LINE WEIGHTS OF CONSTANT MASS (AND SINK RATES) FOR SPANISH-SYSTEM PATAGONIAN TOOTHFISH LONGLINE VESSELS

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Abstract

CCAMLR Conservation Measure 25-02 requires Spanish-system longline vessels to attach 8.5 kg weights at 40 m intervals on longlines to minimise interactions with seabirds. The weights typically used are collections of rocks enclosed in netting bags. During fishing operations the netting bags abrade on the seabed causing rocks to be lost and the weights to become progressively lighter, requiring ongoing repair. This problem can be solved by use of hydrodynamically shaped (e.g. torpedo-shaped) steel weights, which are smaller for equivalent weight, and require no maintenance. An experiment was conducted on a Spanish-system longline vessel to determine the relationship between the sink rates of longlines equipped with bags of rocks (4, 6 and 8 kg) and those with steel weights of equivalent masses. The purpose of the experiment was to provide vessel operators with the option of substituting steel weights for rock weights while remaining in compliance with the sink rates associated with the line-weighting provisions of Conservation Measure 25-02. Both the Spanish system and the newly developed Chilean longline (a modified version of the former method to avoid fish loss by toothed whales) were tested in the experiment. Spanish-system longlines with 8 kg rock weights every 40 m averaged 0.22 m s^{-1} to 2 m depth, which would be equal to, or exceeded by, lines with 5 kg steel weights. Sink rates of Chilean longlines greatly exceeded those of the Spanish system, ranging from 0.68 m s^{-1} (4 kg rocks) to 1.31 m s^{-1} (8 kg steel) in the shallow depth ranges. Hydrodynamically shaped steel weights weighing 5 kg would be an appropriate substitute for 8.5 kg rock weights irrespective of fishing method.

Résumé

La mesure de conservation 25-02 de la CCAMLR exige que les navires utilisant des palangres de type espagnol fixent le long des lignes des lests de 8,5 kg à des intervalles de 40 m pour réduire au minimum les interactions avec les oiseaux de mer. Les lests sont généralement constitués d'un un sac en filet contenant un mélange de pierres. Au cours des opérations de pêche, les sacs s'abrasent sur le fond de la mer, les pierres se perdent et les lests deviennent de plus en plus légers et nécessitent sans cesse des réparations. Ce problème peut être résolu par l'utilisation de lests en acier de forme hydrodynamique (comme une torpille), qui sont de plus petite taille, mais de poids équivalent, et qui ne nécessitent aucun entretien. Des essais ont été réalisés sur un navire utilisant des palangres de type espagnol pour déterminer le rapport entre la vitesse d'immersion de palangres équipées de sacs de pierres (de 4, 6 et 8 kg) et de palangres équipées de lests en acier de poids équivalent. Le but de l'expérience était d'offrir aux armateurs la possibilité de substituer des lests en acier aux lests de pierres tout en restant en conformité avec les dispositions de la mesure de conservation 25-02 relatives à la vitesse d'immersion et au lestage des lignes. Deux systèmes de palangre ont été testés dans l'expérience : le système espagnol et la nouvelle palangre chilienne (une version modifiée de l'ancienne méthode, visant à éviter la perte de poissons due à la déprédation par les baleines à dents). Les palangres de type espagnol sur lesquelles étaient fixés tous les 40 m des lests de pierres de 8 kg ont atteint 2 m de profondeur à une vitesse moyenne de 0,22 m s^{-1}, vitesse également atteinte, ou même dépassée par les lignes sur lesquelles étaient fixés des lests de 5 kg en acier. La vitesse d'immersion des palangres chiliennes était largement supérieure à celle du système espagnol, variant de 0,68 m s^{-1} (4 kg de pierres) à 1,31 m s^{-1} (lests de 8 kg en acier) dans les intervalles de faibles profondeurs. Des lests en acier de 5 kg de forme hydrodynamique pourraient donc remplacer les lests de pierres de 8,5 kg, quelle que soit la méthode de pêche.

