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Entanglement of Antarctic fur seals at Bird Island, South Georgia

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ABSTRACT

Between November 1989 and March 2013, 1033 Antarctic fur seals *Arctocephalus gazella* were observed entangled in marine debris at Bird Island, South Georgia. The majority of entanglements involved plastic packaging bands (43%), synthetic line (25%) or fishing net (17%). Juvenile male seals were the most commonly entangled (44%). A piecewise regression analysis showed that a single breakpoint at 1994 gave the best description of inter-annual variability in the data, with higher levels of entanglements prior to 1994 (mean = 110 ± 28) followed by persistent lower levels (mean = 28 ± 4). Records of entanglements from other sites monitored in the Scotia Sea are also presented. Legislation imposed by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) has, to a certain extent, been effective, but persistent low levels of seal entanglements are still a cause for concern at South Georgia.

1. Introduction

Plastic litter and other objects which have been lost or discarded at sea are recognised as a major source of marine pollution. In particular, the ingestion of, and entanglement in, man-made debris is a potentially significant cause of injury and death in marine animals (Derraik, 2002; Fowler, 1987; Gregory, 2009). In a review of entanglement data worldwide, Laist (1997) reported that at least 135 marine species including seabirds, marine mammals and sea turtles have been found entangled in marine debris. For marine mammals, observed entanglements are most common in pinnipeds (seals and sea lions), particularly the otariids (fur seals and sea lions), with at least 11 of 14 species (78%) reported entangled (Laist, 1997). Pinniped entanglements commonly consist of loops of non-biodegradable buoyant material encircling the neck, often referred to as 'neck collars' (Allen et al., 2012; Bonner and McCann, 1982; Fowler, 1987; Hanni and Pyle, 2000; Pemberton et al., 1992; Raum-Suryan et al., 2009).

Over the last four decades, international concerns over marine pollution of anthropogenic origin have lead to the introduction of mitigation measures. The International Convention for the Prevention of Pollution from Ships, 1973 as modified by the Protocol of 1978 (MARPOL 73/78) is intended to minimise pollution of the seas. The problem of marine debris is covered in Annex V which prohibits ocean dumping of plastics and other waste from ships. Annex V entered into force on 31 December 1988 and (as of October 2009) 139 countries representing over 97% of the world's tonnage had become party to it. In Antarctic waters, the prevention of marine pollution is covered by Annex IV of the Protocol on Environmental Protection to the Antarctic Treaty.

In the Antarctic and sub-Antarctic the monitoring of marine debris and its impact on marine biota is overseen by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR). In the early and mid-1970s small numbers of Antarctic fur seals (*Arctocephalus gazella*) were observed entangled at Bird Island, South Georgia (Payne, 1979a), and at the time of the inception of MARPOL Annex 5 the entanglement of marine mammals in the Southern Ocean was not thought to be of major concern (Arnould and Croxall, 1995; Wallace, 1985). However, the number of entanglements, particularly those involving plastic packaging bands, increased through the late 1970s and early 1980s (Bonner and McCann, 1982) and increasing concerns about marine pollution led to the establishment of a systematic survey of marine mammal entanglements at Bird Island. This took place during the pup rearing season of 1988/89, with neck collars observed on 208 seals and removed from 170 of these animals (Croxall et al., 1990). Significant numbers of Antarctic fur seal entanglements have subsequently been reported from throughout their distributional range including at Heard and Macquarie Islands (Slip and Burton, 1991), Livingston Island (Hucke-Gaete et al., 1997), Marion Island (Hofmeyr and Bester, 2002), and Bouvetøya (Hofmeyr et al., 2006).

Based on the results of the study by Croxall et al. (1990), CCAMLR increased the level of publicity regarding the correct conduct for the disposal of marine debris of sea, by using placards and distributing information leaflets to all fishing vessels (Arnould and Croxall, 1995). In 1993, CCAMLR conservation measure (CM) 63/XII was established, which prohibited the use of packaging bands on bait boxes from the 1995/96 season, and on any sort of boxes for

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vessels without incinerators from 1996/97. In 2008, CCAMLR added the requirement in CM 26-01 to cut packaging bands into 30 cm sections prior to disposal, so that bands were not re-tied to create a loop which could cause entanglements. CCAMLR has also made it compulsory for members to report the loss of fishing equipment (e.g. nets) and any incidental mortality of marine vertebrates associated with fishing activities, whether commercial or scientific (Sabourenkov and Appleyard, 2005).

Currently, the main fisheries operating around South Georgia target krill (*Euphausia superba*), mackerel icefish (*Champsocephalus gunnari*) and toothfish (*Dissostichus eleginoides*) and generally operate during the austral winter period (Agnew, 2004). As a condition of their licence these ships are required to adhere to the CCAMLR conservation measures described above, with the aim of mitigating the disposal of marine debris into the local ecosystem. In some years there has been a degree of illegal, unreported and unregulated fishing (IUU) for toothfish in the South Georgia region which might be a potential source of debris items. The level of IUU at South Georgia has been estimated by CCAMLR since 1989 using data from patrol vessel sightings (Agnew, 2004), and largely due to an increased patrol presence in the region, there has been no IUU recorded since 2006 (SC-CAMLR, 2011).

