Common Bottlenose Dolphin Associations with a Fish Farm in Hawai‘i: Long-Term Associations and Impacts on Other Delphinids

Annette E. Harnish[1], Robin W. Baird[1], Enrico Corsi[1], Antoinette M. Gorgone[1], Doug Perrine[2], Alicia Ward[3], and Emily Sepeta[4]

[1]Cascadia Research Collective, 218-1/2 W 4th Ave., Olympia, WA 98501
(email: aharnish@cascadiaresearch.org)
[2]76-223 Haoa St., Kailua-Kona, HI, 96740
[3]73-4328 Ka Mua Place, Kailua-Kona, HI 96740
[4]West Hawai‘i Explorations Academy, 73-4460 Queen Ka‘ahumanu Hwy #105,
Kailua-Kona, HI, 96740

Abstract

The global expansion of mariculture offers numerous potential benefits, but may also pose a threat to wildlife populations that are attracted to or repelled by mariculture installations. A fish farm that is operated near shore off the west coast of Hawai‘i Island produces kanpachi (*Seriola rivoliana*), and sits within the known range of several resident species of odontocetes. Almost daily common bottlenose dolphin (*Tursiops truncatus*) associations with the kanpachi farm have been reported by farm staff, but little information is available regarding the extent or long-term impacts of these associations. We analyzed photos from 20 encounters that occurred between 2007 and 2019 at the farm in the context of over 250 encounters off Hawai‘i Island from between 1987 and 2020. From 67 identifications we identified 28 unique individual bottlenose dolphins that associated with the farm. The rate of discovery of new individuals at the farm is not leveling off. In spite of our limited sample, seventeen of the farm associates were repeatedly sighted at the farm, and six individuals were sighted at or within 5 km of the farm over timespans exceeding ten years. One individual in particular, an adult male with a severe mouthline injury stemming from a fishery interaction, was identified at the farm 10 times, and within 5 km of the farm an additional three times over an 11-year timespan. A crawl model using satellite-tag data from four individuals revealed one individual that may have associated with the farm that was not documented there using photo-identification. Association analyses revealed that farm-associated dolphins are widely distributed throughout the social network, suggesting that the behavior of associating with the farm may continue to spread to other individuals within the population. Bottlenose dolphin aggression involving farm associates towards other species of dolphins (including spinner dolphins (*Stenella longirostris*), pantropical spotted dolphins (*S. attenuata*), and false killer whales (*Pseudorca crassidens*)) appears to be increasing, demonstrating the potential for impacts to multiple protected species. Increased monitoring of bottlenose dolphin associations with the farm and the potential spread of this behavior among the resident dolphin community is needed.

Introduction

Oceanic aquaculture, or mariculture, has grown substantially over the past few decades, driven by increased demand for fish from a global population that is growing in both number and affluence. Mariculture offers numerous potential benefits, including job opportunities, a predictable supply of fish products that offer an alternative to other animal proteins, and reduced pressures on some wild fish stocks (Tacon & Halwart, 2007). However, there are also numerous environmental drawbacks that must be taken into consideration, including potential nutrient loading around farms, increased risk of disease transmission to wild populations, depletion of some wild fish stocks for feed, risk of farmed species escaping into the environment, disruption of benthic communities, and potential impacts to other marine life attracted to or repelled by the farms (Holmer, 2010; Krkošek et al., 2006; Tacon & Halwart, 2007; Würsig & Gailey, 2002). Wildlife can be attracted to or repelled by mariculture installations because of the species being farmed, the presence of physical structure, excess feed and wastes, altered nutrient levels and community structure in the benthos, predator exclusion devices, or the presence of aggregated communities around the installation (Callier et al., 2017; Morton & Symonds, 2002; Würsig & Gailey, 2002).

Mariculture installations around the world have been the focus of intense scrutiny regarding odontocete interactions. Shellfish farming in Shark Bay, Australia has been shown to displace female Indo-pacific bottlenose dolphins (*Tursiops aduncus*), and mussel farms in New Zealand and Chile may be having a similar effect on other odontocete species that forage within or near areas now being used for farming (Kemper et al., 2003; Markowitz et al., 2004; Ribeiro et al., 2007; Watson-Capps & Mann, 2005). In contrast, mussel farming in Galicia, Spain seems to be associated with an increase in the presence of common bottlenose dolphins (*T. truncatus*), rather than a decrease (Díaz López & Methion, 2017).

Generally, finfish farming appears to attract odontocetes rather than displace them. Common bottlenose dolphins in the Gulf of Corinth exhibit a preference for habitat within close proximity of fish farms, and have been shown to opportunistically forage near farm cages (Bearzi et al., 2016; Bonizzoni et al., 2014, Bonizzoni et al., 2019). This is particularly concerning given that some of the Gulf of Corinth farms are located near industrial areas, heightening the levels of risk associated with increased exposure to pollution (Bonizzoni et al., 2014). An ecosystem model of the inner Ionian Sea showed that the expansion of mariculture in the region had led to increases in the number of bottlenose dolphins observed in the area, which were presumably taking advantage of comparatively large associated populations of wild fish surrounding the farm (Piroddi et al., 2011). Additionally, the expansion of a fish farm in the Gulf of Olbia off Sardinia is thought to have contributed to significant increases in bottlenose dolphin sighting rates in the area, and further investigation revealed that several individuals were repeatedly visiting the farm (Díaz López et al., 2005; Díaz López & Bernal Shirai 2007). Continued work at the Gulf of Olbia farm has shown that over the course of nine years of study, dolphin interactions at the farm have increased, and a few individuals have shown high site fidelity to the farm (Díaz López, 2017). Interestingly, an examination of Chilean dolphin (*Cephalorhynchus eutropia*) presence relative to the placement of salmon farms in Chile revealed that farm presence did not seem to impact either movements or habitat use, though the authors suggest that this may be due to either a lack of aggregated fish outside the cages or the fact that the farms sit outside the dolphins' known preferred habitat (Ribeiro et al., 2007).

Fish farms are also known to impact the behavior of odontocetes in potentially detrimental ways. Differences in behavior and social structure among associated bottlenose dolphins were noted at the farm in the Gulf of Olbia; dolphins used unique feeding strategies to capture fish from the farm, and social associations between animals were weaker when dolphins were feeding at versus off the farm (Díaz López 2006; Díaz López & Bernal Shirai 2008). Attraction to fish farms can also have fatal results; multiple odontocete entanglements in anti-predator netting have been reported at finfish farms in Australia, Tasmania, Chile, and Italy (Kemper et al., 2003; Kemper & Gibbs, 2001; Díaz López & Bernal Shirai 2007; Espinosa-Miranda et al., 2020). In Australia, stomach content analyses of entangled dolphins from tuna feedlots showed that they had likely been feeding on associated wild fish populations that may have attracted them to the area (Kemper & Gibbs, 2001).

There are limited finfish mariculture operations in Hawai‘i at present. Blue Ocean Mariculture currently operates a fish farm off the west coast of Hawai‘i Island that produces kanpachi (*Seriola rivoliana*), also known as kampachi, kahala, Almaco Jack or Hawaiian yellowtail, and has the capacity to produce over 400,000 kg of fish/year, using anchored cages that can be raised or lowered within the water column (NOAA Office of Aquaculture, 2019; Seafood Watch, 2020). The farm was originally established by Kona Blue Water Farms in 2005, which dissolved in 2011 shortly after Blue Ocean acquired the lease for the farm (Wright, 2011). The site is ~750 m offshore of Makako Bay, and is positioned above a bare sandy bottom in ~ 60 m depth with an adjacent stretch of coral reef just south of Unualoha Point. The farm sits within the known range of endangered Hawaiian monk seals (*Neomonachus schauinslandi*), as well as resident populations of four different species of odontocetes: endangered main Hawaiian Islands insular false killer whales (*Pseudorca crassidens*), spinner dolphins (*Stenella longirostris*), pantropical spotted dolphins (*S. attenuata*), and common bottlenose dolphins (hereafter “bottlenose dolphins”). Makako Bay is known as a traditional resting area for spinner dolphins (Tyne et al., 2018), and pantropical spotted dolphins sometimes join spinner dolphins in these resting bays. False killer whales from the endangered main Hawaiian Islands population have also been documented near the farm (CRC unpublished), but bottlenose dolphins, in particular, have been regularly documented in close association with the farm since around October 2006 (Sims, 2013).