Резюме

Мера АНТКОМа по сохранению 25-02 требует от судов с испанской системой ярусов прикреплять на ярусы грузила весом 8.5 кг с интервалами 40 м, чтобы сократить взаимодействия с морскими птицами. В качестве грузил обычно используются сетки с камнями. В ходе промысловых операций эти сетки повреждаются, цепляясь за дно, камни высыпаются, и грузила становятся все легче, требуя постоянной починки. Эту проблему можно решить путем использования стальных грузил, имеющих гидродинамическую форму (напр., торпедообразную), которые при том же весе имеют меньший размер и за которыми не нужно следить. На одном из ярусоловов с испанской системой был проведен эксперимент по определению соотношения между скоростью погружения яруса с прикрепленными сетками камней (4, 6 и 8 кг) и яруса со стальными грузилами такой же массы. Цель эксперимента заключалась в том, чтобы дать операторам судов возможность заменять грузила из камней стальными грузилами, соблюдая при этом соответствующее требование о скорости погружения в положениях Меры по сохранению 25-02 о затоплении яруса. В ходе эксперимента испытывались как испанская система, так и недавно разработанный чилийский ярус (модифицированный вариант первого метода, позволяющий предотвратить потерю рыбы в результате нападения зубатых китов). Ярусы испанской системы с грузилами из камней весом 8 кг, прикрепленными через каждые 40 м, погружались на глубину 2 м со средней скоростью 0.22 м/с, которая достигалась или превышалась при использовании ярусов со стальными грузилами весом 5 кг. Скорости погружения чилийских ярусов были намного выше, чем у ярусов испанской системы, и составляли от 0.68 м/с (4 кг камней) до 1.31 м/с (8 кг стальные грузила) на небольших глубинах. Стальные грузила гидродинамической формы весом 5 кг могут быть подходящей заменой грузил из камней весом 8.5 кг независимо от промыслового метода.

Resumen

La Medida de Conservación 25-02 de la CCRVMA exige que los barcos que utilizan el sistema de palangre español coloquen pesos de 8.5 kg a intervalos de 40 m en las líneas para minimizar las interacciones con las aves marinas. Los pesos utilizados normalmente consisten de varias rocas dentro de una bolsa de malla. Durante las operaciones de pesca las bolsas se rompen al raspar el lecho marino con la consiguiente pérdida de rocas, haciéndose cada vez más livianas y requiriendo de constante reparación. Este problema puede resolverse mediante el uso de pesos de acero de forma hidrodinámica (p. ej. en forma de torpedo), que son más pequeños en comparación con pesos equivalentes, y no requieren mantenimiento. Se realizó un experimento en un palangrero que utilizó el sistema español para determinar la relación entre las tasas de hundimiento de los palangres a los que se colgaron bolsas con rocas (4, 6 y 8 kg) y aquellos con pesos de acero de igual magnitud. El objetivo del experimento fue dar la opción a los operadores de barcos para que sustituyesen las bolsas con rocas por pesos de acero cumpliendo en todo momento con las tasas de hundimiento requeridas por la Medida de Conservación 25-02. Tanto el sistema español como el nuevo sistema de palangre chileno (una versión modificada del método anterior para evitar la pérdida de peces por la depredación de las ballenas odontocetas) fueron probados en el experimento. La tasa de hundimiento promedio de los palangres españoles con bolsas de rocas de 8 kg cada 40 m fue de 0.22 m·s^{-1} a una profundidad de 2 m, valor igual o inferior a la tasa de hundimiento de líneas con pesos de acero de 5 kg. Las tasas de hundimiento de los palangres chilenos excedieron en gran medida las del sistema español, variando entre 0.68 m·s^{-1} (rocas, 4 kg) y 1.31 m·s^{-1} (pesos de acero de 8 kg) en los estratos de menor profundidad. Las bolsas de malla con rocas de 8.5 kg podrían ser sustituidas por pesos de acero de 5 kg de forma hidrodinámica, independientemente del método de pesca utilizado.

