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The effects of aquaculture on bottlenose dolphin (*Tursiops* sp.) ranging in Shark Bay, Western Australia

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Abstract

The increasing presence of aquaculture in coastal waters calls for a better understanding of its environmental effects. Currently little information is available on the impact of shellfish farms on cetaceans. Here we compare long-term ranging patterns of adult female bottlenose dolphins (*Tursiops* sp. in Shark Bay, Western Australia) before and during full-scale pearl oyster farming operations, to determine if they were displaced. When the exact location of the oyster farm was determined, the dolphins decreased their use of that area after the farm was in place. Tracks of adult female dolphin movement near the oyster farm were compared to tracks of dolphin movement near an ecologically similar area where no oyster farm existed. Tracks near the oyster farm were less likely to enter the oyster farm itself than tracks near an ecologically similar location. This suggests that shellfish aquaculture could have a large impact on small cetaceans. The analytical techniques discussed apply broadly to aquatic and terrestrial animals.

Keywords: Ranging; Displacement; Aquaculture; *Tursiops* sp.; Oyster farm

1. Introduction

Aquaculture, the farming of finfish or shellfish, has grown 11% in the last decade, becoming the fastest growing industry in the world food economy (Newton, 2000). Aquaculture has the potential to reduce the amount of fish and shellfish taken from the ocean and to bring substantial income to an area; it produced 37.8 million metric tons of fish and shellfish and $55.7 billion USD in 2002 (Food and Agriculture Organization of the United Nations, 2003). However, farming of carnivorous fish that require food from the ocean still results in a net take of wild stocks (Naylor et al., 2000). Furthermore, if finfish or shellfish are farmed in a natural marine environment, concern arises over the effects of increased biodeposition from fecal and pseudofecal matter, introduction of new species, genetic mingling of wild and captive stock, antibiotics and medicines, as well as competition with, displacement of and interaction with other fauna (Fleming, 1994; Buschmann et al., 1996; Würsig and Gailey, 2002). The described impacts of shellfish farming primarily involve competition with local bivalves, deposition of organic matter, altered benthic communities, and introduction of exotic species (Mirto et al., 2000; Naylor et al., 2000, 2001; Henderson et al., 2001; La Rosa et al., 2001).

Potential impacts on marine mammals as a result of aquaculture interaction include death or injury through entanglement in gear, displacement, altered food chain, disruption of migration pathways (for large cetaceans), and human intervention (marine mammals killed or relocated). Most of the literature to date has focused on otters and pinnipeds that prey on finfish and some

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shellfish, but there is a paucity of information on cetaceans and aquaculture (reviewed in Würsig and Gailey, 2002; Kemper et al., 2003). Unlike pinnipeds, cetaceans have not been reported to consume fish or shellfish out of farms, but have been known to get entangled in equipment, resulting in the damage of gear, release of fish, and self injury (Dans et al., 1997; Kemper and Gibbs, 2001; Crespo and Hall, 2002; Hall and Donovan, 2002). Displacement of cetaceans by aquaculture may also occur because they frequently share the same coastal habitat (Crespo and Hall, 2002; Würsig and Gailey, 2002; Markowitz et al., 2004).

Unlike finfish farms that are netted at the periphery, shellfish farms typically have open areas that are large enough to allow small cetaceans to swim through the farm. Nevertheless, cetaceans may still avoid shellfish farms because of ropes, equipment, human activities, water clarity, prey availability, or other habitat factors. In the last few years, several reports to management agencies (Mann and Janik, in litt.; Slooten et al., in litt.; Paton et al., in litt.) have highlighted the potential displacement of dolphins by oyster and mussel farming operations. For example, dusky dolphins (*Lagenorhynchus obscurus*) use a green-lipped mussel (*Perna canaliculus*) farm area less than nearby areas in Marlborough Sounds, New Zealand (Markowitz et al., 2004).

Bottlenose dolphins (*Tursiops* spp.) are appropriate and useful study animals in this case because of their world-wide distribution in tropical and temperate coastal waters. Because of their cosmopolitan distribution, the information gained in our study can be applied to management of shellfish farms world-wide and, because they share valuable coastal habitat with humans, bottlenose dolphins may be particularly affected by aquaculture. Variable coastal habitats may provide niches important for dolphin foraging or as a refuge from predators. For example, dolphins that specialize in habitat-specific foraging strategies (Mann and Sargeant, 2003) may be seriously affected if they are displaced from that area. Resident communities of dolphins are likely to be most affected and displacement could result in a population decline. Furthermore, the pressures of aquaculture on the dolphin population may add to existing anthropogenic pressures, such as boat traffic (see Chilvers et al., 2005 for an example of human impacts on marine mammals in Moreton Bay, Australia).