At Bird Island, South Georgia, year-round standardised surveys of the incidence of marine mammal entanglements have been undertaken each year since 1989 to assess trends in entanglement, determine inter-annual variation and monitor the effectiveness of CCAMLR measures preventing the at-sea disposal of material hazardous to marine vertebrates. Additionally, surveys of beached marine debris have taken place each year since 1990 (Walker et al., 1997), and surveys of debris associated with seabirds at Bird Island have been recorded annually since 1993 (Huin and Croxall, 1996; Phillips et al., 2010). All data on marine debris are submitted to CCAMLR on an annual basis.

Arnould and Croxall (1995) presented data from entanglement surveys at Bird Island between 1989 and 1994 and reported that rates of entanglement were variable year to year but were approximately half that of the 1988/89 pup-rearing season described by Croxall et al. (1990). In this paper we report data on Antarctic fur seal entanglements for the period between 1 November 1989 and 31 March 2013, extending the time series of Arnould and Croxall (1995). We do not include the data presented by Croxall et al. (1990), as this was a summer-only pilot study and not part of the continuous monitoring programme. We examine the incidence of entanglements by sex and age of animals, severity and type of material, and aim to identify trends in the occurrence of entanglement. For comparison, we also present a shorter non-continuous time-series of entanglement data from a number of locations around mainland South Georgia and from Signy Island in the South Orkneys. Animals entangled at these sites are likely to be from the same population as those at Bird Island (Boyd et al., 1998; Waluda et al., 2010).

2. Materials and methods

2.1. Entanglements at Bird Island, South Georgia

Incidences of seal entanglements in marine debris at Bird Island, South Georgia (54°S, 38.05°W; Fig. 1) were recorded following the methods described in Croxall et al. (1990) and Arnould and Croxall (1995). Data were collected continuously between 1 November 1989 and 31 March 2013. Obvious re-sightings of entangled animals are not included in the statistics presented here. Entanglements were removed by holding the animal down by hand (in the case of pups) or by restraining the animal with a noose pole and cutting the collar with a recessed blade (attached to the end of a pole for larger animals). If the entangling material was loose enough, it was lifted off using a stick. However in some cases (23%), entanglements could not be removed, this was usually through difficulty in accessing the animal.

The age and sex of entangled seals were recorded following the methods of Staniland and Robinson (2008), with sub-adult males included in the 'juveniles' category in the current analysis. Information on material type, the severity of entanglement, and the diameter of the entangling loop were also recorded where possible.

Type of entangling material was assigned to one of six categories: fishing net, packaging band, plastic bag/tape, rubber band, synthetic line (including mono- and multi-filament fishing line and synthetic string) and unknown material. The severity of entanglement was defined as 'loose' (material loose); 'tight' (material tight but not breaking the skin); 'severe' (cutting through the skin), or 'very severe' (cutting through both the skin and underlying fat layer).

2.2. Analyses

Entanglement data from Bird Island were divided into the austral winter (April–October) and austral summer (November–March) periods, consistent with previous studies (Arnould and Croxall, 1995). This was done because (i) different parts of the population are present in the two periods; while the winter population is almost exclusively males (mainly juveniles), the summer population is mainly lactating females and their pups together with a smaller number of adult males. (ii) Different levels of search effort are employed, with between six and eight personnel involved in the summer surveys and three to four in the winter.

As the Antarctic fur seal breeding cycle does not synchronise with the calendar year we defined a year as the period between 1st April and 31st March. This encompasses a single breeding season; females mate a few days after giving birth in December but implantation (and therefore the start of active gestation) does not take place until April, around the time that the previous pup reaches independence (Lunn and Boyd, 1993). A winter–summer cycle was used as any material derived from the region's fishing activity would most likely be introduced in the winter. Additionally most entangled animals from the winter period would not be observed until the following summer when the majority of seals return to land.

In order to identify trends in the total number of entanglements in each year we used a piecewise regression with the distribution of residuals and residual standard error used to determine the number of segments and the position of the break points on the time axis. As packaging bands and synthetic line are the two most common entangling materials (Croxall et al., 1990; Arnould and Croxall, 1995) with specific measures in place to reduce their impact, this regression was then repeated using only incidents involving each of these two materials.

Using the total number of entanglements each year after the April 1994 breakpoint (see Section 3), we built a series of generalised linear models with a negative binomial distribution using forward and backwards stepwise model selection (step function, R Development Core Team, 2011). Model fits were compared based on the lowest Akaike Information Criterion (AIC) and the approximate significance of the terms. Residual plots and partial residual plots were also used to assess model suitability. Explanatory variables used in the models were: year (April–March) where 'year' is the first part of the split year e.g. April 1994–March 1995 = 1994 (*year*); the number of pups surviving to weaning on a study beach on Bird Island in the summer (November–March) (*no. pups*); the total amount of beached debris collected over the year

