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Reducing the environmental impact of shark-control programs: a case study from KwaZulu-Natal, South Africa

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Abstract. Large-scale shark-control programs at popular beaches in New South Wales and Queensland, Australia, and KwaZulu-Natal (KZN), South Africa, provide protection against shark attack. Although these programs have enhanced bathing safety, reducing the environmental impacts of decades of fishing for large sharks and the associated by-catch remains a challenge. Over the past three decades, there have been several interventions to reduce such impact in the KZN program. The first was the release of all live sharks, including those species known to be responsible for fatal shark attacks. Measures to reduce catches of sharks associated with the winter influx of shoals of sardines, *Sardinops sagax*, have been increasingly successful. In addition, extensive removal of nets has resulted in a major reduction in effort. Collectively, these initiatives reduced mortalities of sharks by 64%. Baited lines, termed drumlines, were introduced at 18 beaches, where they replaced some of the nets. The former had a far lower by-catch of rays, turtles and cetaceans and significantly lower catches of certain shark species. Replacement of some nets with drumlines is planned for the remaining beaches. Only two attacks, both non-fatal, have occurred at protected beaches in KZN over the past three decades, indicating that the program has maintained its public safety mandate while it has succeeded in reducing its impact on the environment.

Additional keywords: bycatch, drumlines, gill-nets, mortalities, *Sardinops sagax*.

Introduction

The objective of shark-control programs is to provide the public with protection against shark attack at popular beaches (Dudley and Gribble 1999). This is achieved by fishing for sharks directly off the beaches, using large-mesh gill-nets or baited lines or both, thereby reducing the likelihood of a dangerous shark coming into contact with humans. Unlike small-mesh shark-exclusion nets that are deployed in waters sheltered from currents and wave action, the shark-control gear does not form an impenetrable barrier and hence does not eliminate the risk of shark attack completely. Shark-control programs have been successful in greatly reducing the number of shark attacks (Dudley 1997), thereby meeting their goal of providing the general public with a safe swimming environment.

Shark-control programs are not only expensive in that the equipment deployed requires regular boat-based maintenance, but they also incur associated environmental costs. Catches are not confined to dangerous shark species, but include species that pose little threat to human safety. In addition, a diverse by-catch, comprising largely rays as well as cetaceans and other marine mammals, sea turtles and teleosts, is also taken (Paterson 1979; Dudley and Cliff 1993; Krogh and Reid 1996; Gribble *et al*. 1998*a*; Dudley and Cliff 2010*a*). The programs were introduced at a time when 'the only safe shark is a dead shark' (Smith 1961: p. 29) and there was little, if any, concern for their impact on the environment. Criticism of the programs for their lack of selectivity and the possible impact of the removal of large predators from nearshore waters has increased over time, resulting in mounting pressure to reduce mortalities, especially of by-catch groups (van der Elst 1979; Cockcroft 1990; Paterson 1990; Anonymous 1992; Sumpton *et al*. 2010). This pressure has to be balanced against the original mandate of providing protection against shark attack, which is integral to maintaining the economic benefits of beach tourism.

There are currently three large long-standing shark-control programs. The first, the New South Wales Shark Meshing Program (NSW SMP), commenced in 1937. This was after a series of fatal shark attacks off metropolitan surfing beaches and in Sydney Harbour had led to a lack confidence in bathing and it was acknowledged that total enclosure of some beaches to exclude sharks was not feasible because of frequent rough seas (Coppleson 1962). The KwaZulu-Natal (KZN, formerly Natal) shark-control program on the eastern coast of South Africa commenced in 1952 when shark nets were introduced at Durban, following a spate of attacks on the city's beaches. At the time, the costs were 'considered to be small in relation to the benefit which is derived by the City of Durban and its numerous visitors' (Davies 1964: pp. 87, 88). The third program, also on the eastern coast of Australia, the Queensland Shark Control Program (QSCP), was established in 1962, also following several fatal shark attacks. From the outset, a combination of baited lines (colloquially known as drumlines) and nets was deployed to reduce local shark populations near major swimming beaches. At the time, drumlines represented a new concept

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in shark control, in which a large hook is suspended below a large anchored float. The hook is baited regularly and the fresh bait attracts any sharks in the general vicinity, with the float providing strong resistance to set the hook when a shark takes the bait (Gribble *et al*. 1998*b*).

In 1964, the Natal Anti-Shark Measures Board, renamed the Natal Sharks Board in 1985, was formed by the provincial government of Natal to advise municipalities on the deployment of shark nets, which were installed and maintained by municipal employees or private contractors. In 1974, the Board began to assume direct responsibility for the operation of all the province's 'anti-shark measures'. The Board's original defining legislation, the Natal Sharks Board Ordinance (Ordinance 10 of 1964), was replaced by the KwaZulu-Natal Sharks Board Act (Act 8 of 2008), with the resultant name change to the KwaZulu-Natal Sharks Board (KZNSB). The new legislation states that, in addition to its long-standing mandate of safeguarding bathers in KZN against shark attack, the KZNSB must also endeavour to reduce negative impact on all biodiversity and enhance the survival of caught sharks and other marine animals (Anonymous 2008). Although this concern for the environment was not reflected in the initial legislation of 1964, several measures to reduce environmental impact were introduced over the past three decades. Our paper documents the changes aimed at reducing the environmental impact of the KZN shark-control program and assesses the effectiveness of these efforts.

Materials and methods

Details of the netting operation of the KZN shark-control program are provided by Wallett (1983) and Cliff and Dudley (1992). The nets are made of polyethylene braid; most are 214 m long, 6.3 m deep and have a stretched mesh of 51 cm. They are set parallel to the shore in water 10–14 m deep and 300–500 m offshore. Where they occur, drumlines (each with a single Mustad 4480DT 14/0 J hook (Gjøvik, Norway) suspended beneath a large float) are anchored adjacent to the nets. On average, the gear is checked 18 times each month and the hooks are baited with southern rover *Emmelichthys nitidus* (Emmelichthyidae) or jacopever species (Scorpaenidae), both a by-catch in the demersal trawl fishery for hake, *Merluccius capensis* (Merlucciidae). Fishing gear is deployed in fixed locations throughout the year, although there may be discretionary removal in winter, particularly in the south of the province, to reduce catches of predators associated with the sardine run (Cliff and Dudley 1992; Dudley and Cliff 2010*b*).