Even though these data are from only one bottlenose dolphin study site, it is appropriate to extrapolate to other areas. Shark Bay represents one of the longest running and extensive studies on small cetaceans; it is the only site where ranging information prior to a pearl oyster farm is available. Comparisons of Shark Bay to other sites show similar bottlenose dolphin social structure and behavior (Connor et al., 2000). Therefore, our study offers the best available test to date of the effects of an oyster farm on small cetacean ranging.

Marine mammals, including cetaceans, not only attract public interest, but are also protected in Australia under the Environmental Protection and Biological Conservation Act 1999. To manage a growing industry, more information on the effects of aquaculture on cetaceans is needed.

The aim of this paper is to determine if ranging patterns of bottlenose dolphins have been altered by an oyster farm in Shark Bay, Western Australia. To do this we analyzed their movements near the farm before and during its operation. We addressed the following questions: (1) do bottlenose dolphins change their use of an area once farming begins there; (2) do they move away from the farm; and (3) do they move around (but not through) the farm? We also make recommendations for future research and management. The analytical techniques discussed apply broadly to aquatic and terrestrial animals.

Shark Bay was designated in 1991 as a World Heritage Area for its extensive seagrass beds and dugong (*Dugong dugon*) population (United Nations Educational, Scientific, and Cultural Organization, 1991). Although Shark Bay is not a World Heritage Area because of the dolphins that inhabit it, the dolphins are a significant tourist draw to the area; currently four dolphins are hand fed daily and attract more than 100,000 tourists per year (Mann and Kemps, 2003). Feeding is regulated by the Western Australian Department of Conservation and Land Management. These four, and hundreds of other dolphins, have been part of a long-term research project since 1982 and have been continuously studied since 1984 (Connor and Smolker, 1985; Connor et al., 2000).

2. Methods

2.1. Study site

Mann has been researching mother and calf behavioral ecology since 1988, collecting data on 99 calves born to 67 females. Eleven females that regularly used the bay (Red Cliff Bay) where the oyster farm is located were the focus of this analysis. The study area is located off the campground and resort of Monkey Mia (25°47′S, 113°43′E) on the eastern side of Peron Peninsula, which bisects Shark Bay. Red Cliff Bay is adjacent to Monkey Mia, with Whale Bight (also called Hell's Gate) to the north. These two areas represent the core of our 200 km^2 study site.

2.2. Recent history of pearling in Shark Bay

In the late 1980s, a small oyster farm and shark baiting operation designed for tourists was established. In 1993, this operation changed into a full-scale oyster

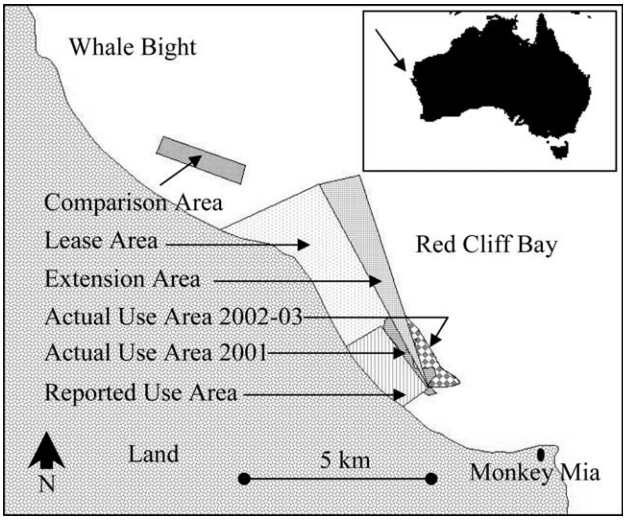

Fig. 1. Schematic of Red Cliff Bay and the different oyster farm areas.

farm able to produce pearls and shell for sale to the public; tours continued on a glass bottom boat but shark baiting ended. The farm in Red Cliff Bay (Fig. 1) operates in a way similar to other pearl oyster farms of its size. The entire oyster farming process lasts approximately eight years before pearls are available for sale. Racks containing *Pinctada albina* and/or *Pinctada margeritifera* are suspended above the seafloor at a relatively shallow depth (2–4 m) by ropes attached to a long line connecting several racks together and marked by buoys. The lines are approximately 300 m long with an oyster rack every 10–20 m and there are approximately 25 parallel lines in the entire farm spread out approximately 75 m from each other. Some racks are placed directly on the seafloor.