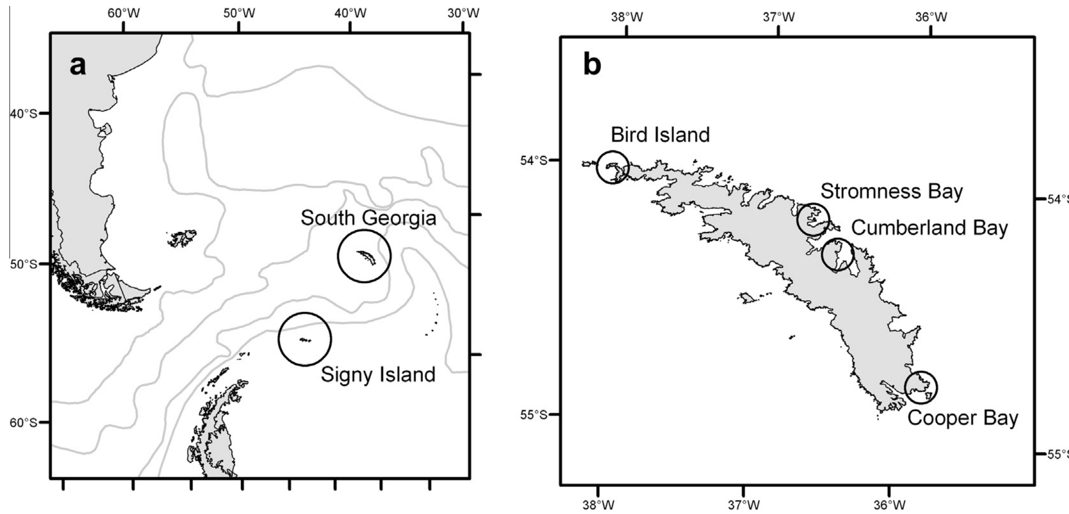

Fig. 1. Areas surveyed for entangled Antarctic fur seals showing (a) South Georgia and Signy Island, South Orkneys and (b) location of survey sites on South Georgia. Data were obtained from Bird Island, South Georgia (continuously from November 1989 to March 2013), Stromness Bay (January and February 1989), Cumberland Bay (November 2008 to March 2013), Cooper Bay (December 2005 to February 2006) and Signy Island, South Orkneys (summer only, January–March 1997–2013).

(April–March) from Main Bay, Bird Island (*beached debris*) (see Walker et al., 1997 for details); the total catch from regulated fisheries for toothfish, icefish and krill (weighted by the average catch for that species) each year (*licensed fishing*); and a measure of illegal, unreported and unregulated fishing calculated by CCAMLR (*IUU fishing*).

Chi squared tests were carried out using the chisq.test() function in R and used to test for differences in contingency tables summarising data on sex/age class, season, type of material and severity of entanglement.

2.3. Entanglements at other sites in the Scotia Sea

Data on entangled seals were also available from a number of other sites in the Scotia Sea, monitored using the same methodology, although records span shorter durations. These were: three sites on mainland South Georgia; Stromness Bay (Cape Saunders to Kelp Point; 54.16°S 36.71°W; during January and February 1989), Cooper Bay (54.8°S 35.78°W; during December 2005–February 2006) and Cumberland Bay (54.28°S 36.5°W; during November 2008–March 2013) and at Signy Island, South Orkneys (60.43°S 45.36°W; summer only data; January to March from 1997 to 2013) (Fig. 1). Entanglements from Cumberland Bay and Signy Island are routinely recorded as part of a long term marine debris monitoring programme, whilst data from Stromness Bay and Cooper Bay were collected opportunistically by field parties working in the area. As effort in recording entanglements at Signy Island is summer-only and on mainland South Georgia covers a relatively short and non-continuous time period, these data are reported here for comparison with Bird Island but are not included in our analyses.

3. Results

3.1. Entanglements at Bird Island, South Georgia

In total, 1033 incidences of entanglements of Antarctic fur seals in man-made debris were recorded between 1 November 1989 and 31 March 2013 (Fig. 2). Of these, 376 (36%) were during the austral winter (April to October) and 657 (64%) during the austral summer (November–March) (Table 1). The highest levels of entanglement were observed in 1989 (160 seals; data for the summer only)

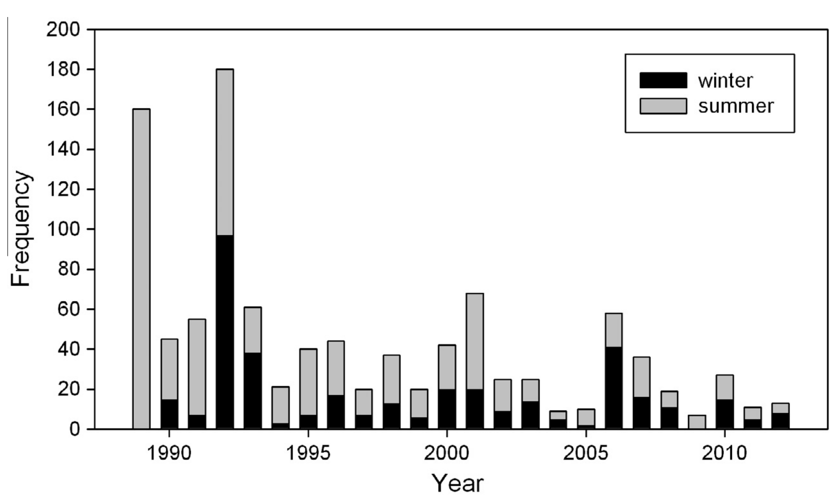

Fig. 2. Entanglements by year where ‘winter’ is April to October and ‘summer’ is November to March. ‘Year’ corresponds to the first part of the split year (e.g. 1989 = April 1989–March 1990). Note that there are no winter data for 1989 (April–October 1989). No incidences of entanglements were recorded in winter 2009.