Kona Blue was troubled by accusations and documented instances of detrimental wildlife interactions, including provisioning and “take” of bottlenose dolphins, the killing of a tiger shark (*Galeocerdo cuvier*) that had been frequenting the farm in 2005 (in response to which the company established a shark management plan with Hawai‘i State Division of Aquatic Resources), and a major fish escape caused by a Galapagos shark (*Carcharhinus galapagensis*) that bit through a net in 2009 (Baird, 2016; Food & Water Watch, 2010; Seafood Watch, 2020; Sims, 2013). Blue Ocean has taken steps to reduce predator interactions with the farm, including the use of predator-resistant netting materials and the prompt removal of dead fish, and has stated that they avoid the use of any proactive predator deterrents (Blue Ocean Mariculture, personal communication September 2018 as cited in Seafood Watch, 2020). They also required to engage with state and federal management agencies to ensure the sustainability of their farm operations, and have publicly stated that minimizing impacts to the environment surrounding the farm is a priority in their operation (Blue Ocean Mariculture, 2021). However, between 2011 and 2017, wildlife interactions were still the determined cause of 46% of fish escape events, and in 2017 a Hawaiian monk seal was found dead in one of the net pens, indicating that wildlife interactions with the farm remain an ongoing concern in spite of their best efforts (Carretta et al., 2020; Seafood Watch, 2020). In publicly available and easily accessed wildlife monitoring reports from

2016-2020, Blue Ocean has disclosed that the farm is visited regularly by Hawaiian monk seals, and visited on an almost daily basis by bottlenose dolphins (Blue Ocean Mariculture 2016, 2017, 2018, 2019, 2020).

Bottlenose dolphins off Hawai‘i Island have been recognized as a discrete stock, with high levels of site fidelity and genetic differentiation from other populations in the Hawaiian Islands, making it vulnerable to localized threats (Baird et al., 2009; Martien et al., 2011). A recent study showed that the abundance of this stock appears to be relatively stable, although there is considerable uncertainty associated with the abundance estimates (Van Cise et al., 2021). In 2013, a case study of the farm by then Kona Blue CEO Neil Sims stated that while groups of bottlenose were regularly present, only a single dolphin, identified by a fishhook and line caught in its jaw, had taken up permanent residence at the farm and was regularly spotted between 2009 and 2010. According to Sims (2013), this animal first showed up at the farm in poor body condition, though it gradually recovered over the course of its stay at the farm, presumably as a result of feeding on the additional aggregated fish species that were present outside of the cages. This individual's repeated presence at the farm was again noted in a 2011 undergraduate thesis examining bottlenose interactions with the farm over the course of 17 survey days (Woodward, 2011). The comparative distinctiveness of this animal likely contributed to its regular identification, as did its reported permanent residency at the cages, but little information is available regarding whether other less-distinctive individuals have also repeatedly associated with the farm.

Cascadia Research Collective (CRC) has been conducting a long-term study of the population structure, ecology, and movements of odontocetes in Hawaiian waters since 2000, and first began working off Hawai‘i Island in 2002, including extensive work with bottlenose dolphins. During this time, CRC has taken over 39,000 photographs of bottlenose dolphins off Hawai‘i Island from 127 encounters, collected 55 biopsy samples, and deployed four satellite tags onto individuals encountered off Hawai‘i Island. In addition to CRC's directed efforts, photos or video from 130 encounters have been obtained by other individuals working on the water off the island and have been contributed to CRC's bottlenose dolphin photo-identification catalog. This longstanding effort has allowed for characterization of the population of bottlenose dolphins off the island, as well as the ability to evaluate the relative impacts of associations with the fish farm. We analyzed 36 encounters that occurred at or within close proximity of the Makako Bay kanpachi farm between 2007 and 2020, and explored the broader social implications of farm associations using social networks. We describe long-lasting associations with the farm, including an over 11-year regular association of an adult male bottlenose dolphin. We also describe several instances of aggressive inter-species interactions between bottlenose dolphins and other odontocetes at or near the fish farm, a behavior that appears to be increasing in frequency, and an aggressive interaction between a bottlenose dolphin and an unidentified species of shark. The wide distribution of farm associates throughout the social network, combined with evidence of fisheries interactions and the repeated occurrence of documented aggressive inter-species interactions at the farm suggests that long-term association of bottlenose dolphins with the farm is contributing to novel behavioral patterns and interactions that may have detrimental impacts on populations of multiple species.

Methods

CRC undertook surveys off the island of Hawaiʻi every year from 2002 through 2019, with from 17 to 65 survey days per year (median=36.5 days). Survey efforts were focused on multiple species and attempted to cover as broad an area as possible along the west side of the island and far offshore (Baird et al., 2013), weather conditions permitting, with only limited time spent in typical bottlenose dolphin habitat (i.e., <500 m bathymetric depth) and with only occasional passes by the location of the Makako Bay farm. In addition to CRC survey efforts, photos and video of bottlenose dolphins were contributed from community scientists, including both above- and below-water images. Photos from CRC surveys through April 2019, and the majority of community-scientist contributed photos available through 2019, were included in these analyses. A small number of community scientist photos from 2020 were also included for encounters of bottlenose dolphins involved in aggressive interactions towards other species – additional photos available from 2020 have not yet been matched to our catalog. Encounters involving aggressive inter-specific interactions were detailed based on analysis of video footage or notes provided by observers.

In accordance with standard CRC protocols, all photographs were first sorted by individuals within encounters, then matched to a long-term catalog of all individuals encountered off Hawaiʻi Island (Baird et al., 2009). Encounters at or within close proximity (i.e., within 5 km) of the farm were identified based on GPS coordinates, provided sighting details, or presence of the cages in photographs. Photo quality scores from 1-4 were assigned for each individual within an encounter based on the best photograph available following the protocols of Baird et al. (2009), with PQ = 1 for poor, PQ = 2 for fair, PQ = 3 for good, and PQ = 4 for excellent photographs. Distinctiveness scores from 1-4 were assigned based on the number of dorsal fin notches and the presence of permanent scarring following the protocols of Baird et al. (2009), with Dist = 1 not distinctive, Dist = 2 slightly distinctive, Dist = 3 distinctive, and Dist = 4 very distinctive. Sexes of some individuals were determined based on genetic analysis of biopsy samples (undertaken by the Southwest Fisheries Science Center), by documentation with a calf in close attendance at any point in an animal's sighting history, or by morphology (e.g., presence of mammary slits or visible penis).

Group sizes were not always provided for contributor encounters, so group size estimates were based on CRC encounters. We tested whether group sizes differed by encounter location (at farm, < 5 km, or > 5 km) with a Kruskal-Wallis ranked sums test, as group sizes were not normally distributed and encounter locations have radically different sample sizes. We also explored an alternative approach where we compared the number of unique individuals identified through photo-identification in both CRC and contributed encounters to take advantage of the entire dataset, and conducted a second Kruskal-Wallis ranked sums test in conjunction with Dunn's test.

Individuals encountered together in the same group were considered associated. Association data of all animals sighted off Hawaiʻi Island were processed in SOCPROG 2.9 (Whitehead, 2009) using a half-weight index to generate a social network (Whitehead & James, 2015). The association data processed by SOCPROG 2.9 was then imported into Gephi 0.9.2 (Bastian et al., 2009) in order to calculate network metrics and generate social network graphs.

We calculated the number of associates for each node in the network, also known as degree (Croft, Krause & James, 2004). A social network graph was generated, with node size increasing with degree, and color representing the span and number of times an individual was documented at the fish farm. To reduce the inclusion of mismatches and missed matches, all encounters with PQ = 1 or Dist = 1 were removed from the network. Individuals only sighted once were also removed from the network.

Satellite tags were deployed on four bottlenose dolphins off Hawai‘i Island, following protocols that have been described elsewhere (Schorr et al., 2009). All tags were deployed after the farm was established. Location data from satellite tag deployments were processed through the Kalman smoothing algorithm (Lopez et al., 2015) and subsequently filtered through the Distance, Angle, Rate filter of the Douglas-Argos filter (Douglas et al., 2012) accessed through Movebank, to remove erroneous locations (Kranstauber et al., 2011). User-defined filter settings were specified as follows: maximum sustainable rate of movement (MINRATE) was set to 20 km/h; maximum distance between consecutive locations (MAXREDUN) was set to 3 km; the tolerance level for turning angles (RATECOEF) was set to 25; and positions with a location quality class of 2 or 3 were exempt from filtering (KEEPLC).

Resultant locations were then fit to a continuous-time correlated random walk model using the package crawl v2.2.3 (Johnson et al. 2008; Johnson & London, 2018) in the program R v4.0.2 (R Core Team, 2020) and predicted at 30-minute intervals. As a result of the nature of near-shore movements of bottlenose dolphins around Hawai‘i Island, Argos locations transmitted on land were common among all deployments. Therefore, the fix_path function within the crawl package (Johnsen et al. 2008; Johnson & London, 2018) was used to re-route predicted segments around land, with the barrier buffer set to 200 m. Briefly, the function designates a polygon of the island as restricted area, identifies segments of trajectories that intersect with the restricted area, and generates new segments around the restricted area using model-fitted parameters. Distances of 30-minute time step positions from the fish farm were calculated using the function st_distance within the package sf v0.9.5 (Pebesma, 2018).