Key words: longline fishing, Spanish system, Chilean method, line weights, sink rates, seabird mortality, cooperative research, CCAMLR

Introduction

Spanish-system longline vessels fishing for Patagonian toothfish (*Dissostichus eleginoides*) deploy buoyant longlines with weights attached at regular intervals to make them sink. Weights enable fishers to sink gear as part of a fishing strategy, allowing baited hooks between weights to loft off the seabed, and to land gear in specific areas on the deep seabed (e.g. shelf breaks) against the forces of currents. Weights added to longlines are also important in efforts to sink gear expeditiously to reduce interactions with seabirds. Spanish-system longlines are particularly dangerous to seabirds in the first several seconds after deployment, because the buoyant lines between weights float momentarily. The mass of the weights used to sink longlines is especially significant because it overrides in importance the effect of other factors, such as setting speed and distance between weights (Robertson et al., 2008a). To deter seabirds, CCAMLR Conservation Measure 25-02 requires Spanish-system vessels to deploy 8.5 kg weights at 40 m intervals on hook lines (CCAMLR, 2005). This line-weighting regime arose from Agnew et al. (2000) who showed a reduction in mortality of black-browed albatrosses (*Thalassarche melanophrys*) and white-chinned petrels (*Procellaria aequinoctialis*) at South Georgia with an increase from 4.25 kg at 40 m to 8.5 kg at 40 m on longlines (the 8.5 kg weight expressed to the nearest 0.5 kg is a consequence of the heavier weight being a multiple of the lighter weight). Research subsequent to Agnew et al. (2000), who did not measure sink rates, revealed that longlines equipped with the heavier regime reached, for example, 2 m depth and 5 m depth 24% (8 s c.f. 11 s) and 29% (13 s c.f. 19 s) faster respectively than longlines with the lighter regime (Robertson et al., 2008a). This highlights the importance of the mass of the weights in sinking longlines in the water depths likely to be most dangerous to seabirds.

The weights used by Spanish-system operators typically comprise collections of rocks held in bundles by netting bags stitched together from trawler net. This is an antiquated line-weighting method that creates problems with regard to consistency of mass, gear sink rates, the capacity of vessels to meet the line-weighting provisions of Conservation Measure 25-02 and the capacity of observers to report accurately on this. During fishing operations the netting bags are easily broken, causing rocks to fall out (nets abrade on the seabed and are broken when thrown around the vessel during retrieval). Unless the netting bags are regularly maintained and the weights frequently weighed, which is difficult at sea due to the large number of weights involved and the rise and fall of the vessel, the weights become lighter – and sink rates slower – as fishing operations progress. Until the advent of longlines with integrated weight for autoline vessels, torpedo-shaped steel weights (typically referred to as 'jigger' weights) were used routinely by autoline vessels in the Antarctic toothfish (*D. mawsoni*) fishery in the Ross Sea. These weights are smaller, denser, more hydrodynamic, easier to handle and store, and because of their smooth profile and absence of netting enclosure require no maintenance. They are also less likely to snag on the seabed, potentially reducing the amount of gear lost in benthic habitats.

This paper presents the results of an experiment designed to determine the relationship between the sink rates of longlines equipped with bags of rocks and those equipped with torpedo-shaped steel weights. It is important to understand this relationship so that substitution of steel weights for rock weights does not compromise the sink rates associated with the line-weighting provisions of Conservation Measure 25-02. The Spanish system was recently redesigned to avoid toothfish depredation by sperm whales (*Physeter macrocephalus*) and killer whales (*Orcinus orca)*, with the variant being called the 'Chilean longline' (Moreno et al., 2008). If these species are not present on the fishing grounds, the Spanish system is reputed to catch more fish than the Chilean method (the former method deploys more hooks per set), but if sperm whales and killer whales are present, the reverse is true. To maximise fish catch rates, fishers may choose which method to use depending on fish abundance and prevalence of sperm whales and killer whales around vessels, and may switch between methods in the same sets. Since both methods are likely to be used to varying degrees in the future, the sink-rate relationships between weight types for both the Spanish system and the Chilean longlines were examined.

Materials and methods

Spanish system

The Spanish system has been described by Robertson et al. (2008a). Briefly, the Spanish system uses two lines set in parallel – a heavy hauling line ('retenida') and a light-weight hook line ('linea madre'). Numerous secondary connecting lines or branch lines ('barandillos') join the hauling line to the hook line (Figure 1). During line setting, the hauling and hook lines are payed out from opposing sides of the vessel. The hook line is kept in sections in baskets, with each basket containing two lengths of hook line. The lengths of hook line are tied together to form a continuous line, and weights are tied to the join in the centre and at each end of the basket. As lines are payed out, crew connect the hauling and hook lines with the branch/connecting lines, making the various components a cohesive unit.