Catch records were kept from the onset of the program; however, the earlier data, particularly in terms of species identification and documenting by-catch, are poor and under-reporting also cannot be excluded. The quality of the data improved with time, as the KZNSB assumed control of operations, and species-specific data for sharks are considered reliable since 1978 and for by-catch since 1981 (Cliff and Dudley 1992).

Catches are divided into two groups – *sharks*, which comprise large predatory sharks (Table 1), and *by-catch*, which also includes small, non-predatory shark species, such as *Mustelus* and *Rhizoprionodon* (Table 2). The catch data by species or groups have been divided into three periods. The first

Table 1. Catches (by number) of predatory sharks of large species in the KwaZulu-Natal shark-control program, 1978–2009

Drumline data exclude catches taken on three drumlines at Richards Bay, April 2005–February 2007. Total includes incidental catches of additional species. %rel., percentage released

Species name	Common name(s)	Annual catch 1978–1989 (nets)			Annual catch 1990–1999 (nets)			Annual catch 2000–2009 (nets)			Annual catch February 2007–February 2010 (drumlines)		
		Mean	s.d.	%rel.	Mean	s.d.	%rel.	Mean	s.d.	%rel.	Mean	s.d.	%rel.
Carcharhinus amboinensis	Java/pigeye	17	10.2	10	11	5.1	13	10	4.7	17	0	0.0	–
Carcharhinus brachyurus	Copper/bronze whaler	149	137.8	8	79	56.5	21	15	16.7	19	6	4.2	5
Carcharhinus brevipinna	Spinner	144	43.4	4	128	41.9	17	51	17.8	8	<1	0.6	0
Carcharhinus leucas	Zambezi/bull	60	19.5	9	37	9.0	22	17	4.1	19	<1	0.6	100
Carcharhinus limbatus	Blacktip/common blacktip	139	37.9	4	82	20.6	7	64	18.7	10	3	1.2	25
Carcharhinus obscurus	Dusky	294	121.9	5	211	66.9	16	104	28.9	12	76	13.1	22
Carcharhinus plumbeus	Sandbar	30	18.3	10	15	5.8	12	9	6.6	12	2	2.6	0
Carcharias taurus	Spotted ragged-tooth/grey nurse	242	104.3	26	180	86.7	41	81	15.1	29	<1	0.6	0
Carcharodon carcharias	Great white/white	42	14.1	3	33	12.3	15	25	7.8	10	8	1.7	21
Galeocerdo cuvier	Tiger	45	11.9	13	51	14.1	44	49	15.8	39	14	5.7	37
Isurus oxyrinchus	Shortfin mako	15	5.3	1	12	3.0	10	8	4.6	8	1	1.2	50
Sphyrna lewini	Scalloped hammerhead	190	59.4	1	115	42.2	2	66	23.3	1	17	4.0	0
Sphyrna mokarran	Great hammerhead	16	5.9	0	7	1.6	2	2	2.0	0	0	0.0	–
Sphyrna zygaena	Smooth hammerhead	66	67.5	1	89	51.3	3	59	39.5	1	10	8.5	3
Total		1465	400.7	8	1058	222.8	19	567	124.5	14	139	19.1	19

Table 2. Catches (by number) of species other than large predatory sharks in the KwaZulu-Natal shark-control program, 1981–2009
Drumline data exclude catches taken on three drumlines at Richards Bay, April 2005–February 2007. %rel., percentage released

Species name	Common name(s)	Annual catch 1981–1989 (nets)			Annual catch 1990–1999 (nets)			Annual catch 2000–2009 (nets)			Annual catch February 2007–February 2010 (drumlines)		
		Mean	s.d.	%rel.	Mean	s.d.	%rel.	Mean	s.d.	%rel.	Mean	s.d.	%rel.
Birds		2	1.8	0	2	1.1	7	4	3.1	0	0	0	–
Caretta caretta	Loggerhead turtle	44	13.8	35	41	8.0	45	39	7.7	62	2	1.2	80
Dermochelys coriacea	Leatherback turtle	6	2.7	36	6	3.7	37	3	2.2	36	<1	0.6	100
Turtles (other species)		19	3.7	33	17	4.4	36	11	5.1	28	1	0.6	50
Delphinus capensis	Long-beaked common dolphin	30	20.1	4	52	43.8	4	21	14.8	1	0	0	–
Sousa chinensis	Indo-Pacific humpback dolphin	7	3.5	0	6	2.7	0	6	3.5	2	0	0	–
Tursiops aduncus	Indian Ocean bottlenose dolphin	34	10.8	<1	45	13.6	3	27	7.0	3	0	0	–
Dolphins (other species)		2	2.4	5	1	0.9	0	1	1.1	0	0	0	–
Whales		1	0.7	0	3	1.3	58	5	3.1	83	0	0	–
Rhynchobatus djiddensis	Giant guitarfish	130	42.8	75	115	34.2	74	40	19.4	68	0	0	–
Manta spp.	Mantas	52	32.6	65	70	33.9	67	43	28.8	59	<1	0.6	100
Rays (other species)		188	69.6	68	166	46.9	65	142	50.6	45	0	0	–
Sharks		39	13.3	35	47	15.1	40	26	8.2	25	19	13.2	39
Teleosts		52	38.2	4	83	68.4	1	55	31.7	1	3	2.6	11
Total		606	168.1	49	653	108.9	45	456	86.5	42	25	16.3	41

commenced when all species-specific data were reliable (sharks: 1978; by-catch: 1981) and ended in 1989 by which time all live sharks were released. The second period, 1990–1999, was before the major reduction in effort. The third period was the next 10 years, 2000–2009. Three years of catches on the drumlines, commencing in February 2007 when 76 were deployed in place of 19 nets, are also presented. Overall annual statistics on catch and effort were compiled and used to investigate changes in the program over time.