Results

Twenty bottlenose dolphin encounters were documented at the Makako Bay kanpachi farm between 2007 and 2019, and an additional 16 took place within 5 km of the farm, out of 257 total encounters with bottlenose dolphins off Hawai‘i Island. From the 20 encounters there were 67 identifications (i.e., not accounting for re-sightings) of bottlenose dolphins. From those, 28 unique individuals were identified, 17 (60.7%) of which were seen at the farm on more than one occasion (Table 1). A discovery curve of identifications at the farm showed that the number of individuals identified is continuing to rise over time (Figure 1). Sixteen of the 28 individuals identified at the farm had additional sightings within 5 km of the farm, and an additional 37 individuals were identified within 5 km of the farm. The distribution of the number of encounters at the farm, and the span of years spent at the farm are right-skewed (Figure 2), but when viewed as proportions of the total number of encounters and the total span of years that an animal has been documented (including encounters > 5 km from the farm) the distributions shift slightly towards the right (Figure 2).

The 28 individuals identified at the farm included five individuals (17.9%) that were slightly distinctive, nine (32.1%) that were distinctive, and 14 (50.0%) that were very distinctive. Of the 37 additional individuals encountered within 5 km of the farm there were nine individuals (24.3%) that were not distinctive, eight (21.6%) that were slightly distinctive, five (13.5%) that were distinctive, and 15 (40.5%) that were very distinctive. For the 28 farm associates, the mean number of times that individuals were sighted at the farm was 2.4 (min = 1, max = 10, median = 2), and the mean number of additional times sighted within 5 km of the farm was 1.3 (min = 0, max = 4, median = 1). The number of encounters at the farm varied by distinctiveness, though results were heavily biased for Dist = 2 in particular because of the influence of a single individual of Dist = 2 with ten resightings (mean Dist2 = 3.0, mean Dist3 = 2.3, mean Dist 4 = 2.2). For the additional 37 individuals encountered in close proximity, the mean number of times that individuals were sighted within 5 km of the farm was 1.3 (min = 1, max = 3, median = 1). There was also variation in the number of encounters within 5 km of the farm between the distinctiveness scores (mean Dist1 = 1.0, mean Dist2 = 1.2, mean Dist3 = 1.2, mean Dist4 = 1.5). Of the 28 dolphins identified at the farm, sex was determined for seven individuals, of which two were male (one based on genetic analysis, and one based on morphology) and five were female (three based on calf presence, and two based on genetic analysis; Table 1). Of the 37 dolphins identified within 5 km of the farm sex was determined for eight individuals, three of which were males (all based on genetic analysis), and five were females (two based on genetic analysis, three based on calf presence).

Mean group size for CRC encounters at the farm was 4.3 individuals (n = 4, min = 1, max = 6, median = 5), compared to 10.0 individuals (n = 2, min = 6, max = 14, median = 10) for encounters within 5 km of the farm, and 9.4 individuals (n = 121, min = 1, max = 60, median = 6) for encounters that did not take place at or within 5 km of the farm (Figure 3). Differences in group size were not significant between encounter locations (Kruskal-Wallis test: KW = 1.5049, df = 2, p = 0.4712), although this is likely due to the small number of CRC encounters at the farm. When we expanded the dataset to include contributor encounters, and considered group sizes as the number of unique individuals identified in each encounter, mean group size for encounters at the farm was 3.4 individuals (n = 20 , min = 1, max = 16, median = 2), compared to 5.2 individuals (n = 16, min = 1, max = 12, median = 5) for encounters within 5 km of the farm, and 5.9 individuals (n = 202, min = 1, max = 56, median = 3) for encounters that did not take place at or within 5 km of the farm (Figure 3). Differences in the number of identified individuals per encounter were significant between encounter locations (Kruskal-Wallis test: KW = 6.718, df = 2, p = 0.0347). Post-hoc pairwise comparison using Dunn’s test with the Benjamini-Hochberg method between encounter locations revealed that differences were significant between encounters within 5 km versus at the farm (Dunn’s test p.adjusted = 0.0496), as well as between encounters not at versus those at the farm (Dunn’s test p.adjusted = 0.0334).

During three of the encounters, dolphins were recorded consuming fish that closely resembled kanpachi, though species ID was not confirmed. In one of these encounters, caught on video, an individual dolphin slowly approaches a gate on one of the submerged cages, then suddenly jerks its body closer to the cages, spooking the fish near the netting, and causing them to push against the gate. This action causes the gate to lift slightly and allows a single fish from inside the cage to escape, which was rapidly captured afterwards by a dolphin (Figure 4).

Additionally, a contributor noted that during a fourth encounter dolphins were feeding on what looked like escaped fish, though this behavior was not photographed.

One individual in particular, HITt0201, was sighted 10 times at, and 3 times in close proximity to the farm over an 11-year timespan, and was the most frequent associate of the farm based on number of encounters (Table 1; Table 2). Based on morphology, HITt0201 is an adult male. This individual was most easily identified in 2009-2010 based on the presence of a fish hook covered in barnacles in the right corner of its mouthline (Table 2; Figure 5). Photos taken away from the farm revealed that by 2014, the fishhook had worked its way out of, or was ripped from HITt0201's mouthline, resulting in tissue loss that healed over, leaving behind a gap in the mouthline through which the animal's teeth were visible (Table 2; Figure 5).

The social network reveals that all individuals associated with the farm link to the main component of the Hawaiʻi Island social network (Figure 6). All farm associates were documented associating directly with other individuals that had been documented at the farm (not shown), but the farm associated individuals were spread over a substantial portion of the social network and included extensive connections to non-farm associates (Figure 6).

Aggressive interspecies interactions involving bottlenose dolphins were observed on seven occasions, with evidence of aggression from an eighth occasion, and five of those instances taking place at or within 5 km of the farm (Table 1; Table 2). On three occasions in 2016 (twice in October and once in November) a single dolphin (HITt0201) was filmed attempting to mate with spinner dolphins over 5 km from the farm. In one of the October encounters HITt0201was documented chasing a spinner dolphin[1], and in November 2016 was filmed biting the fluke and peduncle of a spinner dolphin. In the other October 2016 encounter[2] HITt0201 was filmed attempting to mate with a different spinner dolphin. While no overt aggression was filmed during this encounter, the spinner dolphin had severe fresh rake marks on its fluke that were of the appropriate size to have come from a bottlenose dolphin. On 14 February 2018 there was an interaction at the farm between an unidentified species of shark and a bottlenose dolphin (HITt0813) carrying a fish that closely resembled a kanpachi. Video footage showed the dolphin diving from the surface, being approached by the shark, which then rapidly accelerates towards the dolphin and begins to pursue it downwards. The dolphin quickly veers away while the shark continues to dive. On 15 September 2018 a group of six bottlenose dolphins (HITt0201, HITt0630, HITt0812, HITt0814, HITt0894, HITt1748) at the farm rapidly approached a passing mother-calf pair of false killer whales, identified as members of the endangered main Hawaiian Islands population. In this encounter, the dolphins appeared to harass the mother-calf pair, attempting to steal a fish they were carrying, and closely flanking and repeatedly leaping at them for a period in excess of 45 minutes. The false killer whales were visibly agitated during the encounter, and began tail slapping the water at one point. On 18 December 2018 a pair of bottlenose dolphins (HITt0201, HITt0813) were observed interacting with a mother-calf pair of pantropical spotted dolphins at the farm. In this encounter, the bottlenose dolphins separated the spotted dolphin calf from its mother, and briefly chased it. The calf repeatedly leapt from the water, with one of the bottlenose dolphins underwater close behind

[1] https://youtu.be/wWEVFiiPPq4
[2] https://www.youtube.com/watch?v=xrHW3iZ_MDw

it. The encounter ended with the calf and one of the bottlenose dolphins (HITt0813), swimming side-by-side for a while. It is unknown whether the calf was reunited with its mother.