The location of the oyster farm ropes in the water changed during the course of our study. In 1988, JM began dolphin research in Shark Bay and a small pearling and shark baiting operation was already present. The farm began full-scale oyster farm operation in 1993 and shark baiting ceased. A wildlife tour boat also started operations from Monkey Mia during that year. In 1998, the oyster farm requested an extension to its lease area and reported the area it was currently using within their lease area; a second wildlife tour boat also began operations out of Monkey Mia that year. The oyster farm operators placed their requested extension in the water illegally during early 1999; it was removed by the Department of Fisheries in September of the same year. In May of 2000, global positioning system (GPS) accuracy was increased through the removal of selective availability (an intentional introduction of error by United States Military on personal GPS units for security reasons). In 2001, 2002, and 2003, we directly recorded the location of the oyster farm's ropes in the water. The 2001 measurement placed the oyster farm east of the area it reported to be using in 1998; this could be explained by the difference in GPS accuracy or a change in datum used between the two times. However, neither explanation can account for the further shift to the east documented between 2001 and 2002; the oyster farm had extended east into deeper water and removed some of its more westward panels. There was no change in location of the oyster farm between 2002 and 2003. Because of these changes, different areas were considered the 'oyster farm' for different analyses depending on which years of data were used (see Table 1).

The oyster farm owners requested an area extension in 1998 to enable them to farm a different species (*P. margeritifera*) in deeper water (Fig. 1). The Western Australian Department of Fisheries solicited information on the potential effects of the extension on the dolphins. In their report to Fisheries, Mann and Janik (in litt.) stated that "the Red Cliff Bay females (all seven combined) use the area with existing oyster lines only

Table 1
List of relevant areas and their descriptions

Name	Area (ha)	Description
Reported use area	221	Portion of the lease area that was reported in 1998 to contain ropes and oyster panels (oyster farm), used to determine if females changed their use of the area after oyster farming began there (1988–1992 vs. 1993–2000) and if females moved away from the area after oyster farming began (1990–1992 vs. 1993–2000)
Extension area	287	Area they applied for to extend the oyster farm into in 1998 and where lines and oysters were placed in 1999, used to determine if females changed their use of the area after oyster farming began there (1988-1998 vs. 1999) and if females moved away from the area after oyster farming began (1992-1998 vs. 1999) or changed their mean distance after it stopped (1999 vs. 2000)
Actual use area 2001	69	Area around the oyster farm as outlined by the authors using a GPS in 2001, used to determine if females moved around rather than through the oyster farm area
Actual use area 2002	94	Area of the oyster farm as outlined by the authors using a GPS in 2002, located about 300 m east of the 2001 area, used to determine if females moved around rather than through the oyster farm area
Actual use area 2003	117	Area of the oyster farm as outlined by the authors using a GPS in 2003, similar to the area in 2002, used to determine if females moved around rather than through the oyster farm area
Comparison area	104	An area in Whale Bight which has similar bathymetric structure and survey coverage but with no oyster farm

0.36% of the time, but used the proposed extension area 10.58% of the time." This was determined using focal follows of adult females that spent most of their time in Red Cliff Bay. Based primarily on this result and concern for how the extension might affect the dolphin tourism industry, the Western Australian Minister for the Environment delayed a decision on the application until more information was available. We were unaware of the illegal extension in 1999 until the Department of Fisheries removed the illegal lines. Subsequently, the extension was denied, but the farm owners were granted a lease area in Herald Bight, 25 km north of Monkey Mia. Furthermore, a pre-existing pearl oyster farm lease area, located in nearby Whale Bight, became active in 2000.

These events provided us with an opportunity to compare ranging of female dolphins that frequently used the area near the oyster farm before, during, and after (in the case of the removal of the extension) a formal operation was in place.