Results

Effect of the number of protected beaches and the length of netting on catches

Between 1952 and 1961, Durban was the only net installation. There was a steep rise in the number of protected beaches and the length of netting in the 1960s. After 1970, few new installations were added, although the length of netting continued to increase, peaking at 45 km in 1992, when there were 44 protected beaches (Fig. 1). Between 1994 and 2000, protection was removed from a small number of beaches for socioeconomic reasons. Between 1999 and 2004, a phase of intensive net reduction at most beaches resulted in a decline in the length of netting down to 27 km.

Shark catches increased sharply in the 1960s, with the increase in effort. The next two decades were characterised by large inter-annual fluctuations (Fig. 2). Annual shark catches averaged 1465 (s.d. = 401) in the first period (1978–1989) (Table 1), dropping to 1058 (s.d. = 223) and then to 567 (s.d. = 125) in the ensuing two decades, an overall decline of 61%. There was a significant ($P < 0.001$) positive relationship between catch, excluding the highly variable influence of the sardine run (see later), and effort between 1978 and 2009 (Fig. 3). By-catch declined to a far lesser extent (25%), with a rise from 606 per annum in the 1980s to 653 per annum in the 1990s, falling to 456 in the 2000s (Table 2). The giant guitarfish, *Rhyncobatus djiddensis*, was the only by-catch species to show a marked decline, with catches falling by 69%.

Survival rates and the release of all live sharks

Initially, all large sharks found alive were killed. This practice changed very gradually with the release of smaller individuals of those species that posed little or no threat. By 1989, all sharks were released (Cliff and Dudley 1992), including the species identified as posing the greatest threat, namely Zambezi shark, *Carcharhinus leucas*, white shark, *Carcharodon carcharias*, and tiger shark, *Galeocerdo cuvier* (Cliff 1991). This change resulted in the release rate rising from 8% in the first period to 19% in the second (Table 1). In the second and third periods, the release rate reflects the actual survival rate. Tiger and spotted raggedtooth sharks, *Carcharias taurus*, had the highest survival rates at ~40% and the three species of hammerheads, *Sphyrna* spp., the lowest, with very few individuals being found alive. Between 1984 and 2009, KZNSB staff tagged over 4000 sharks, most of them being released from the nets (Sabine Wintner, KZNSB, unpubl. data).

The release of all by-catch found alive has always been standard practice. The overall percentage released for each of the three decades fluctuated between 42% and 49%, with a wide