Two additional aggressive interspecies interactions involved spinner dolphins, and took place within 5 km of the farm. On 2 February 2020, a pair of bottlenose dolphins (HITt0201, HITt1748) were photographed in close association with a spinner dolphin. HITt0201 was photographed leaping onto the spinner dolphin in what may have been an attempt to push it underwater, and the spinner dolphin had several open rake marks across its dorsal fin. On 4 August 2020 HITt0201 was again seen interacting with a spinner dolphin. During this encounter, HITt0201 initially gently mouthed the spinner dolphin, but gradually became increasingly aggressive, exposing its penis, and pursuing and biting at the peduncle, pectoral fins, and fluke of the spinner, leaving behind severe open rake marks. Eventually, HITt0201 appeared to be attempting to hold the spinner dolphin underwater by dragging down on its pectoral fins. The spinner dolphin leapt out of the water repeatedly during the encounter, and appeared to be trying to escape. Both of the 2020 encounters ended when the photographers left the scene, and the final outcome for the spinner dolphins in both encounters is unknown.

Based on photo-identification of individuals at the farm, only one previously tagged individual was a known repeat associate of the fish farm, HITt0927 (TtTag021), though HITt0327 (TtTag033) had been spotted twice within 5 km of the farm. TtTag021 was deployed in 2014, prior to HITt0927 being first documented at the farm, while TtTag033 was deployed in 2017, after HITt0327 was first sighted within 5 km of the farm. A crawl model showed that both TtTag021 and TtTag033 had multiple crawl locations within 1km of the fish farm (Figure 7; Table 3). Additionally, the crawl model revealed that the remaining two animals tagged off Hawaiʻi Island also passed within 5 km of the farm, in spite of not having been documented within 5 km of the farm through photo-identification (Figure 7; Table 3). One of these animals, HITt0687 (TtTag011), had 14 crawl locations within 1 km of the farm, and 138 within 5 km of the farm.

Discussion

Bottlenose dolphin associations with the kanpachi farm in Makako Bay have been previously reported, but the true extent and long-term effects of these associations remains unclear. Blue Ocean has reported that associations occur on an almost daily basis, meaning that the potential for cumulative population-level impacts may be significant (Blue Ocean Mariculture 2016, 2017, 2018, 2019, 2020). We examined 36 encounters with bottlenose dolphins that took place at or in close proximity (i.e., within 5km) of the kanpachi farm between 2007 and 2020, and identified 65 unique individuals, 28 of which were documented in association with the farm, and 37 of which were identified within 5 km, suggesting that more than just a few individuals are associating with the farm. Additionally, a discovery curve of identifications at the farm indicates that our sample likely represents only a portion of the total number of individuals that may be associating with the farm (Figure 1). Given the relatively small number of encounters at the farm, this suggests that a relatively large proportion of individuals from the resident population may associate with the farm. Seventeen of the farm associates were repeatedly documented at the farm, and six individuals were sighted either at or within 5 km of the farm over timespans exceeding ten years. One individual in particular

(HITt0201), primarily identifiable by a severe mouthline injury stemming from a fishery interaction, was sighted at or within 5 km of the farm 13 times over an 11-year span.

Individual sighting histories were valuable in assessing the longevity and frequency of interactions with the farm, as well their relative importance. With the exception of one individual that has only been encountered twice, both times at the farm, less than half the sightings of individual dolphins were at the farm (Figure 2), indicating that they were still moving elsewhere. This highlights the importance of sighting data that doesn't come from the farm, because it provides context with which to interpret the farm data itself. Group sizes at the farm were on average less than half those of group sizes away from the farm (Figure 3), although our sample size of CRC encounters at the farm was small. This may be a consequence of the dolphins using novel hunting strategies at the farm that require less group cooperation, or that associating with a fixed food source, rather than ranging widely around the island (Figure 7), increases inter-individual competition, favoring small groups. This finding stands in contrast to Díaz López and Bernal Shirai (2008), who found that dolphins in association with a fish farm off Sardinia had similar group sizes while feeding at versus away from the farm. Further research will be needed to determine whether behavioral differences in feeding strategies at the farm or inter-individual conflict drive different degrees of group cooperation and group size.

Sexes were determined for seven of the 28 individuals that associated with the farm, and for an additional eight individuals spotted within 5 km of the farm on the basis of either genetic analysis, morphology, or calf presence. Among both the farm associates and those individuals encountered within 5 km of the farm, sexes were biased towards females (5 females vs. 2 males at the farm, 5 females vs. 3 males within 5 km of the farm), indicating that females may be more likely to associate with the farm than males. This is in line with previous work on Hawaiian odontocetes, which has shown that females may be more likely to interact with fisheries than males, possibly as a consequence of trying to meet the increased energy demands associated with reproduction (Baird et al., 2015, 2017; Gill et al., 2019; Vanderzee et al., 2019). However, it is also possible that more females were documented at the fish farm because females are more easily recognized by calf presence. This possibility is supported by the fact that restricting sex determination methods to genetic analysis of biopsy samples results in the number of males and females being equal (n = 4 for both). Interestingly, there were no non-distinctive individuals that were documented at the farm, in contrast to almost a quarter (24.3%) of the individuals documented within 5 km of the farm that were considered not distinctive. Given that non-distinctive individuals are usually young, not having had time to acquire markings on the dorsal fin, this suggests that mothers with small calves are not feeding around the farm.

During three of the 20 encounters at the farm, dolphins were recorded feeding on fish that closely resemble kanpachi, and were reported to be feeding on escaped fish in a fourth encounter where this behavior was not photographed. These instances demonstrate that the bottlenose are probably not present to predate on other finfish species attracted to the cages as suggested by Callier et al. (2017) but more likely have consistently returned to the cages because of the kanpachi themselves. Blue Ocean has admitted to regular minor fish escapes (Blue Ocean Mariculture 2020, 2019, 2018, 2017, 2016; Seafood Watch, 2020), and these events may play a role in attracting dolphins to the farm location. In one instance captured on video, a bottlenose dolphin was observed spooking the fish within a net pen, causing them to push against a cage door and allowing one fish to escape (Figure 4). Whether freeing the fish was the dolphin's intention is unclear, but given that they are capable of complex cognition it seems likely. This troublesome behavior shows that at least some of the bottlenose present at the farm may have devised a way to extract fish from the net pens, which may reinforce their associations with the farm. This type of behavior is problematic for the farm as well, which may be losing valuable fish to escapes and stress in these interactions. It is important to note, however, that wild populations of kanpachi also exist in Hawaiʻi, meaning that we cannot prove that all fish consumed by dolphins at the farm are escapees.

One individual in particular, HITt0201 in the CRC long-term bottlenose photo-identification catalog, was identified at the farm 10 times, and within 5 km of the farm an additional 3 times over an 11-year timespan (Table 2). This animal was most easily recognized by the presence of a fish hook caught in the right corner of its mouthline that is evidence of a previous fishery interaction (Figure 4), as its dorsal fin was, and still remains mostly unmarked. In 2009 the Pacific Islands Region Marine Mammal Response Network attempted a removal of the hook, although the attempt was unsuccessful (Bradford & Lyman, 2015). Sims (2013) described this individual's initial time spent at the farm in 2009 and 2010, stating that while the animal was initially lethargic and in poor condition, it gradually improved over its stay as a likely consequence of feeding on aggregated fish populations around the net pens. Woodward (2011) also described this same individual, adding that the animal was observed periodically rubbing the hook caught in its mouth against the net pens. The emphasis that both Sims (2013) and Woodward (2011) place on the fish hook as an identifying feature of HITt0201 has some interesting implications, especially given the relatively unmarked nature of this animal's dorsal fin. HITt0201 was first documented by CRC in May 2003 and is a known Hawaiʻi Island resident with a high resighting rate, so it is possible that the animal visited the farm earlier than 2009, but was not regularly recognizable to farm staff until it was hooked. This could mean that the hooking took place after its initial interactions with the farm, and possibly as a consequence of habituation to human activities stemming from regular farm operations. There is also evidence that this may not be an isolated case; another hooked bottlenose dolphin, identified in the CRC catalog as HITt0682, was partially freed from fishing line by divers in Makako Bay in 2013 (Bradford & Lyman, 2018). While HITt0682 was not among the individuals that we documented at the fish farm, other sources have stated that this individual was known to associate with the farm (Carretta et al., 2020). Additionally, some staff during the farm's early years were reportingly feeding bottlenose dolphins (Baird, 2016), which may have further encouraged some individual animals to not only maintain associations with human activities, but to actively seek them out, as has been suggested at other fish farms where provisioning takes place (Díaz López, 2017). Regardless of the order in which HITt0201's initial association with the farm and hooking took place, the fact remains that this individual has repeatedly been spotted at the farm over a 10-year span (Table 2). Such long-term associations may lead to unknown consequences at a population level, especially if they alter social structures, as has been the case with bottlenose dolphins in other fish farm operations (Díaz López & Bernal Shirai, 2008). Additionally, long-term associations may create patterns of dependency that could have negative impacts if the farm is ever removed.