Chilean longline

The Chilean longline has been described by Moreno et al. (2008). Briefly, this method has its origins in the mid-1990s in the Chilean artisanal toothfish fishery (Moreno et al., 2006) to minimise fish loss to toothed whales and was recently adapted (and changed) by the industrial toothfish fleet for the same reasons. The Chilean longline involves the removal of the hook line from the Spanish system. Hooks are attached to short snoods in clusters near the ends of the branch/connecting lines, and a weight is attached to the end of each one (Figure 1). The branch/connecting lines can be fitted with a wind-sock-shaped netting sleeve ('cachalotera') (named for the Spanish 'cachalote', the sperm whale). Being made from buoyant material (polypropylene), during setting and when at fishing depth, cachaloteras float up the branch/connecting lines, freeing the lower sections of line with the baited hooks which are exposed to toothfish. When lines are hauled off the seabed, the branch/connecting lines are drawn through the cachaloteras which encircle caught fish and protect them from attack by whales as lines are brought to the surface.

Fishing vessel, location and gear

The experiment was conducted over two days, on 9 and 10 June 2007, on the FV *Tierra del Fuego* near Isla Nueva (55°13.0'S 66°25.4'W) which lies in the eastern junction of the Beagle Channel and the South Atlantic Ocean. The vessel was chartered especially for the experiment and was not engaged in commercial fishing. The *Tierra del Fuego* is a 53.6 m Japanese-built (1972) tuna vessel converted to the Spanish system of fishing. In terms of vessel features that may affect sink rates of longlines, the *Tierra del Fuego* has a single, 2 m diameter two-blade variable pitch propeller (nominal rpms: 400 at 6 knots). Longlines were deployed into the upswing area of the propeller wash from a position 2.5 m above sea level. Longlines were set twice only, once for the Spanish system and once for the Chilean longline. Setting speed for both sets was 6 knots and wave height during both sets was <0.5 m. Water depth ranged from 120 to 550 m.

The Spanish system set from the *Tierra del Fuego* comprised gear purpose-built for the experiment to CCAMLR line-weighting specifications (40 m between weights). Gear comprised a 16 mm diameter polypropylene hauling line, 8 mm diameter polypropylene branch/connecting lines (20 m long) and a new hook line (3.5 mm diameter monofilament nylon). By this design (see Figure 1), branch/connecting lines were spaced 80 m apart on longlines. Hook-bearing snoods were 2 mm in diameter, 0.7 m long, monofilament nylon attached to the hook line with swivels every 1.6 m. Gear for the Chilean longline comprised the same hauling and branch/connecting lines as for the Spanish system with branch/connecting lines (and line weights) 40 m apart. The dimensions of cachaloteras and lengths and locations of the hook line and snoods differed from Moreno et al. (2008), but only slightly. On the *Tierra del Fuego* each branch/connecting line was fitted with a mix of 1.8 m or 2.0 m long cachaloteras (dry weight 1.8 m cachalotera: 1.23 kg; 2.5 m long cachaloteras are also used in the fishery). Two