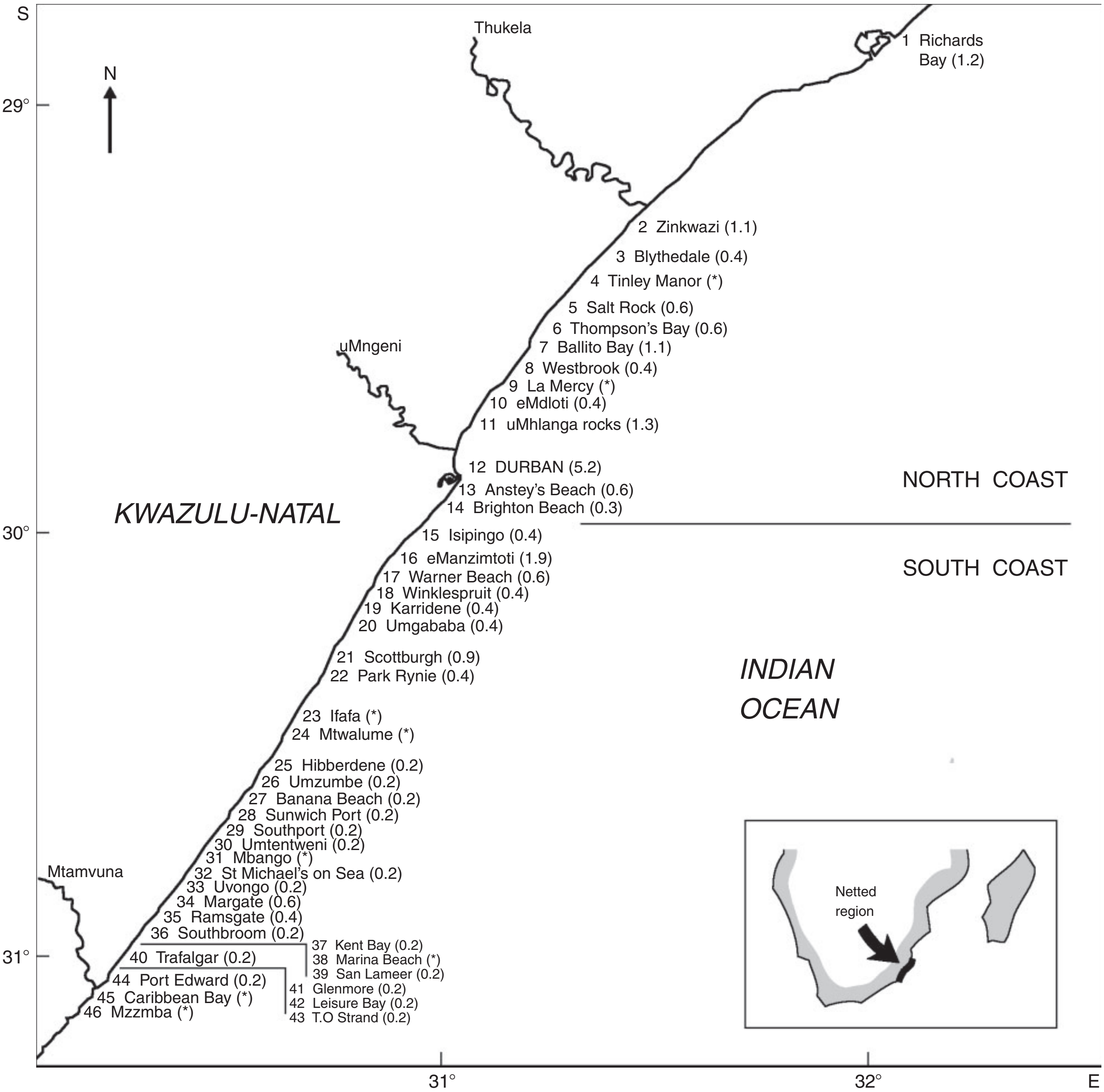

Fig. 1. Protected beaches on the KwaZulu-Natal coast and, in parentheses, the length of nets in kilometres in December 2009. Several net installations (*) were permanently removed during the study period 1978–2009. Drumlines were introduced at Richards Bay (Beach 1) in place of some netting in 2005 and all beaches from Hibberdene (Beach 25) to Port Edward (Beach 44), except Southport (Beach 29) in 2007.

range in survival rates among the various species and groups (Table 2). The rays had among the highest survival rates at 45–75% and dolphins the lowest at 0–5%. Whales, most of which were humpback, *Megaptera novaeangliae*, also had very high survival rates. At least one-third of sea turtles were released alive.

Experimentation with nets of a larger mesh size

In 1991, a series of experiments was initiated with nets of a larger mesh size (70 cm) for comparison with catches in the existing nets (51 cm; Dudley 1995). Larger mesh nets are easier to handle, cheaper (because they require less twine) and are less prone to drag in the current; however, the primary incentive was the potential reduction in catches of smaller animals, especially young dolphins. Although the sample sizes of non-shark animals caught in the experiments were small, catches of giant guitarfish and dolphins were lower in the larger mesh, whereas the catch of disc-shaped batoids was higher. All differences were non-significant. More importantly, the larger mesh (70 cm) showed a reduced relative selectivity (from 81% to 25%) for large sharks (>1.6 m precaudal length, PCL), raising concerns that the

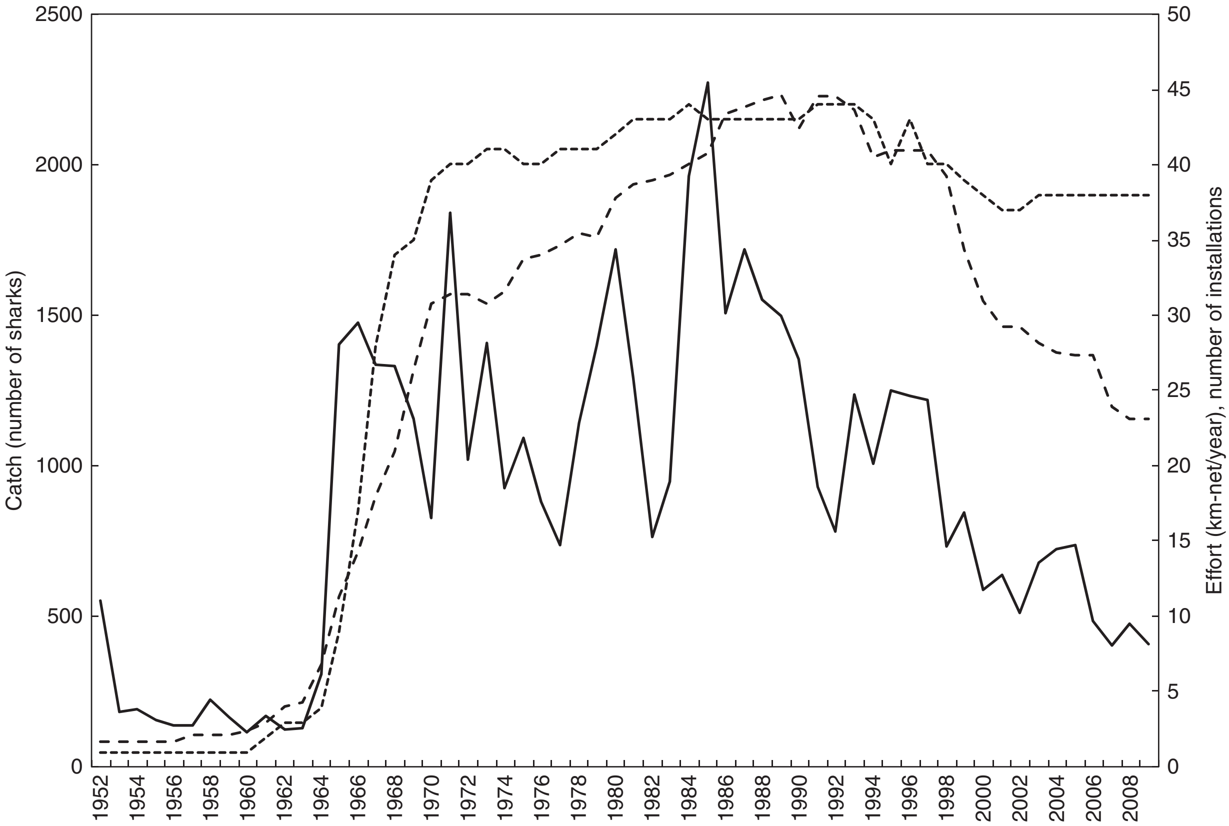

Fig. 2. Total annual shark catch (solid line) and effort (number of installations, dotted line; kilometres of net per year, dashed line) in the KwaZulu-Natal shark-control program, 1952–2009.