The social network analysis shows that most of the individuals observed repeatedly at the farm appear to share fairly close connections, but are also widely distributed throughout the network (Figure 6). This suggests that the habit of frequenting the fish farm might be spreading from the original individuals who first engaged in this behavior to their more proximate associates. Common bottlenose dolphins are known to socially share information, with evidence suggesting cultural transmission of behaviors (King & Janik, 2015; Simões-Lopes et al., 2016). Furthermore, similar social diffusions of behaviors have been documented in other taxa, such as primates, which often live in similarly complex social groups (Botting et al., 2018; Dindo et al., 2008). Given that, with the exception of a few one-time frequenters, the vast majority of individuals regularly seen at the fish farm occupy adjacent positions in the social network, there is reason to suspect that the habit of feeding at the aquaculture facility might be gradually spreading to other individuals.

Of the 36 encounters we examined at or near the farm, five included instances of interspecies aggression, all of which took place during the later years of the study (Table 1; Table 2). Over the course of normal field efforts off Hawaiʻi Island, and off the Hawaiian Islands in general, with the exception of killer whales (*Orcinus orca*) attacking other species of dolphins, instances of interspecies aggression involving two species of delphinids have rarely been observed, making the Makako Bay farm and surrounding area a hotspot for these types of interactions. In spite of extensive effort and photographic contributions off the island we had no documented encounters of similar interspecies aggression from any years prior to 2016, indicating a recent increase in the frequency of this type of behavior. The fact that these interactions involved multiple combinations of species indicates that the fish farm may be impacting multiple populations, either directly by altering distributions or indirectly by bringing species into closer proximity to one another for longer periods of time than if the farm were absent. For example, observations (Tyne et al., 2018) and predictive habitat modelling (Thorne et al., 2012) have shown that nearby Makako Bay is an ideal resting habitat for spinner dolphins, who use shallow water areas during the daytime. The presence of the farm likely brought bottlenose dolphins into closer regular association with nearby spinner dolphins than might be expected otherwise, increasing the opportunities for aggressive interspecies interactions to occur. In recent years, there has been a decline in the sighting rates of spinner dolphins in Makako Bay (E. Sepeta, pers. obs.), possibly due to the increased presence of bottlenose dolphins. Additionally, a 2010 telemetry study of sandbar and tiger shark movements in Hawaiʻi found that sandbar sharks (*Carcharhinus plumbeus*) showed site fidelity to a now-removed mariculture installation off Oʻahu, while tiger sharks were transient visitors at the then Kona Blue kanpachi farm (Papastamatiou et al., 2010). The farm may therefore act as an aggregator of multiple predator species, and it is reasonable to hypothesize that the presence of multiple species of predators in a small area where they may be competing for access to the same resources (i.e., escaped kanpachi or aggregated fish populations) could lead to conflict. Similar situations have been documented elsewhere both within and between species where wildlife are regularly provisioned as part of tourist activities (Newsome et al., 2004; Wrangham, 1974). Additionally, as the 2016 encounters between the frequent farm associate HITt0201 and spinner dolphins illustrate, these effects may be spread out beyond just the immediate area surrounding the farm. The frequent occurrence and increasing rate of interspecies aggression in association with the farm is concerning, especially given the endangered or depleted status of some of the species involved (i.e., false killer whales).

Our analysis of data from four satellite tags deployed after the farm was established off Hawai‘i Island provides another layer of evidence that the farm may be attracting bottlenose dolphins, and has some interesting implications. Both the tagged animal identified as a farm associate (HITt0927), and the tagged animal documented within 5 km of the farm (HITt0327) through photo-identification passed within 1 km of the farm while tags were transmitting (Figure 7; Table 3). Additionally, a third tagged animal not photo-identified at or in close proximity to the farm (HITt0687 – TtTag011) passed within 1 km of the farm, and a fourth tagged animal not photo-identified at the farm (HITt0817 – TtTag003) passed within 5 km of the farm. The fact that additional animals are passing within close proximity to it suggests that the number of individuals we photo-identified at the farm is at best a conservative estimate of the total number of individuals associating with it. The tag data also provides a nuanced picture of the amount of time that the four tagged animals spent at the farm relative to the amount of time they spent elsewhere. Interestingly, the percentage of crawl locations within 1 km of the farm represented a small proportion of the total number of locations, and movements were still quite broad (Figure 7). This suggests that associations with the farm are fleeting, echoing Sims' (2013) statement that dolphins spotted at the farm were usually only present for short periods. However, tag data is inherently short-term, and may fail to capture seasonal or long-term temporal variations in individual associations with the farm. Further research will be needed to elucidate how the farm is impacting spatial use.

This study also highlights the value of community science contributions to research efforts in the study of Hawaiian cetaceans. Thirty-two out of the 36 encounters we examined at or within close proximity of the fish farm were contributed to CRC by community members, constituting the vast majority of encounters examined. Several of the contributed encounters also included underwater footage and photographs that allowed us to view bottlenose interactions with the farm from an expanded perspective. Underwater footage provided crucial insights into dolphin behavior around the farm, including into fish consumption and aggressive interspecies interactions. Elsewhere, examination of underwater footage surrounding fish farms in the Mediterranean has also provided high resolution perspectives of behavior not visible from the surface, further highlighting the value of this type of data (Díaz López, 2006).

Conclusion

Blue Ocean's Kona-based kanpachi farm has publicly expressed a strong commitment to sustainability and environmental stewardship (Blue Ocean Mariculture, 2021). Their measures to limit environmental impacts and prevent predator interactions are to be commended, as is their proactive engagement with state and federal management agencies. However, evidence indicates that bottlenose dolphins are frequently interacting with the farm in spite of these measures and are establishing long-term associations with the farm. The consequences of these interactions are unknown at present, both for the Hawai‘i Island bottlenose dolphin population as a whole, as well as for populations of other top predator species that may be impacted. A recent abundance estimate indicated that the Hawai‘i Island stock of bottlenose dolphins appears to be stable (Van Cise et al., 2021), which suggests that the farm isn't currently having an impact at the stock level. However, regardless of the cumulative impact predator/farm interactions should always be minimized, and a precautionary examination of the consequences of interactions is merited. We recommend continued monitoring and public disclosure of bottlenose associations with the farm by both Blue Ocean and objective third party monitoring groups, and open good faith dialogue between the farm management, government, researchers, and conservationists to discuss and collaboratively develop solutions that reduce interactions between bottlenose dolphins and the farm. It is our belief that through working together, we can achieve improved outcomes for both marine mammals and the mariculture industry as a whole.

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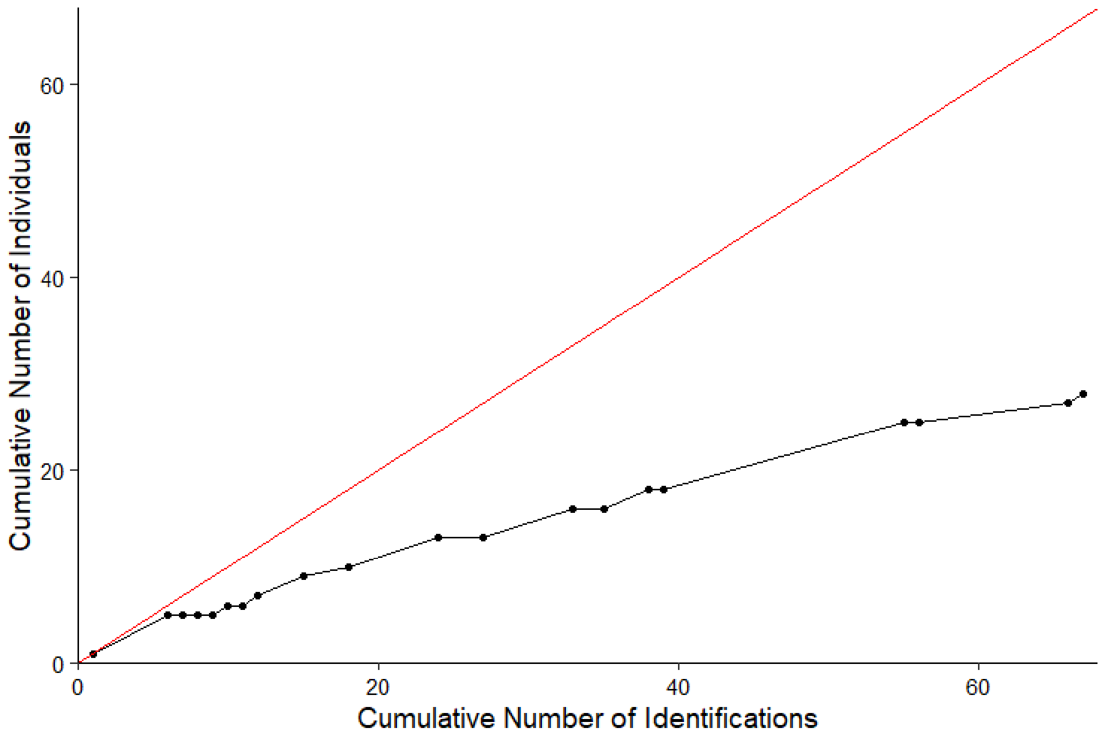

Figure 1: Discovery curve of individuals identified at the farm (black line). Points on the black line represent encounters. A reference 1:1 trendline is shown in red.

