behaviour and population dynamics, as detailed above). However, there is evidence that although food provisioning may cause short-term behavioural changes for some species, it may not drive their long-term movements (Laroche *et al.* 2007; Brunnschweiler and Barnett 2013; Huveneers *et al.* 2013; see also Trave *et al.* 2017). Given that smooth stingrays are common scavengers of recreational fishery discards throughout their range (J. Pini-Fitzsimmons, pers. obs.; H. Cadwallader, pers. obs.; C. Elston, pers. obs.), it is important that there is continued research into the role that recreational fishery discards play in the behavioural ecology of smooth stingrays and other animals, to facilitate the effective implementation of management plans.

Supplementary material

Supplementary material is available online.

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