Table 1
Type of material entangling seals at Bird Island, South Georgia 1989–2013.

Type of material	Summer	Winter	Total
Packaging band	287	155	442
Synthetic line	149	112	261
Fishing net	128	52	180
Plastic bag/tape	31	32	63
Rubber band	16	5	21
Unknown	46	20	66
Total	657	376	1033

Table 2
Distribution of fur seals entangled in marine debris by age, sex and season. Figures in brackets are weighted values to reflect the different durations of winter (7 months) and summer (5 months) periods.

	Adult	Juvenile	Pup	Summer	Winter	Total
Male	47	455	25	319(273)	208(249)	527
Female	150	136	18	228(195)	76(91)	304
Unidentified	0	163	39	110(94)	92(110)	202
Total	197	754	82	657	376	1033

and 1992 (180 seals) (Fig. 2). In total, 791 entanglements were removed (77%); there was a slightly higher proportion in the summer (78%) compared to winter (73%). All entangled seals were alive except for one incidence in February 2012 involving a nylon rope loop found on a decomposed juvenile male seal. Data showing the annual number of entanglements are given in Appendix A.

Juvenile fur seals were the most commonly entangled age group, accounting for 754 (73%) entanglements, with 82 pups (8%) and 197 adults (19%) also observed. Male seals (51%) were more commonly entangled than females (29%), with 20% (pups/young juveniles) not sexed (Table 2). Overall, the most commonly entangled demographic group were juvenile male seals (44%; Table 2). There were significantly more female entanglements in summer than in winter ($\chi^2 = 28.25$, $df = 2$, $p < 0.01$), but males and unsexed animals showed little difference between seasons even when data were weighted for the different durations of the two periods (5 and 7 months for summer and winter respectively) (Table 2).

Packaging bands were the most commonly recorded material, present in 43% of entanglements (Table 1). Entanglements in synthetic line were observed in 25% and fishing net in 17% of cases. There were no differences between summer and winter in terms of these three types of entangling material ($\chi^2 = 3.26$, $df = 2$, $p = 0.196$). Other entanglements involved plastic bag/tape (6%) and rubber bands (2%), with the remaining 6% of entanglements involving unknown materials. Data showing entanglement material by year are given in Appendix B.

Over half (54%) of all entanglements were recorded as 'tight', with 33% either 'severe' or 'very severe' (Table 3). There was no difference in the level of entanglement severity between male and female seals ($\chi^2 = 4.52$, $df = 3$, $p = 0.210$) and the only effect of seal age class was that pups had a much higher likelihood of having entanglements defined as 'loose' ($\chi^2 = 63.04$, $df = 9$, $p < 0.001$). When considering the three most common entangling materials (where $n > 100$; Table 1), there were fewer 'loose' entanglements caused by fishing net than expected ($\chi^2 = 13.49$, $df = 6$, $p = 0.036$). There were a higher proportion of 'very severe' entanglements in winter compared to summer ($\chi^2 = 18.95$, $df = 3$, $p < 0.001$).

The loop diameter was recorded for entangling material removed from 90 animals. Loops were between 11 and 69 cm in diameter (median = 18 cm). Loop diameter was related to age class when adult females and adult males were differentiated. Pups were most commonly entangled in smaller loops (median = 15.5 cm) whereas loop diameters from juveniles and adult females were very similar (median; adult females = 17 cm, juveniles = 18 cm). Adult males were more likely to be entangled in the largest loops (median = 34 cm).

A piecewise regression analysis showed that a single breakpoint at 1994 gave the most parsimonious description of the total number of entanglements per year (AIC; no breakpoint = 243.28, 1994 = 240.40, 1994 and 2003 = 243.81). The number of seals entangled each year prior to 1994 were highly variable (mean ± s.e. = 110 ± 28) but at that break point showed a significant drop followed by a gentle decline (mean ± s.e. = 28 ± 4, No. entanglements = 2814.97–1.390*year). Analyses examining only those entanglements that involved one of the two main entangling materials (either packaging bands or synthetic line) showed very similar results to the analysis considering all entanglements; there was high variability prior to 1994 followed by a slow (non-significant) decline after the break point (No. packaging bands = 958.67–0.627*year, No. synthetic line = 648.6–0.319; 0.319*year Fig. 3).

Stepwise model selection and examination of the residuals showed that the model with the lowest AIC value used only the number of pups as an explanatory variable which had a positive effect on the number of entanglements (Table 4; Fig. 4). In the best fitting model the negative binomial distribution had a theta of 5.333 and a residual deviance of 18.416 on 16 degrees of freedom. This model also showed the best fit for the residuals. Year was not included in the best fitting model suggesting no temporal trend in entanglements since 1994.