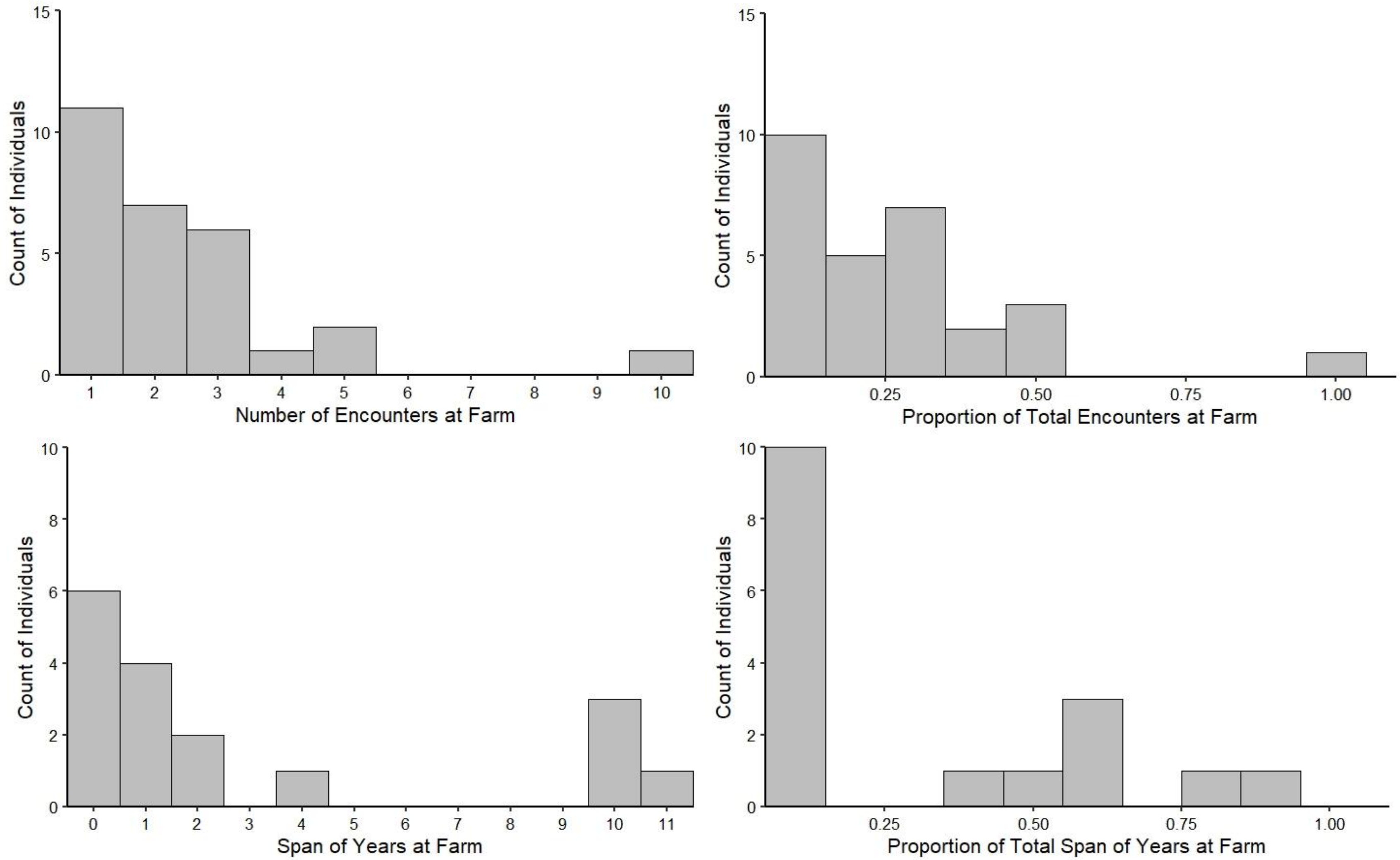

Figure 2: Associations of bottlenose dolphins with the Makako Bay fish farm, including individuals considered slightly distinctive or greater. Top left: number of encounters at the farm for all associates. Top right: proportion of total encounters at the farm for all associates in relation to all sightings of those individuals. Bottom left: span of years at the fish farm for all repeat associates. Bottom right: proportion of the total span of years observed that are at the farm for all repeat associates.

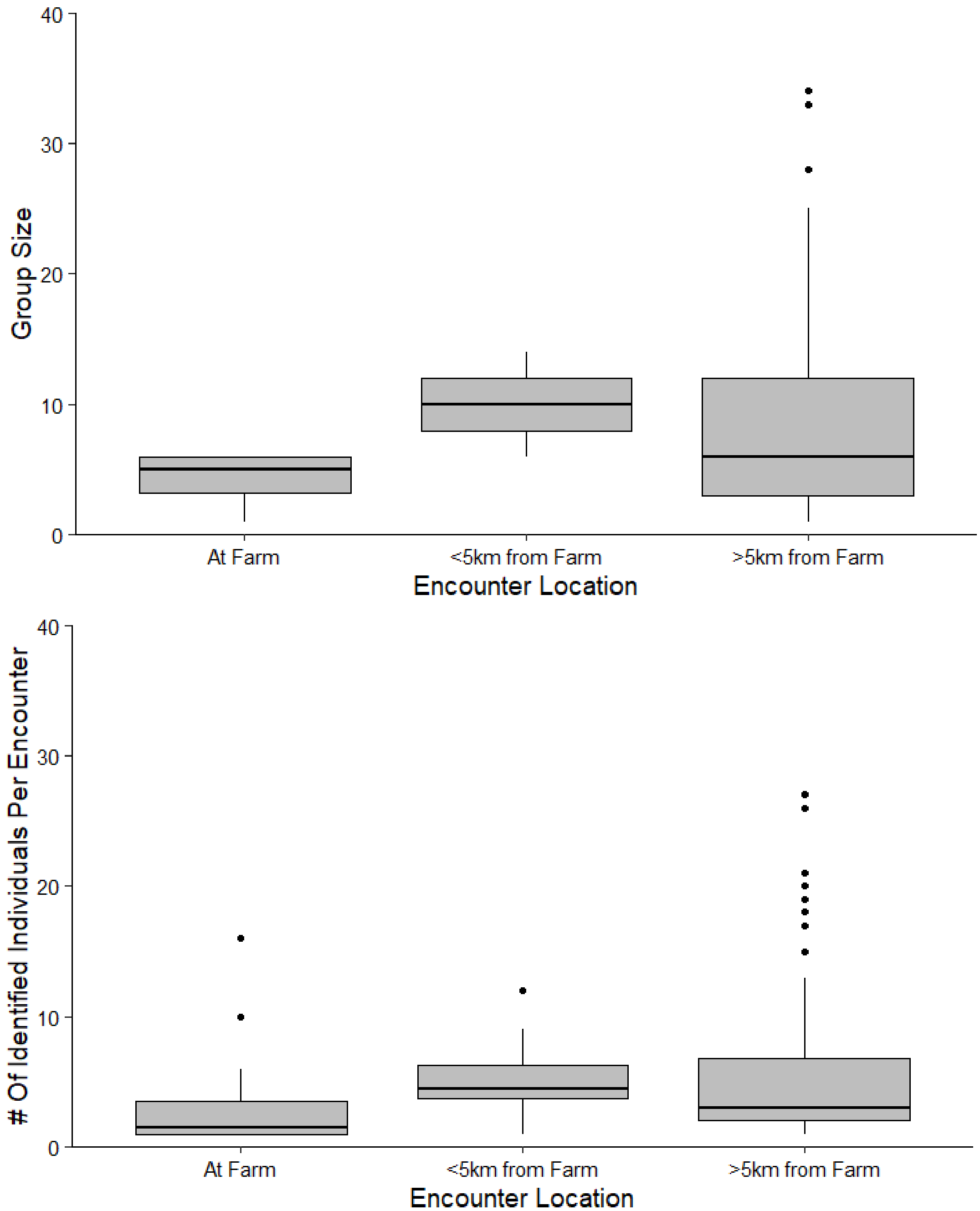

Figure 3: Distribution of group sizes by encounter location. Top: Using best estimates of group sizes from CRC encounters (one outlier was removed from the upper end of the distribution of encounters not at the farm to better highlight differences between groups). Bottom: Using the number of unique individuals identified in each encounter, including contributed encounters (four outliers were removed from the upper end of the distribution of encounters not at the farm to better highlight differences between groups).