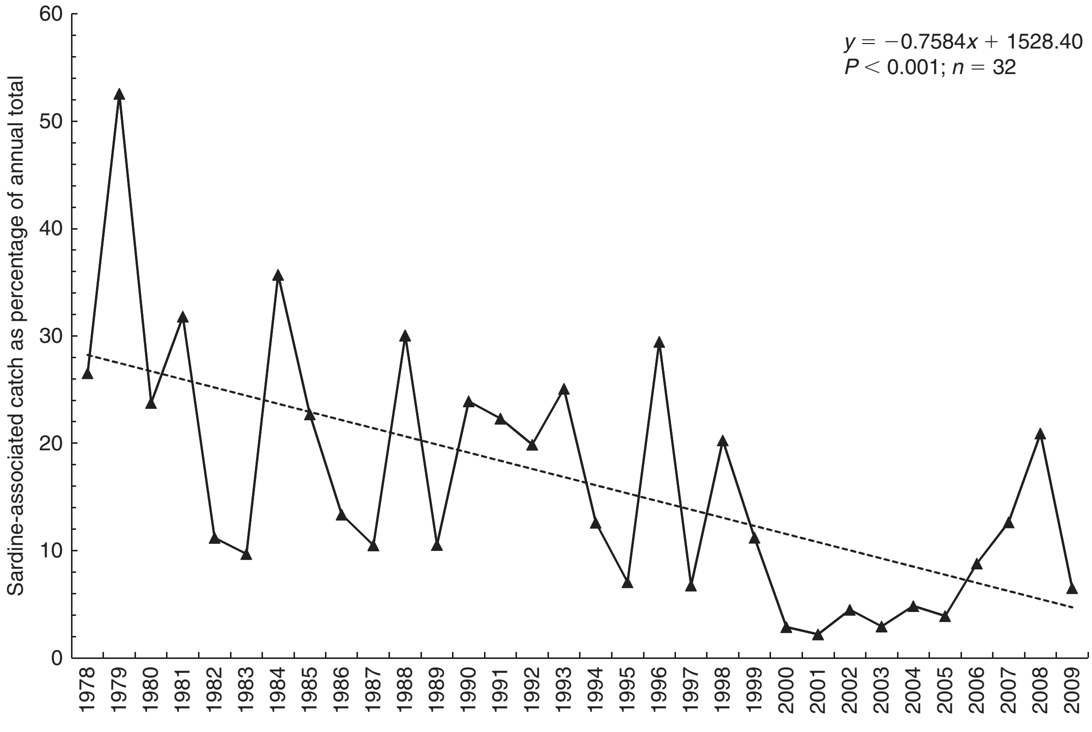

Fig. 3. Shark catch at all protected beaches south of Durban in June and July, 1978–2009, as a percentage of the annual catch at all beaches.

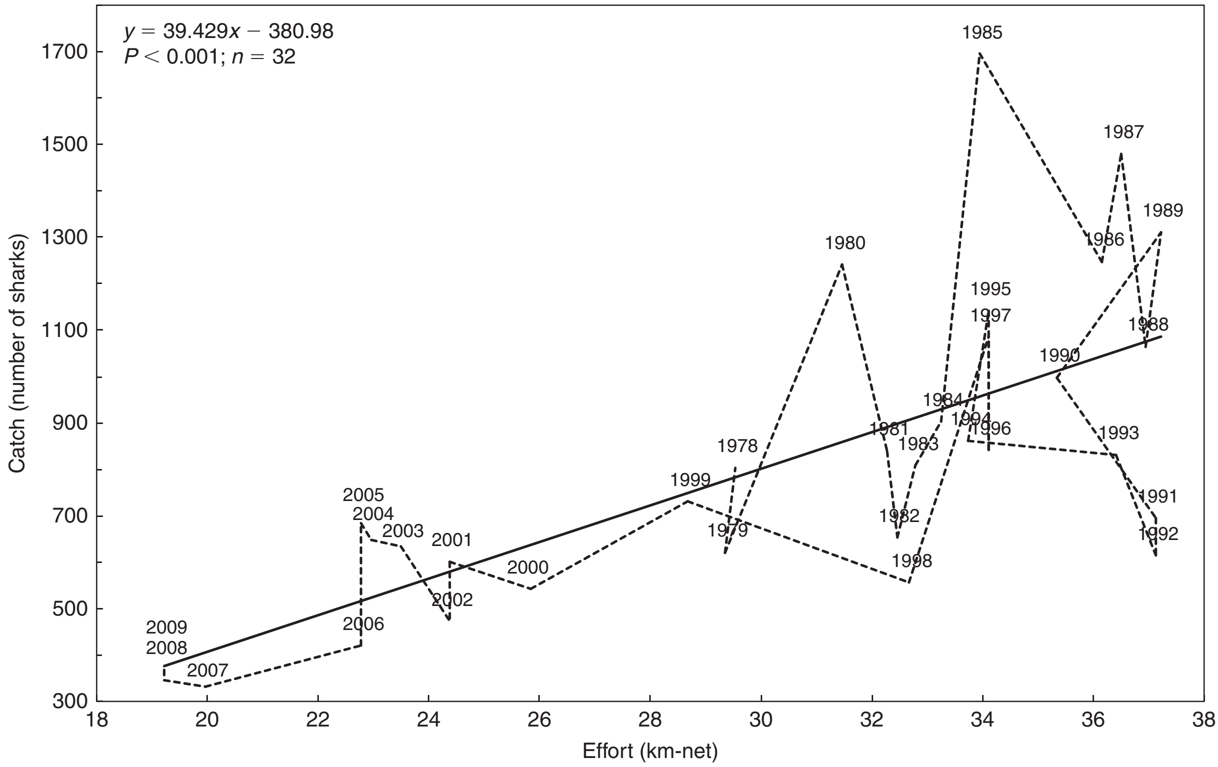

Fig. 4. Shark catch and associated shark-net effort, 1978–2009, with catch taken during June and July excluded and effort expressed as ten-twelfths of the average for each year.

deployment of these nets would result in an unacceptable reduction in bather-safety levels (Dudley 1995). As a result, the experiments were abandoned and the mesh size remained at 51 cm.