3.2. Entanglements at other sites in the Scotia Sea

From the three surveyed sites on mainland South Georgia (Fig. 1) there were 79 records of entangled Antarctic fur seals. This included one juvenile and four adult females (all observed during the austral summer), three adult males, 15 juvenile males and 56 unsexed juveniles. The most commonly identified materials were packaging bands (44%) fishing net (30%) and synthetic line (14%). Entangling material was removed from 43 animals (54%).

Between January and March 1997–2013 there were 48 entanglements of Antarctic fur seals at Signy Island, South Orkneys. Additionally, a single adult male Weddell seal was sighted in December 2011 severely entangled in an unknown material. All entangled Antarctic fur seals reported at Signy Island were males including one adult (recorded in March 2011) and 47 juveniles. The most common entangling materials were fishing net (34%),

Table 3
Distribution of the severity of fur seal entanglements in marine debris between age and sex classes and major ($n > 100$) debris types.

Age/Sex						Material type			
Severity	Female	Male	Adult	Juvenile	Pup	Fishing net	Synthetic line	Packaging band	Total
Loose	30	67	19	86	31	12	36	65	136
Tight	172	287	118	395	40	113	131	245	553
Severe	59	81	34	140	4	28	54	65	178
Very severe	43	91	26	131	7	27	39	67	164

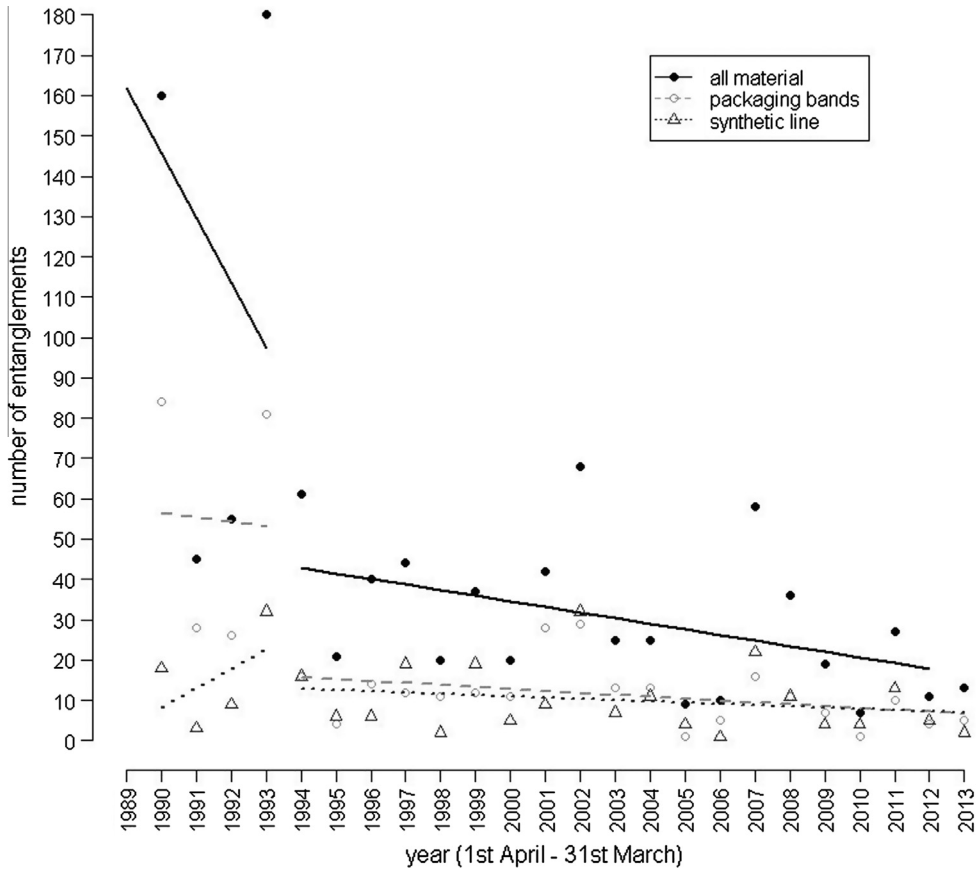

Fig. 3. Piecewise regression of number of entanglements versus year. The most parsimonious split based on AIC values and residuals was 1994. Data for entanglements involving only packaging bands or synthetic line are also shown.

Table 4
Model output showing the estimate of each term fitted, the probability of that term and the AIC of the model with only that term fitted. N.B. the terms were selected using the model with lowest BIC. The best model was number of entanglements ~ number of pups, with a residual deviance of 17.904 on 12 d.f. using a negative binomial distribution theta = 6.50 ± 2.68.

	Estimate	*P*	AIC (with term)
All terms (including interactions)			152.97
No. pups	0.003933	<0.001	144.76
Year	−0.038402	0.246	145.13
IUU fishing[a]	−0.000038	0.907	147.05
Beached debris	0.000113	0.902	146.66
Licensed fishing	−0.149926	0.459	147.16

[a] IUU = illegal, unreported and unregulated fishing.

packaging bands (28%) and synthetic line (28%). Entangling material was removed from seven animals (15%). Data showing the annual number of entanglements at all sites are given in Appendix A.