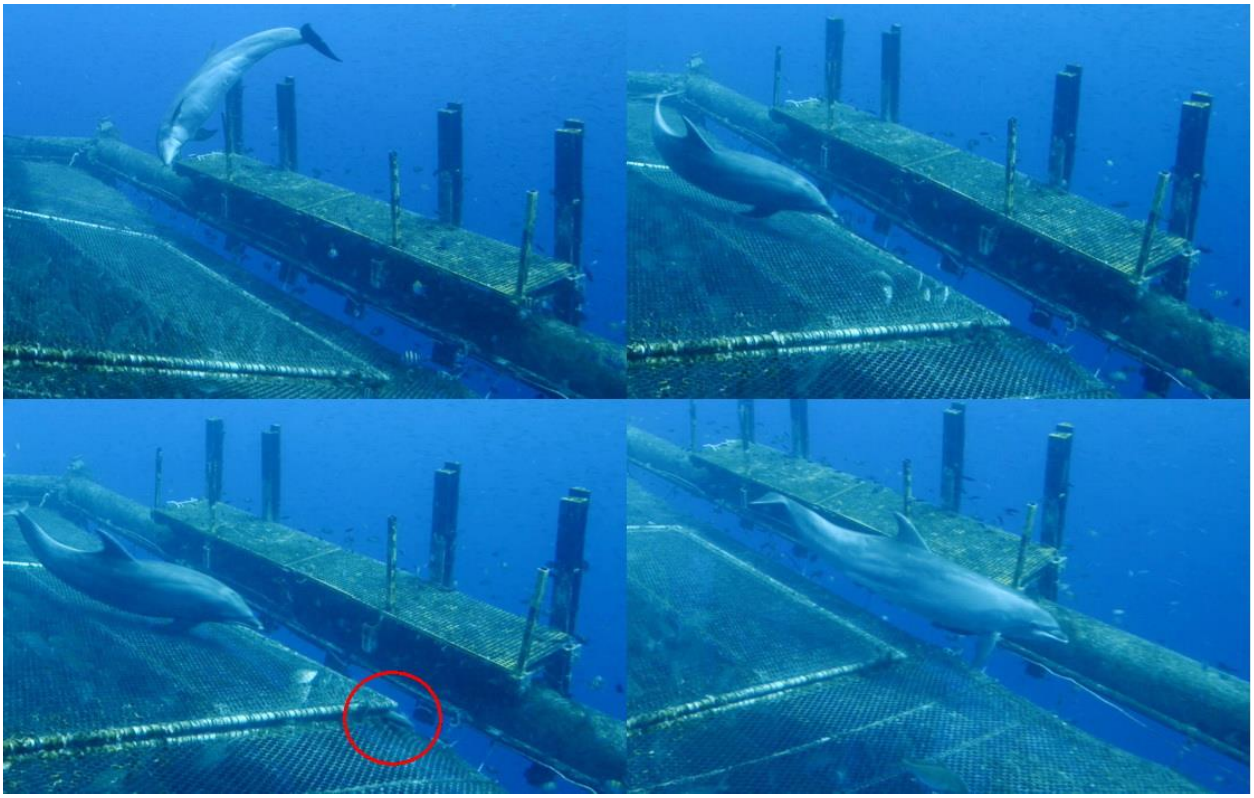

Figure 4: A bottlenose dolphin causes a kanpachi to escape from a cage. Sequentially clockwise from top left: 1) the dolphin slowly approaches the fish cage, 2) the dolphin jerks and twists its body, spooking the fish in the cage and causing them to push upwards on the gate, 3) a kanpachi slips through the gap created by the gate being pushed upwards, 4) the kanpachi is free from the cage, and was consumed shortly by a dolphin shortly afterwards. Stills are from a video taken by Alicia Ward.

Figure 5: HITt0201 with mouthline injury on 5 July 2009, and after the hook detached on 10 November 2018. Photos by Deron Verbeck (left) and Alicia Ward (right).

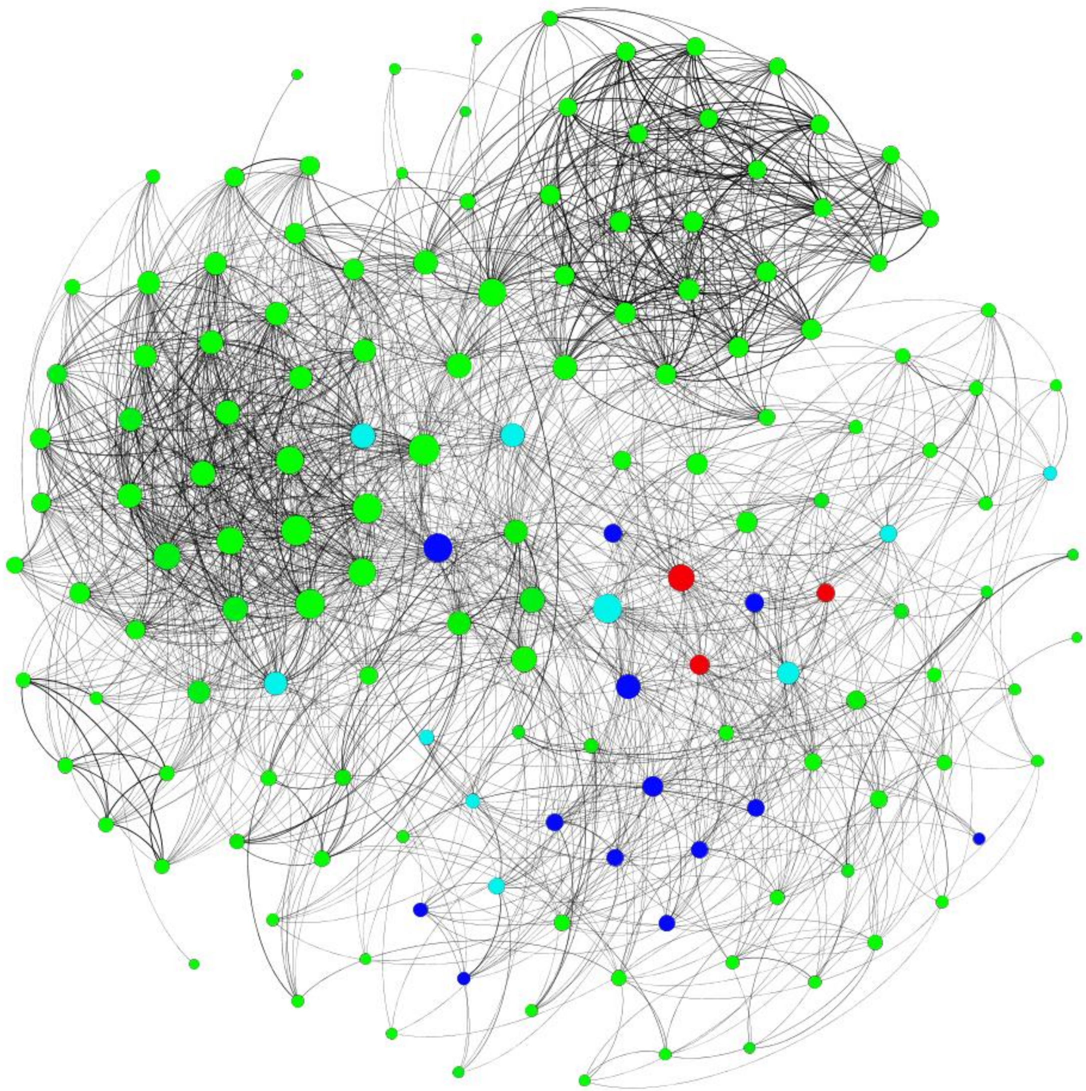

Figure 6: Social network of bottlenose dolphins encountered off Hawaiʻi, restricted to those considered at least slightly distinctive with fair or better quality photos. Node size increases with the number of connections to other nodes, and node color indicates association with the farm (green – not documented at farm; light blue – once at farm; dark blue – repeatedly at farm but <5 years; red – repeatedly at farm for >5 years).