Reducing catches associated with the sardine run

In a phenomenon known as 'the sardine run', shoals of sardines *Sardinops sagax* enter southern KZN coastal waters in June and July (Armstrong *et al*. 1991; Dudley and Cliff 2010*b*). Sardines and accompanying predators are often present in the surf zone, where the former are caught in beach seine nets. At such times, the larger predators, which include several species of carcharhinid sharks and two species of dolphins, are extremely vulnerable to capture in the shark nets. The extent of each year's run is highly variable and in some years the sardine shoals remain in deeper waters well beyond the surf zone, so neither they nor the accompanying predators are evident from the shore (Fréon *et al*. 2010).

Much of the vast inter-annual fluctuation in shark catches evident in the first two periods (Table 1, Fig. 2) was attributed to the sardine run (Dudley and Cliff 2010*b*). An improvement in the ability of the KZNSB to monitor the movements of the shoals and a willingness to remove the nets for longer periods reduced shark catches associated with the sardine run (June and July). These catches dropped from 315 per annum in the 1980s to 42 in the 2000s, resulting in a significant decline in the contribution of the sardine-run shark catches to the total annual catch (linear regression $P < 0.001$, Fig. 4). Many predators, such as the dusky shark, *Carcharhinus obscurus*, spinner, *C. brevipinna*, and blacktip, *C. limbatus*, and the Indian Ocean bottlenose dolphin, *Tursiops aduncus*, which accompany the sardines, are caught throughout the year. One exception is the copper/bronze whaler, *Carcharhinus brachyurus*, which is rarely caught outside the sardine run. Annual catches of this species in the final decade were only 10% of that in the first (Table 1).

Reducing cetacean catches

Trials initiated in the late 1980s with low-cost devices to reduce dolphin catches (Peddemors and Cockcroft 1994) were discontinued because of a lack of success. In 1996, small air-filled floats were introduced into the meshes of half of the nets deployed at Margate to establish whether the sonar of bottlenose dolphins could detect the air-filled floats and thereby avoid accidental entanglement. In 11 years, more bottlenose dolphins (16) were caught in the Margate nets with small, air-filled floats than without (11) and so the experiment was terminated.

Acoustic deterrents, termed 'pingers', are widely used in the fishing industry to alert dolphins to the presence of fishing nets (Cox *et al*. 2007). In 1999, commercially manufactured 10-kHz deterrents were introduced at Richards Bay to prevent catches of Indo-Pacific humpback dolphins, *Sousa chinensis*. The program was expanded to five other beaches in an attempt to reduce catches of bottlenose dolphins. On several occasions, a bottlenose or humpback dolphin was caught within 10 m of a dolphin pinger, suggesting that the animal may have been attracted to the sound source. This prompted a decision to move the two pingers out of each net and to attach each pinger to one of the ropes demarcating the net's anchors. Catches of humpback dolphins

Table 3. Summary of Hibiscus Coast (beaches 25–44) shark catch in nets and on drumlines, from February 2007 to February 2010
Catch data for the sardine run (June and July) are excluded. Shading indicates that the difference between nets and drumlines was significant ($P < 0.05$) according to Lord's range test (catch) or Mann–Whitney test (median precaudal length, PCL)

Species	Average catch (no. year^{-1})		Median length (PCL, cm)		Standardised catch rate (CPUE)		Ratio of net CPUE to drum CPUE
	Nets 07–10	Drums 07–10	Nets 07–09	Drums 07–09	Nets (no. net^{-1} year^{-1})	Drums (no. drum^{-1} year^{-1})	
Copper	2.7	5.7	198.0	195.0	0.1524	0.0895	1.7
Spinner	16.3	0.3	165.0	130.0	0.9333	0.0053	177.3
Zambezi	3.0	0.3	170.0	130.0	0.1714	0.0053	34.2
Blacktip	8.7	2.3	170.0	174.5	0.4952	0.0368	13.4
Dusky	9.3	59.7	197.0	118.0	0.5333	0.9421	0.6
Sandbar	0.7	1.7	139.0	100.0	0.0381	0.0263	1.4
Spotted ragged-tooth	16.7	0.0	184.5	178.0	0.9524	–	–
Great white	6.7	6.0	186.0	215.5	0.3810	0.0947	4.0
Tiger	7.0	11.7	184.0	132.5	0.4000	0.1842	2.2
Shortfin mako	0.7	0.7	220.0	210.0	0.0381	0.0105	3.6
Scalloped hammerhead	6.3	16.7	108.0	110.0	0.3619	0.2632	1.4
Smooth hammerhead	4.0	8.3	100.0	106.5	0.2286	0.1316	1.7
Total	82.7	114.7	175.0	120.0	4.7238	1.8105	2.6

persisted at Richards Bay, so the pingers were replaced with louder whale alarms, operating at lower frequencies. An analysis is currently being undertaken to assess the efficacy of these alarms in reducing catches of bottlenose dolphins, and initial impressions suggest that their deployment has not had the desired effect.

Whale catches, mainly humpback, showed a small increase over the three decades under review (Table 2). In 2005, whale alarms were manufactured in-house and deployed each whale season (June–December) at beaches with the highest sightings of whales. The alarms operate over a frequency range of 2.9–3.4 kHz. Subsequent modifications to the device improved water-proofing and sound generation. For operational reasons, the deployment of alarms varied from year to year, both in terms of the beaches selected and the number of alarms deployed. In 2009, 48 alarms were used at 17 beaches. As the whale alarms were not deployed in a consistent manner from year to year, it is difficult to ascertain their efficacy.