2.3. Data collection and analyses

From 1988 to 2003, with the exception of 1995, surveys were conducted in Red Cliff Bay and surrounding waters in our study area always starting from the Monkey Mia campground (Fig. 1). Surveys did not systematically cover our search area because our primary research focus at the time was to find particular females. The search area changed from year to year and tended to get larger every year (from 1453 ha in 1988 to 13,281 ha in 2000). Because of this change, only data from the smallest search area were used for comparison of distance to the oyster farm, which is why the years used changes slightly in the following analyses. All dolphins seen while searching for a particular focal animal were surveyed. Surveys consisted of approaching the animals in a small (4–5 m) boat and determining individual identification using photographs of their dorsal fins as unique natural markers (Würsig and Würsig, 1977).

The location of the boat while near (within 10–20 m) dolphins was recorded using either compass bearings to prominent landmarks (1988–1994) or a GPS (1996–2003). The compass bearings were converted through triangulation to latitude and longitude using the Locate II computer program (Nams, 1990). This process had an average error $\pm$ SE of 290 ± 49 m (mean distance between GPS measures and points plotted using compass bearings, $n = 32$). The GPS locations were recorded using the WGS84 datum and had a random error of up to 200 m until May 2000, when the error decreased to 30 m. The distances to the reported use area of the oyster farm and the proposed extension area (positions provided by the Department of Fisheries report to Shire of Shark Bay, 1998) were then calculated with ArcView 3.2 using a Universal Transverse Mercator projection 1983, zone 49.

To analyze the change in use of and the movement away from the reported use area and the extension area, we included only females that were sighted at least 10 times during the relevant time periods and had 50% or more of their total sightings in Red Cliff Bay. Only one sighting per day was considered independent because these dolphins were able to transverse their range in this time. For the detailed analysis of tracks, all adult females with focal follow data near the oyster farm were used.

2.3.1. Change in use of an area

We plotted an outline of the oyster farm (reported use area and the extension area) and overlaid independent points for the individual adult female dolphins ($n = 10$ or 11 depending on the time period). Next we calculated the percentage of points inside the area out of all the points for each individual. We then compared the mean percentage of points in the area before, during and after the oyster farm was present. The means were compared using Fisher's paired randomization tests because of the small sample sizes (Jadwiszczak, 2003).

2.3.2. Movement away from the oyster farm

A regression using general estimating equations was employed to compare the average distance from the oyster farm (reported use area and the extension area) between time periods while accounting for variation between individuals, year, month, and time of day (Liang and Zeger, 1986; SAS v8). General estimating equations are used to analyze longitudinal data by accounting for repeated observations which may be correlated. Two different general estimating equation models were run, one comparing distance to the reported use area (before full-scale operation: 1990–1992 vs. during full-scale operation: 1993–2000) and one comparing distance to the illegal extension area (pre-extension: 1992–1998 vs. during extension: 1999 vs. post-extension: 2000). A common search area was needed to compare ranging shifts between time periods. Data from 1988 and 1989 were excluded because our search area was small compared to other years.

2.3.3. Movement around the oyster farm

To examine detailed movement around the oyster farm we used years (2001–2003) when we had confirmed the locations of oyster farming lines (ropes) and when dolphin locations during focal follows were recorded with high accuracy (<30 m error). Any follows that occurred within 2 km of the oyster farm were plotted on a map with an outline of the oyster farm ($n = 17$ females from 36 follows). An ecologically similar area in Whale Bight, the neighboring bay, was also examined for comparison ($n = 10$ females from 16 follows). Because an oyster farm began operation in 2000 in the comparison area, only follows before this time were used there.

For each follow we then calculated the percentage of segments that went into the oyster farm out of the number that had the potential to go into the oyster farm based on their length and the starting point of the segment. A segment is a line between two consecutive GPS points taken 30 min apart. Thirty-minute intervals were chosen because it was the longest time between points. All locations before 2001 were determined every 30 min. Location data collected in 2001 and later were collected every 5, 10, or 15 min. These data were sub-sampled so that only 30 min segments were used in this analysis. We used a Fisher's randomization test (Jadwiszczak, 2003) to compare the mean percentage of segments that went into the oyster farm out of all those that had the potential to do so, compared to the mean percentage of segments that went into the comparison area. Individuals were considered the sampling unit. If more than one follow was observed per individual in a category (oyster farm or comparison area), the mean percentage for that individual was used.

3. Results

3.1. Change in use of an area

Sighting frequency within the reported use area did not differ between before and after full-scale farming occurred ($n = 10$ females, one-tailed, $p = 0.70$; Fig. 2). However there was a significant decrease in sighting frequency in the extension area when oyster lines were put into place compared to before ($n = 11$, one-tailed, $p = 0.04$), and then no change after the lines were removed ($n = 11$, two-tailed, $p = 0.25$; Fig. 2).