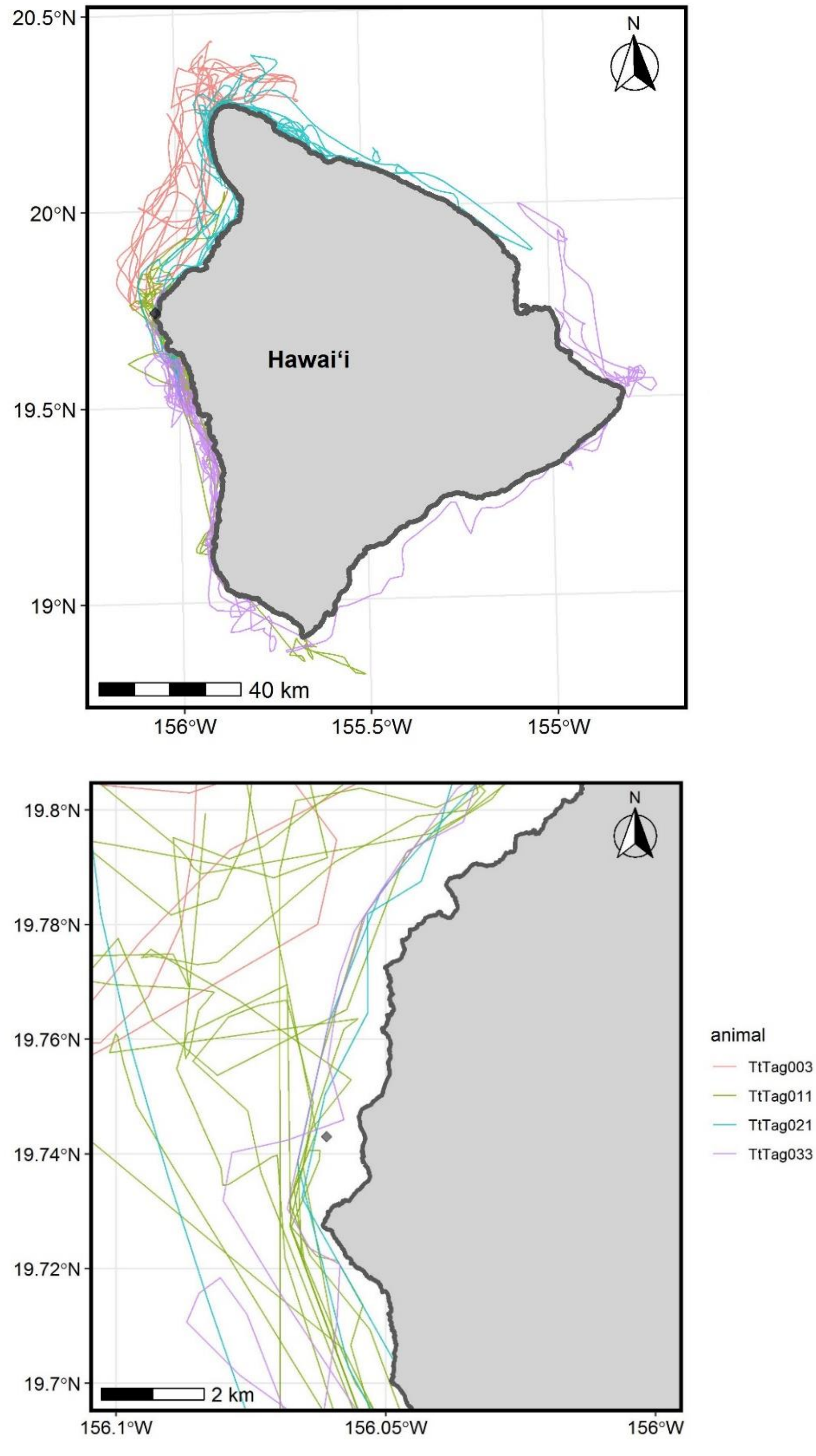

Figure 7: Crawl model results with tracklines colored by tagged animal and the location of the fish farm shown by a black diamond.

Table 1: Sighting histories of 28 individuals associated with the farm, sorted in descending order by the number of encounters at the farm. Sex was determined based on analysis of genetic samples (g), calf presence (c), or morphology (m). Species involved in aggressive interspecies interactions at the farm: unidentified shark (shark), false killer whales (*Pc*), pantropical spotted dolphins (*Sa*), and spinner dolphins (*Sl*). One individual (HITt0927) had been previously satellite tagged (see Table 3).

ID #	High. Dist.	# Encounters			Span of Years			Sex	Aggressive Interspecies Interaction?
		At Farm	< 5km from farm	Total	At Fish Farm	At Fish Farm/ < 5km	Total		
HITt0201	2	10	3	31	10.17	11.09	17.27	M (m)	*Pc*, *Sa*, *Sl*
HITt0812	4	5	4	14	0.60	4.16	6.95		*Pc*
HITt0894	3	5	2	13	0.60	3.85	5.18		*Pc*
HITt0768	3	4	1	12	0.86	3.95	7.16	F (c)	
HITt0150	4	3	0	10	10.44	10.44	16.73		
HITt0159	4	3	1	11	0.20	0.58	17.09		
HITt0501	4	3	2	21	10.62	10.64	12.05	F (g)	
HITt0589	3	3	3	14	10.24	11.20	13.14		
HITt0813	4	3	0	6	3.83	3.83	6.61		shark, *Sa*
HITt0927	4	3	0	9	1.55	1.55	3.55		
HITt0309	4	2	1	17	0.02	0.33	15.32		
HITt0446	4	2	1	10	0.02	3.85	14.93	F (c)	
HITt0585	3	2	3	29	1.55	3.43	17.09	F (g)	
HITt0814	4	2	0	7	0.28	0.28	2.08	F (c)	*Pc*
HITt0819	3	2	1	9	0.58	0.91	6.61		
HITt1748	3	2	4	6	0.06	2.04	2.04		*Pc*, *Sl*
HITt1751	2	2	2	4	0.02	0.04	0.04		
HITt0440	4	1	0	9	0.00	0.00	7.39		
HITt0444	4	1	0	12	0.00	0.00	14.88		
HITt0448	3	1	0	7	0.00	0.00	4.45		
HITt0449	2	1	0	15	0.00	0.00	5.83		
HITt0455	3	1	3	23	0.00	10.47	14.99	M (g)	
HITt0618	4	1	2	15	0.00	0.32	10.38		
HITt0630	2	1	0	8	0.00	0.00	12.49		*Pc*
HITt1357	4	1	0	4	0.00	0.00	2.40		
HITt1518	4	1	0	2	0.00	0.00	0.82		
HITt1749	3	1	0	1	0.00	0.00	0.00		
HITt1750	2	1	3	4	0.00	0.33	0.33		

Table 2: Sighting details of encounters at or within 5 km of the fish farm for HITt0201, an adult male bottlenose dolphin. Other species involved in aggressive interspecies interactions at the farm are false killer whales (*Pc*), pantropical spotted dolphins (*Sa*), and spinner dolphins (*Sl*).

Date	Encounter Source	Mouthline Injury Notes	Aggressive Interspecies Interaction?
5-July-2009	M. Campbell, D. Verbeck	Hook in right corner of mouth	
9-July-2009	M. Campbell, D. Perrine	Hook in right corner of mouth	
17-July-2009	M. Campbell	Hook in right corner of mouth	
21-Feb-2010	D. Perrine	Hook in right corner of mouth	
14-Feb-2018	A. Ward	Healed, teeth visible	
20-May-2018	C. Babbitt, D. Perrine	Healed, teeth visible	
15-Sep-2018	C. Cornforth	Healed, teeth visible	*Pc*
10-Nov-2018	A. Ward	Healed, teeth visible	
18-Dec-2018	E. Sepeta	Mouthline not visible	*Sa*
2-Jan-2019	E. Sepeta	Mouthline not visible	
1-Sep-2019	C. Hankins	Mouthline not visible	
2-Feb-2020	C. Hankins	Mouthline not visible	*Sl*
4-Aug-2020	K. Key	Healed, teeth visible	*Sl*

Table 3: Crawl model results for the four satellite tags deployed off Hawaiʻi Island. Percentages are of the total number of crawl locations, rounded to the nearest tenth of a percent.

Tag	ID #	Date Tagged	# Days Tag Data	# Crawl locations		
				Total	Within 1 km of Farm (%)	Within 5 km of Farm (%)
TtTag003	HITt0817	14-May-2012	15.4	743	0 (0.0%)	6 (0.8%)
TtTag011	HITt0687	22-Oct-2013	17.1	896	14 (1.6%)	138 (15.4%)
TtTag021	HITt0927	26-Nov-2014	19.2	991	2 (0.2%)	11 (1.1%)
TtTag033	HITt0327	15-Jun-2017	30.0	1504	4 (0.3%)	26 (1.7%)