Replacement of nets with drumlines

A major initiative was the introduction of three drumlines in 2005 at Richards Bay, after several years of local experimentation (Dudley *et al*. 1998). In 2007, 76 drumlines replaced almost half (4 km) of the nets at the 17 southernmost protected beaches on the Hibiscus Coast (beaches 25 southwards; Fig. 1), with a replacement ratio of four drumlines to one net (214 m). The drumlines caught significantly more sharks, mainly dusky sharks, and significantly fewer Zambezi, spinner, blacktip and spotted raggedtooth sharks (Table 3). The drumlines caught significantly smaller dusky sharks, many of which were newborns, sandbar sharks and tiger sharks. Of the three species that pose the greatest threat to beach users, the ratio of net to drumline catch rates was 2.2 for tiger and 4.0 for white sharks, whereas it was 34.2 for Zambezi sharks.

There was little difference in the survival rate of all large sharks between the drumlines (19%: Table 1) and the adjacent nets (17%: KZNSB, unpubl. data). The survival rates of dusky sharks (22%: Table 1) and white sharks (21%: Table 1) were higher on drumlines than in the nets (15% and 9%, respectively: KZNSB, unpubl. data), whereas they were similar for tiger sharks (38% and 33%, respectively) and scalloped hammerheads (0%).

The annual by-catch on the drumlines was very low (Table 2), apart from 19 sharks of small species, mainly hound sharks, *Mustelus* spp. It included less than one ray and three turtles, and no cetaceans. The annual by-catch in the adjacent nets included six sharks of small species, three birds, 20 rays, 13 turtles, seven dolphins and two whales (KZNSB, unpubl. data).

Discussion

The results of this work have demonstrated that it is possible to reduce the environmental impact of shark-control programs while still meeting their mandate of public safety. In KZN, the introduction of shark nets reduced the incidence of shark attack at protected beaches by over 90% (Dudley 1997). There have been only two attacks, both non-fatal, at protected beaches since 1980, a period when several measures were introduced to reduce environmental impact of the program. Two of the major initiatives were as a direct result of a detailed comparison with the shark-control programs in Queensland and New South Wales. The first was that fishing effort in KZN was substantially greater than in the other two areas and could be reduced while still providing adequate protection against shark attack (Dudley 1997). The second was that drumlines deployed off the beaches of Queensland were a more selective shark-fishing device than were nets (Paterson 1990; Simpfendorfer 1993; Gribble *et al*. 1998*b*).

Reducing shark mortalities and impacts on shark populations

Extensive effort (net) reduction in the late 1990s and early 2000s, together with the improved management of net removal during the sardine run, greatly reduced catches of sharks. When coupled with the release of all live sharks, shark mortalities fell by 64% over the past three decades. Although drumlines did not reduce shark catches (Dudley and Cliff 2010*a*), the species composition was different and they caught significantly fewer spinner, blacktip and raggedtooth sharks, all being species that pose little threat to bathers and yet were caught in relatively large numbers in the shark nets. Although these interventions reduced catches, declines in population size may have also contributed to the observed drops in catch. Dudley and Simpfendorfer (2006) assessed the population status of the 14 most common shark species over a 26-year period (1978–2003), using trends in catch rate and size. Four species, Zambezi, blacktip, scalloped hammerhead and great hammerhead, *Sphyrna mokarran*, showed a significant decline in catch rate. They concluded that the program potentially had a high impact on dusky and spotted raggedtooth sharks, only because of their very low intrinsic rate of population increase and high catch; however, neither species showed a declining population trend. The potential impact on the Zambezi, scalloped hammerhead and white shark was regarded as medium, and low for the remaining species. Information on catches of these species elsewhere in South Africa or the south-west Indian Ocean is scanty and fishing pressures elsewhere in each species range may have contributed to a decline in catches in the shark-control program. Thus, for most of the shark species caught by the program, there was limited evidence that population declines were responsible for the reductions in catch. This suggests that effort reduction was the main contributor to the reduction in shark catch.

Reducing by-catch and impacts on their populations

Efforts to lower by-catch through net reduction and net removal in the sardine run achieved less success, with a modest decline of 25%, compared with a 61% reduction in shark catches. This may in part be because, apart from dolphins, no by-catch was associated with the sardine run. The extremely low catch of rays, turtles and cetaceans on the drumlines was very encouraging and is strong incentive for further replacement of nets with drumlines. Cockcroft (1990) raised concerns over the impact of catches of bottlenose and humpback dolphins; however, neither species showed a decline in catch rates between 1981 and 2006 (KZNSB data, cited by Dudley and Cliff 2010*a*), suggesting that their abundance had not declined further. Nevertheless, considerable efforts have been made to reduce dolphin catches, the first of which was the use of air-filled floats and nets of a larger mesh size. Both initiatives were discontinued because of other concerns or a lack of effectiveness.

An assessment of the efficacy of 10-kHz dolphin pingers is not complete; however, these devices do not appear to have had the desired effect (KZNSB, unpubl. data). This is not surprising as, according to Cox *et al*. (2007), they were specially developed to deter harbour porpoises, *Phocoena phocoena*. The same pingers reduced dolphin catches in New South Wales from an annual average of 3.3 to 2 (Green *et al*. 2009). In Queensland, these pingers achieved mixed results, reducing dolphin catches by as much as 80% in some areas, whereas in others, there was a 35% increase in dolphin catches (Anonymous 2001). New 70-kHz pingers, which are regarded as being more appropriate for bottlenose dolphins, the species most often caught in the three shark-control programs, are undergoing extensive trials under the supervision of the manufacturers (James Turner, Fumunda Marine, pers. comm.). At present, apart from further replacement of nets with drumlines, the deployment of 70-kHz pingers appears to be the only available solution to reducing dolphin catches in the KZN nets.

The increase in the catches of whales, mainly humpback, despite the use of whale alarms, is likely to be due to the rapid recovery, estimated at ~10% and 7% per annum, respectively, in the populations of humpback (Findlay *et al*. 2011) and southern right whales, *Eubalaena australis* (Best *et al*. 2001), after decades of whaling. The incidence of whale entanglement was highest between July and November (KZNSB, unpubl. data). Captures in July, during the northward migration, are reduced to a certain extent by the extensive removal of nets during the sardine run. Other mitigating factors are the animals' high survival rate and the ability of specially trained release teams from the KZNSB to free calves that lack the strength to break out of the nets.