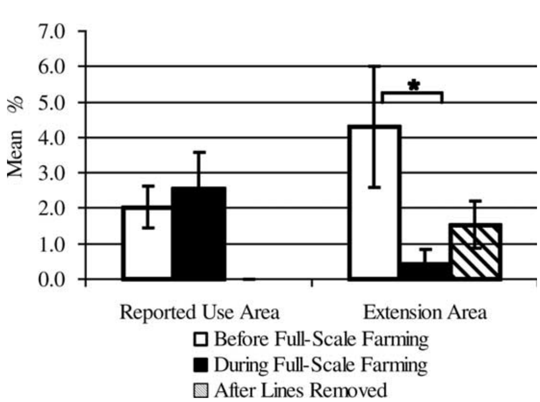

Fig. 2. The mean percentage of observations in two oyster farm areas, the reported use area and the extension area, were compared between different time periods corresponding to changes in farming. $^*p = 0.04$.

3.2. Movement away from the oyster farm

Using a general estimating equation to model the variation between points on the same day and points from the same individuals, we were able to test the difference in distance from the reported use area before and during pearling and from the extension area before, during, and after the oyster lines were present. Adult females did not increase their distance to the reported use area after full-scale farming started (in fact it decreased, mean ± SE pre-oyster farm distance = 1970 ± 39 m, mean during oyster farm distance = 1870 ± 25 m, two-tailed, $z = 2.83$, $p = 0.005$) but they did increase their distance to the extension area after oyster lines were in place (mean pre-extension distance = 1540 ± 23 m, mean during extension distance = 1840 ± 40 m, two-tailed, $z = 3.48$, $p = 0.0005$; Fig. 3). However, we did notice differences in the distance to the reported use area and extension area during many years (Fig. 3). There were also observable differences between months and time of day; these were accounted for in the model.

3.3. Movement around the oyster farm

Adult females appeared to move around the periphery of the confirmed oyster farm rather than inside or

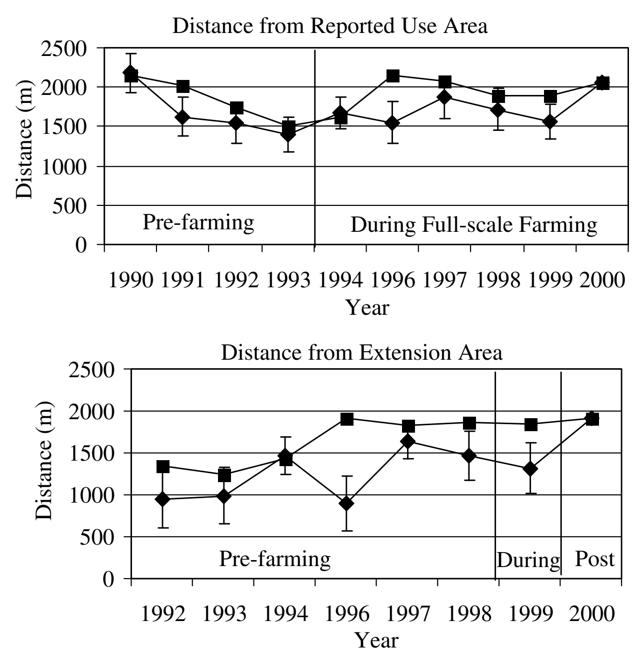

Fig. 3. Squares represent observed mean distances using all of the data. Diamonds represent regressed means accounting for correlated points within individuals, within months and within days; error bars represent two standard deviations except for 2000, which was used as the baseline. Means can be compared horizontally. Two years (1990 and 1991) were excluded from the extension analysis because our search area at the time did not typically include Whale Bight, which we considered important alternative habitat.