4. Discussion

Based on continuous monitoring at Bird Island, South Georgia between November 1989 and March 2013 we found 1033 fur seals to be entangled in man-made debris. Since 1994 there has been a significant drop in the mean number of entanglements per year. This coincides with a ban on fishing without a licence within the 200 mile maritime zone around South Georgia which came into force in 1993 (Agnew, 2004), and the campaign by CCAMLR in 1995/96 to correctly dispose marine debris at sea (Arnould and Croxall, 1995). Compliance with CCAMLR legislation has apparently been effective but has not removed the problem altogether, suggesting that a proportion of the entangling material may originate outside the CCAMLR region.

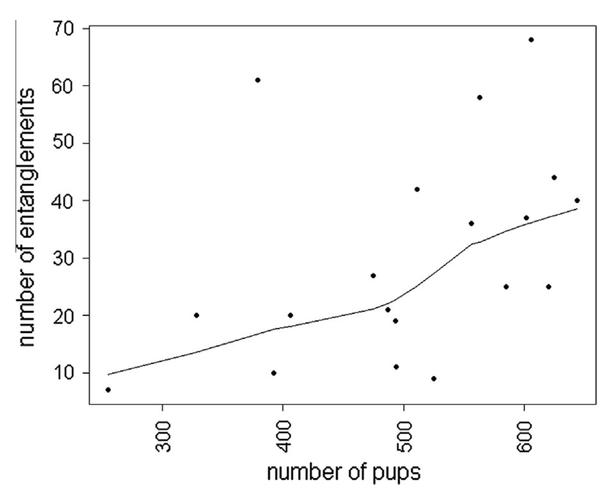

Fig. 4. Relationship between the number of pups surviving to weaning versus the number of entanglements in the same year (1st April – 31st March). The line shows the overall trend based on a lowess smoother using locally-weighted polynomial regression.

4.1. Seasonal differences

Despite the much larger number of seals hauling out at Bird Island in the summer breeding season compared to winter (Payne, 1977) there was no significant difference in the numbers of entangled male or unsexed animals between the summer and winter periods. Female seals were more commonly observed entangled during the summer, which is consistent with their life cycle, with females regularly hauling out to feed dependant pups during the summer breeding season but rarely seen ashore during the winter, as they spend this part of the year at sea (Staniland and Robinson, 2008; Staniland et al., 2012). Similarly, female Antarctic fur seals were disproportionately more likely to be entangled in summer at Bouvetøya (Hofmeyr et al., 2006), and 25% of entanglements reported at Livingston Island during the summer involved female Antarctic fur seals (Hucke-Gaete et al., 1997). Much of the entangling debris appears to be derived from fishing vessels, so more entanglements might be expected during the winter as this is when the fisheries operate around South Georgia (Agnew, 2004). However it is probable that some animals entangled during the winter, particularly females (that are not observed in winter), will not be detected until the following summer.

4.2. Age and sex

Juvenile seals, particularly juvenile males, were the most commonly entangled group at Bird Island. This was also the case at other sites around South Georgia and Signy Island (this study) and in many other studies of pinniped entanglements, particularly the otariids (e.g. Fowler, 1987; Pemberton et al., 1992; Hanni and Pyle, 2000; Hofmeyr and Bester 2002; Hofmeyr et al., 2006; Raum-Suryan et al., 2009). Although adult females are similar in size to juveniles, particularly in the girth of the head and neck (as observed in the similar size of band diameters), juveniles were five times more likely than females to be entangled. This is probably a reflection of the different experience and behaviour of the two demographic groups, with younger animals more likely to interact with entangling material through curiosity and play (Fowler, 1987; Laist, 1987). Adult males were the least likely to be entangled, which may be a result of their broader more muscular necks, their relatively smaller numbers within the overall population or behavioural differences. It is also possible that fewer entangled adults of either sex are observed as many entanglements will be fatal prior to adulthood, such that those individuals prone to entanglement will be selected out of the population at an early age.

4.3. Material and severity

Three types of material (packaging bands, synthetic line and fishing net) made up the majority (85%) of entanglements. All three of these are most likely to derive from fishing activities, although some packaging bands and synthetic line could also originate from non-fishery sources. The same type of material was prevalent in entanglements recorded at other sites at South Georgia, at Signy Island (this study) and elsewhere (Laist, 1997; Hofmeyr et al., 2006; Raum-Suryan et al., 2009). It should be noted that entanglements in fishing net may not necessarily originate from trawl fisheries, as vessels operating the Spanish longline system are required to weigh down their lines, often using rocks enclosed in netting bags (Robertson et al., 2008), which might be a more likely source of this material.

More than half of all entanglements were recorded as 'tight', with 33% 'severe' or 'very severe'. Only 13% were 'loose' which might have been able to be removed without human intervention. This means that 87% of entangled animals are likely to be physically injured and eventually killed by their entanglements. This is a similar proportion to that reported by Croxall et al. (1990), with 19% of entanglements in the 1988/89 season recorded as 'loose'. Pups were significantly more likely to be entangled in loose material which is consistent with their taking short trips close to land, such that they are more likely to be observed soon after acquiring entangling material which has not yet had time to become restrictive.