The decline in catches of the giant guitarfish, *Rhynchobatus djiddensis*, is cause for concern. Dudley and Simpfendorfer (2006) stated that the decline in catch rates appears to be due to heavy fishing by illegal commercial ventures in coastal waters of the south-western Indian Ocean. Between 1981 and 2006, there was no decline in the catch rates of mantas and the six other most commonly caught ray species (KZNSB data, cited by Dudley and Cliff 2010*a*).

Of the five turtle species caught in the KZN shark-control program, the greatest concern is for the two species, loggerhead, *Caretta caretta*, and leatherback, *Dermochelys coriacea*, which breed along the KZN coast, albeit north of the netted section. Nesting populations of these two species within a monitored zone are either increasing (loggerhead) or stable (leatherback) (C. Mulqueeny, Ezemvelo KwaZulu-Natal Wildlife, pers. comm.) and there was no decline in catch rates in the shark nets (KZNSB data, cited by Dudley and Cliff 2010*a*). Because turtle catches on the drumlines were extremely low (<3 per annum), further net replacement with drumlines bodes well for reducing turtle catches.

Deployment of drumlines

The deployment of drumlines for 3 years on the Hibiscus Coast confirmed the findings of Paterson (1990), Simpfendorfer (1993) and Gribble *et al*. (1998*b*) that they are a far more selective shark-control measure than nets. In particular, by-catch on the drumlines was very low in comparison to the adjacent nets. Although drumlines have proved as effective as nets in catching white and tiger sharks, they caught very few Zambezi sharks, which reinforces the recommendation (Dudley *et al*. 1998; Gribble *et al*. 1998*b*) that an optimal solution to ensure bather safety would be a combination of nets and drumlines. Queensland has seen a shift from nets to drumlines, primarily to reduce catches of non-target species, such as sea turtles, because some of the protected beaches are near turtle-nesting grounds (Dudley and Gribble 1999). Where mixed gear is deployed, the catch ratios (nets : drums) of bull (Zambezi) sharks were also far higher than those of tiger and great white sharks (Sumpton *et al*. 2011). Despite this, drumlines are used exclusively at some northern Queensland beaches (W. Sumpton, Queensland Department of Primary Industries, pers. comm.).

In Queensland, drumlines have not proved to be the ultimate panacea in by-catch reduction. Problems were encountered in some areas with the foul hooking of turtles, especially loggerheads, and the rapid scavenging of the bait by dolphins. This necessitated trials with different drumline baits and hook modifications (Sumpton *et al*. 2010). Plastic hook guards reduced the capture of loggerhead turtles by almost 70%; however, they also significantly reduced total shark catch, including that of tiger and bull sharks. They did not deter dolphins from scavenging and, as a result, they were abandoned. Mesh hook guards greatly reduced dolphin scavenging but increased loggerhead turtle catches and so were also abandoned. The problems of foul hooking turtles and scavenging of bait by dolphins have not been encountered with the drumlines in KZN.

The future

The KZN shark-control program has benefitted from the experiences of both the NSW and Queensland programs, particularly in terms of net reduction and the deployment of drumlines. In NSW, nets are removed in the winter months of May–August, for a combination of economic reasons and 'to further mitigate potential impacts on migrating whales' (Green *et al*. 2009: p. 16). Despite the possibility of the gear being out of the water at many KZN beaches for varying periods in winter during the sardine run, no serious consideration has been given to seasonal removal of all the gear along the entire coast. This is because the numbers of beach users in KZN is high in winter, when surf temperatures seldom drop below 20°C.

Despite some disappointing results, the use of pingers and alarms to reduce cetacean catches will continue, as this is a highly emotive issue among critics of shark control. A shift from 10-kHz to the 70-kHz pingers, which are currently under trial elsewhere, is likely. The impact of pingers on shark catches has not been assessed; however, it cannot be overlooked because in Queensland, the deployment of pingers resulted in an 18–90% reduction in shark catches (Anonymous 2001). This was regarded as a real decrease because drumline catches at the same locations did not decrease to the same degree.

The release of live sharks, including the three most dangerous species, will continue in KZN. Release rates of both sharks and by-catch could be boosted by about one-third if the gear were serviced on weekends and public holidays; however, this would add significant expense, which currently cannot be justified. The role out of drumlines is set to take place at the 20 beaches that are currently protected only by nets (Beaches 2–22; Fig. 1). In the foreseeable future, all beaches will be protected by a combination of nets and drumlines, because this appears to be the best way to combine public safety with reduced environmental impact. If drumlines are to be employed along the entire KZN coast, the availability of sufficient bait is a potential problem that will need to be addressed.

In the late 1950s, research into the development of an electrical shark cable that could protect an entire section of beach was initiated (Davies 1964); it was abandoned, after several hiatuses, in the late 1980s (Dudley and Cliff 2010*a*). In the 1990s, the KZNSB developed a personal electrical shark repellent and is currently investigating adapting this technology to create an electrical cable. If this proves feasible, the next challenge will be to maintain the equipment at KZN's surf beaches (Dudley and Cliff 2010*a*).

Beach tourism is a major attraction for KZN; foreign and domestic visitors who frequent the beaches at some point of their stay currently spend ~\$1 billion annually in the province (Karen Kohler, Tourism KZN, pers. comm.). The shark-control program is justified on the grounds of promoting public confidence in the safety of KZN beaches against shark attack. The income generated by beach tourism more than compensates for the financial cost of the program (\$7 million per annum). There is also the associated cost in the form of shark and by-catch mortalities. The KZN program has come a long way in reducing these catches and, hence, environmental impact, thereby demonstrating that there is capacity to achieve a workable balance between impact and safety in shark-control programs.

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