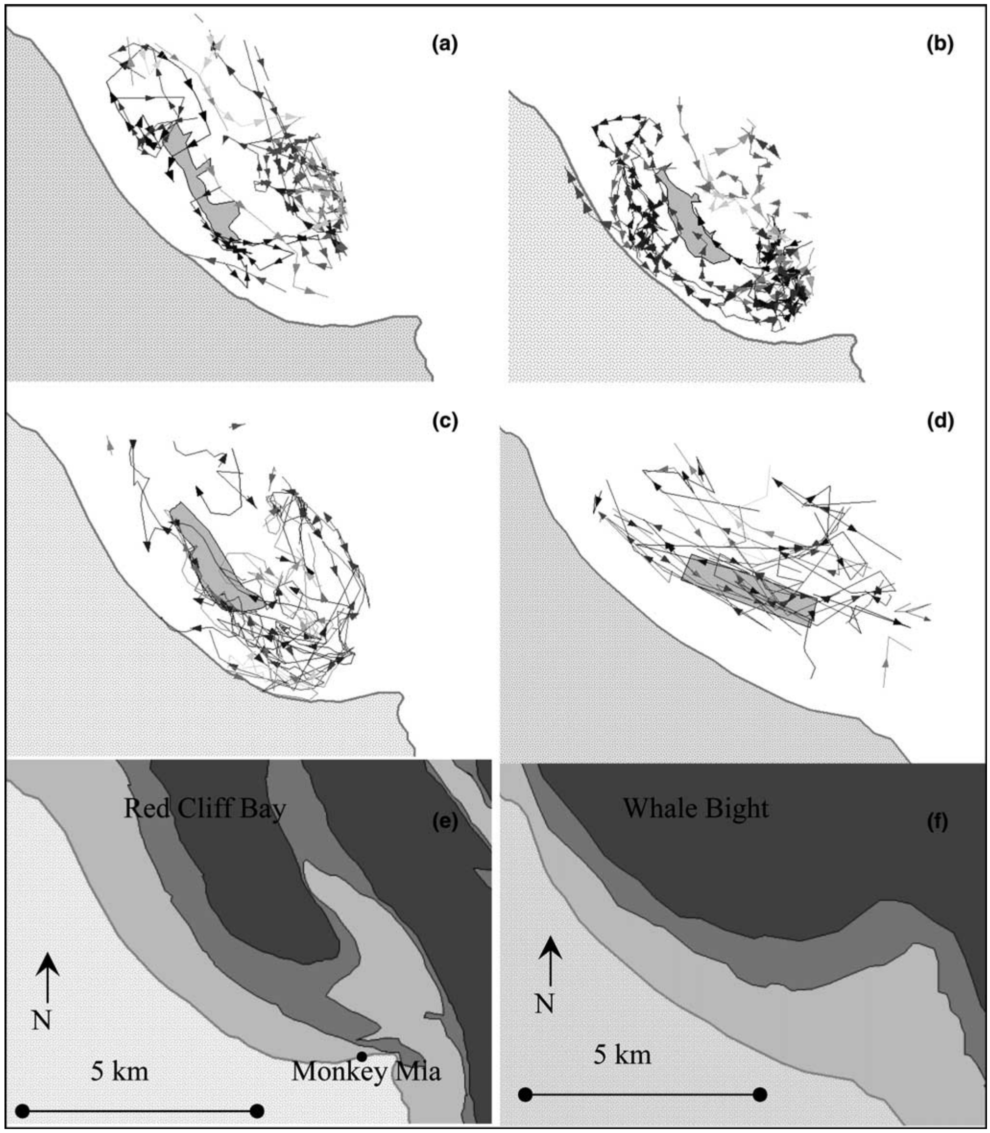

Fig. 4. The actual use areas of the oyster farms in Red Cliff Bay are in gray for 2001, 2002, and 2003 (a, b, and c, respectively). The comparison area in Whale Bight is the gray area in section (d). Each follow has a different shade and the direction of movement is indicated by arrowheads (52 follows of 25 adult females). The time interval between points is 30 min in section (d) and varies from 5 to 15 min in sections (a), (b), and (c). Sections (e) and (f) show the similar bathymetry between the two areas, where land is the lightest gray color and depth increases as the shading darkens (0–4, 4–7, and >7 m).

through the pearling lines. Females' movement through that area does not appear to be restricted to the drop off in depth (Fig. 4). Females were more likely to go into the comparison area (mean ± SE = 53 ± 12% of segments, $n = 10$) than into the confirmed oyster farm (mean ± SE = 14 ± 6% of segments, $n = 17$; one-tailed: $p = 0.005$).