There were fewer loose entanglements in fishing net than expected, which is possibly because animals entangled in netting tend to react violently, which can increase the severity of the entanglement (Feldcamp, 1985). Conversely, the reduced number of loose entanglements in fishing net may be a result of the bulkier material allowing the animal to shake free or gain purchase to pull the net off. If a seal is entangled in a large amount of netting it may not be able to return to land, so only those in small amounts of net are likely to be recorded in a survey of the population ashore (Laist, 1987).

There were significantly more 'very severe' entanglements in the winter compared to the summer; this may be a reflection of the animals hauling out having been away from observation (i.e. at sea or hauled out in areas away from human occupation) for longer periods. In winter the seals hauling out at Bird Island are mostly males, which have a greater neck girth, greater rate of neck growth and higher reserves of blubber than females (Payne, 1979b). These factors could potentially increase the severity of any associated entanglement, especially given the increased time between observations.

Over the period of our study the proportion of seals entangled in packaging bands at Bird Island has declined, with this material causing 58% of entanglements during the 1988/89 pup rearing season (Croxall et al., 1990) and 46% between 1989 and 1994 (Arnould and Croxall, 1995). Between 1994 and 2013 39% of entanglements involved packaging bands, suggesting there has been an encouraging level of compliance with CCAMLR legislation to ban packaging bands from 1995/96 onwards (Arnould and Croxall, 1995). However, closed packaging bands are still a cause of seal entanglements (see Appendix B), and a proportion of bands recovered on the beach at Main Bay, Bird Island between 1994 and 2013 had not been cut (32 closed bands out of 208; 15%; BAS unpublished data).

4.4. Analyses

Our analysis found that a single breakpoint at 1994 gave the best description of inter-annual variability in the number of seals entangled between 1989 and 2013. The annual number of entangled seals prior to 1994 was very variable, but at the 1994 break point the number showed a significant drop followed by a gentle decline. However, year was not a significant term in the model where only the number of pups surviving to weaning showed a positive relationship with entanglements. An overall decline in the number of pups produced since 1994 (Reid and Croxall, 2001 and BAS unpublished data) appears to best explain the decrease in entanglements over this period. The significance of this term is probably because the number of pups surviving to weaning in a year can be used as a simple proxy for the size of the population ashore (Payne, 1979b). Pup production is a strong indicator of how 'good' food resources (particularly krill, *E. superba*) were around the island during both the preceding winter when mothers were pregnant and during the summer when mothers are feeding their pups (Duck, 1990; Lunn and Boyd, 1993; Lunn et al., 1994). When local food resources are abundant there are more seals foraging around South Georgia and this appears to be correlated with higher numbers of entanglements observed.

Our results suggest that there is a residual level of entanglement that has not significantly changed since 1994. As much of the entangling material is non-biodegradable some entanglements may be the result of debris that has been in existence in the region for many years prior to the implementation of legislation to limit its usage. However, if the introduction of marine debris to the region had ceased entirely then we might have expected a strong negative correlation with time, but this was not the case. The origin of the entangling material is not known, although the majority is probably related to fishing activity. We did not find any correlation between the number of entanglements and a measure of licensed or unlicensed (IUU) fishing effort in South Georgia waters. It is possible that entangling material may originate from vessels operating outside of the jurisdiction of CCAMLR or is transported from unregulated areas; most likely to be to the south west of the island given the predominant current flow (Thorpe et al., 2002). Additionally entanglements might also occur a long way from the breeding beaches; fur seals from South Georgia are known to travel large distances reaching as far as the Antarctic Peninsula and Patagonian Shelf (Boyd et al., 1998; Staniland and Robinson, 2008; Staniland et al., 2012; Waluda et al., 2010; Warren et al., 2006), where many fisheries operate and material originating from the continental margins will be encountered. Adherence to marine pollution regulations have been shown to have a positive effect in reducing marine debris in some areas (Edyvane et al., 2004; Hanni and Pyle, 2000), but other studies have shown that the effect on rates of seal entanglements in many areas is negligible (Henderson, 2001; Jones, 1995; Page et al., 2004), highlighting the persistent nature of much of the material likely to cause entanglements.

4.5. Population level effects

The post-1994 mean number of entanglements per year represents around 0.016% of the estimated population at Bird Island (based on a population of 188,000 seals; data from Boyd, 1993). This compares favourably with estimates of entanglement rates at Bird Island of around 0.4% in 1988/89 (Croxall et al., 1990). At Signy Island, rates of entanglement are around 0.02% of the surveyed population (based on a population of 12,595 seals; data from Waluda et al. 2010) and at Maiviken, Cumberland Bay 0.09% (based on a mean population of 1933 seals 2008–2013; BAS unpublished data). As these proportions are low and involve mostly juvenile males, entanglements are unlikely to have a major effect at the population level. However, at an individual level, entanglements, especially in degradation resistant materials such as packaging bands, will ultimately result in death either through starvation, strangulation, blood loss or infection (Laist, 1997; Derraik, 2002; Raum-Suryan et al., 2009). The reported rates of entanglement may be an underestimate as entangled seals are less likely to be observed on land than non-entangled seals; some seals may be entangled in material that prevents them returning to shore, and entangled seals spend more time at sea foraging and have lower survival rates compared to non-entangled seals (Fowler, 1987, 1990). Additionally, as fur is the main means of insulation used by these animals (Bonner, 1968), there will be an effect on the thermoregulation of the entangled individual that is dependent on the severity of the entanglement and the associated damage to the seal's fur.