4. Discussion

The adult female bottlenose dolphins studied here appeared to have been displaced by aquaculture. They showed a significant decrease in use of the extension area when the pearl oyster farming was introduced. The fact that this same pattern was not seen for the reported use area could be attributed to the possibility that oyster farming never actually occurred there. Because of decreased GPS accuracy or human error when the lease was established, and the shallow depth of most of the reported use area, farming may not have taken place in that area. Researchers never observed panels in these shallow waters. The detailed outlines of where the ropes were located as measured by us starting in 2001 were not in this area at all and there was also a shift further from shore between 2001 and 2002, indicating that the oyster farm lines were moved. Another possibility is that the dolphins studied did not heavily utilize that relatively shallow area. In fact, the shallow areas in the Whale Bight comparison area are also not heavily used (Fig. 4).

Even though mean distance to the extension area increased during the one year (1999) it was present, it would be difficult to attribute this pattern to the farming per se because of large year-to-year variation. Most likely other factors such as changes in dolphin-watch tour boat presence and annual variation in predators and prey contribute to this yearly variation.

Detailed movement patterns around the confirmed oyster farm provided the strongest evidence that dolphins are displaced by shellfish aquaculture. Adult female dolphins were less likely to go into areas where farming was occurring compared to an ecologically similar area nearby. From the tracks of the females we can see several instances where females stayed on the periphery of the farm rather than traveling through it. This pattern might indicate a reluctance to swim through ropes in the water, a previously documented occurrence for captive harbour porpoises, *Phocoena phocoena* (Kastelein et al., 1995). Dusky dolphins in Marlborough Sounds, New Zealand were observed to swim only between lanes consisting of ropes and floats in the mussel farm (Markowitz et al., 2004). *Ad libitum* notes taken during follows from our study in the oyster farm indicate that adult females sometimes swim all the way around the ropes (several hundred meters) rather than crossing them, despite ample space to do so. However, adult females have also been observed swimming over lines. Some adult females may avoid the ropes and panels in the water by not entering the oyster farm, while others are less cautious.

Displacement from habitats by aquaculture may be particularly important to foraging specialists, as many of the female dolphins appear to be at this site (Mann and Sargeant, 2003). For example, a subset of adult females use marine sponges to ferret prey from the seafloor almost exclusively in deep-water channels in our study site (Smolker et al., 1997). If they were displaced from these channels they would be prevented from using their predominant foraging type and are likely to have decreased foraging and reproductive success. Furthermore all females have a network of associates whom they rest, travel, and socialize with (Wells et al., 1987; Smolker et al., 1992); if they were forced to move to another area these long-term bonds may be disrupted. Although we have been examining movement patterns of adult female dolphins and not other age/sex classes, any significant impact on adult female reproductive success is likely to have long-term consequences for the population.

This study is unique considering the information available on cetaceans and aquaculture. We were able to control for individual differences, variation over time, and the location of the oyster farm because 15 years of ranging data were available on individually identified dolphins whose sex, approximate age, and reproductive histories were known. However, a serious limitation of this study was that we did not measure the exact location of the farm prior to 2001.

4.1. Future research and management recommendations

Future studies on cetaceans and aquaculture should collect baseline movement and behavioral data at least several years before the site is established to account for yearly and seasonal variation and to establish which habitats are critical for cetaceans. Accurate independent assessment of animal movement and the exact location of the farm are essential (rather than using designated lease areas). Standardized search methods such as transects that cover the entire area are important for detecting changes in cetacean density. Determination of habitat structure and cetacean behavior patterns before, during, and after disturbance can provide insight regarding whether the effects are reversible and, if so, how long it might take to return to the previous state. However, if opportunistic data are the only data available, methods such as those described can be used to assess impacts of a disturbance. Detailed movements of individuals are useful to show how animals interact when they come into contact with the area in question. If behavioral data are not being collected, this may best be done remotely (such as from a theodolite or by radio or satellite tagging). To avoid pseudoreplication only independent locations can be used.

Management of shellfish farms with regard to how they affect marine mammals is currently a pressing issue. Management agencies should forecast that farms with ropes and panels may displace at least some dolphins and potentially impact their fitness. The following recommendations may be useful. Research the distribution of animals before, during and after a small test area has been set up first. Limit the lease numbers or sizes to areas not heavily used by cetaceans. Allow corridors through the shellfish farms for the dolphins to move, such as having a space between parallel lines, so that the animals are not entirely boxed out. In this study, a size of 75 m was sufficient for some, but not all, dolphins to swim through. If dolphin welfare is of concern, then a precautionary approach is warranted. Research on the impact of aquaculture should be carried out before leases are approved.

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