5. Conclusions

Clearly the data reported here are not comprehensive of the South Georgia population. As we have access only to land-based observations this will significantly underestimate the magnitude of the problem as we can only account for animals entangled in buoyant materials that are lightweight enough to allow them to return to shore. In addition, the observer effort only covers a fraction of the seals' distribution range in the Scotia Sea and the cryptic nature of some entanglements means that many incidences will be missed. All these factors suggest that the true magnitude of entanglement is likely to be significantly higher. However, systematic recording at Bird Island at least allows us to investigate trends and, as the methodology and effort has remained consistent, we are confident that the trends reported here are real. This monitoring work is ongoing at Bird Island, Signy Island and Cumberland Bay, and data are reported annually to CCAMLR with the aim of developing effective strategies to reduce the incidence of entangled seals and other marine life.

Tighter regulation on marine debris by CCAMLR and strong enforcement in the South Georgia fisheries has lead to a significant reduction in the incidences of entanglement by fur seals at South Georgia post 1994. However, issues with marine debris have not been eradicated and Antarctic fur seals are still being entangled in significant numbers at South Georgia and the South Orkney Islands. Whilst unlikely to be of concern at the population level, Antarctic fur seal entanglements represent conspicuous victims of the harmful effects of anthropogenic marine debris and could be seen as an indicator for more cryptic species and threats. Given the relatively simple steps required to eliminate such pollution this should be continue to be a goal of marine conservation and fisheries managers in the Southern Ocean and beyond.

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Appendix A

Number of entanglements per year at all sites. Key: –Not surveyed, ^ Stromness Bay $ Cooper Bay * Cumberland Bay.

Season	Bird Island winter	Bird Island summer	Signy Island summer	South Georgia winter	South Georgia summer
April 1989–March 1990		160	–	–	26^
April 1990–March 1991	15	30	–	–	–
April 1991–March 1992	7	48	–	–	–
April 1992–March 1993	97	83	–	–	–
April 1993–March 1994	38	23	–	–	–
April 1994–March 1995	3	18	–	–	–
April 1995–March 1996	7	33	–	–	–
April 1996–March 1997	17	27	12	–	–
April 1997–March 1998	7	13	5	–	–
April 1998–March 1999	13	24	7	–	–

Appendix A (*continued*)

Season	Bird Island winter	Bird Island summer	Signy Island summer	South Georgia winter	South Georgia summer
April 1999–March 2000	6	14	5	–	–
April 2000–March 2001	20	22	0	–	–
April 2001–March 2002	20	48	1	–	–
April 2002–March 2003	9	16	1	–	–
April 2003–March 2004	14	11	0	–	–
April 2004–March 2005	5	4	2	–	–
April 2005–March 2006	2	8	1	–	4$
April 2006–March 2007	41	17	1	–	–
April 2007–March 2008	16	20	3	–	–
April 2008–March 2009	11	8	1	0*	8*
April 2009–March 2010	0	7	0	1*	3*
April 2010–March 2011	15	12	4	3*	9*
April 2011–March 2012	5	6	5	3*	7*
April 2012–March 2013	8	5	0	2*	13*
	376	657	48	9	70

Appendix B

Entanglements by material type and year at Bird Island November 1989–March 2013. –Not surveyed.

Season	Winter (April–October)				Summer (November–March)			
	Fishing net	Packaging band	Synthetic line	Other	Fishing net	Packaging band	Synthetic line	Other
April 1989–March 1990	–	–	–	–	36	84	17	23
April 1990–March 1991	2	12	0	1	4	16	3	7
April 1991–March 1992	2	5	0	0	13	21	9	5
April 1992–March 1993	13	47	21	16	17	34	11	21
April 1993–March 1994	6	9	11	12	7	7	5	4
April 1994–March 1995	0	1	1	1	7	3	5	3
April 1995–March 1996	2	2	2	1	7	12	4	10
April 1996–March 1997	4	3	8	2	6	9	11	1
April 1997–March 1998	1	4	1	1	5	7	1	0
April 1998–March 1999	1	3	9	0	3	9	10	2
April 1999–March 2000	1	3	0	2	0	8	5	1
April 2000–March 2001	2	12	6	0	2	16	3	1
April 2001–March 2002	0	10	6	4	1	19	26	2
April 2002–March 2003	0	4	3	2	0	9	4	3
April 2003–March 2004	0	10	4	0	0	3	7	1
April 2004–March 2005	1	0	4	0	1	1	0	2
April 2005–March 2006	1	0	1	0	1	5	0	2
April 2006–March 2007	9	11	15	6	6	5	6	0
April 2007–March 2008	2	6	7	1	8	5	4	3
April 2008–March 2009	1	2	2	6	1	5	2	0
April 2009–March 2010	0	0	0	0	0	1	4	2
April 2010–March 2011	3	6	6	0	0	4	7	1
April 2011–March 2012	0	3	2	0	2	1	3	0
April 2012–March 2013	1	2	2	3	1	3	1	0
Total	52	155	111	58	128	287	148	94

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