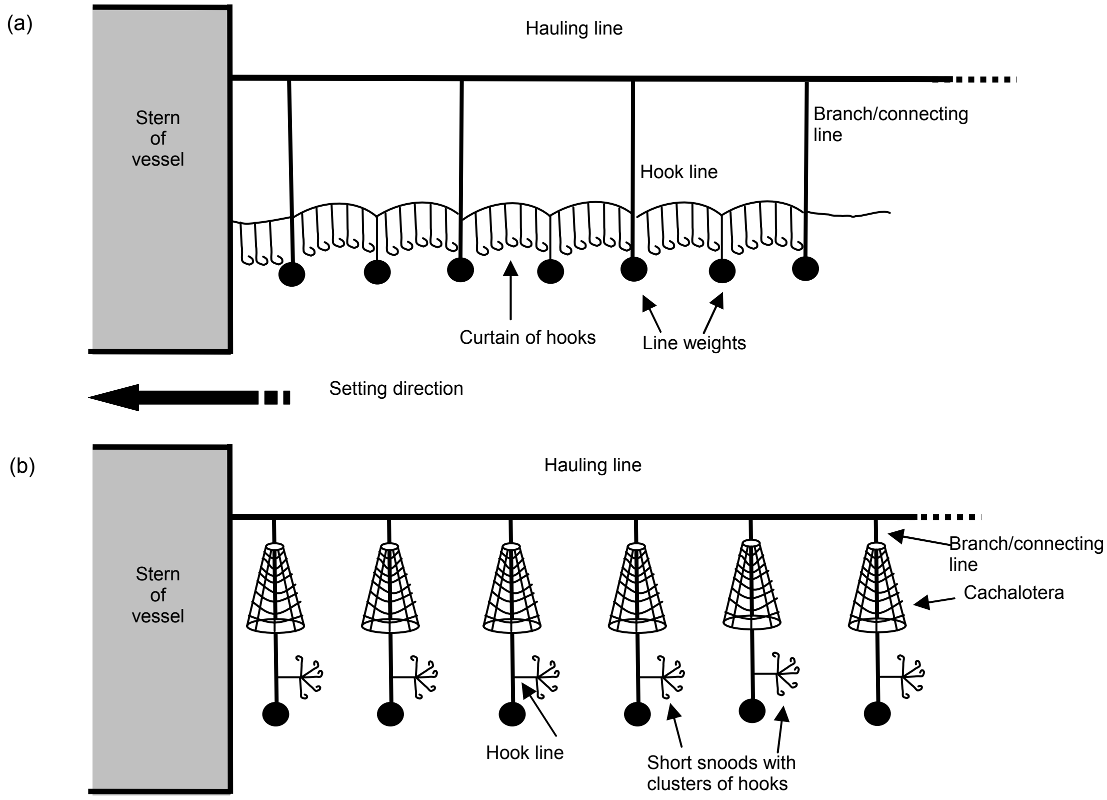

Figure 1: Stylised version (not to scale) of the structure of: (a) the Spanish system, and (b) the Chilean longline as used in the experiment.

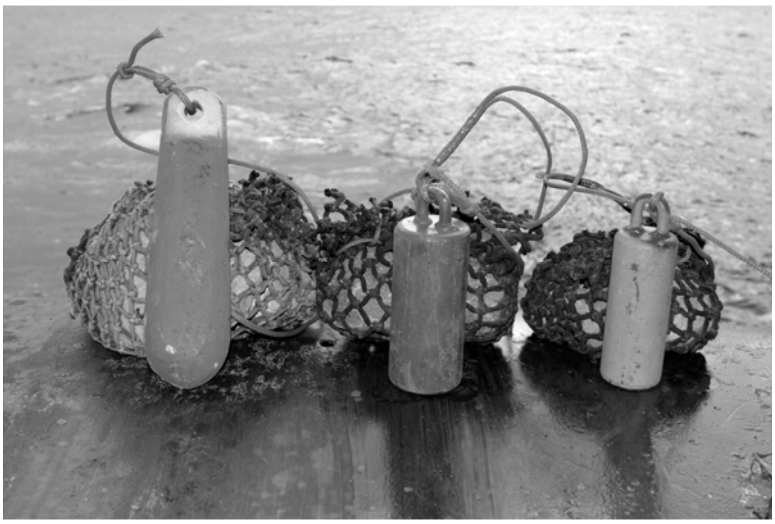

Figure 2: Examples of rock weights (rear) and steel weights used in the experiment. Also shown is the difference in shape between the steel weights produced from a mould (left) and those cut from steel rod. Weights from left to right are 8, 6 and 4 kg.

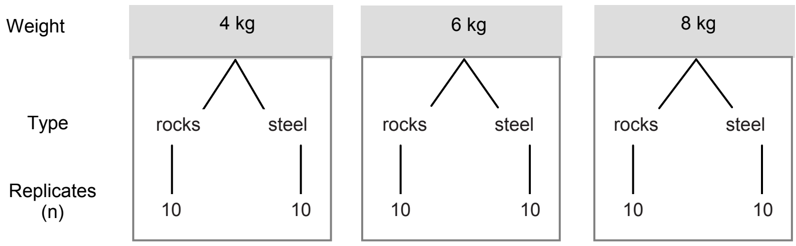

Figure 3: Setting order of replicates within weight types and weight masses used in the experiment for both fishing methods.

short (<0.3 m) sections of hook line, about 0.5 m apart, and each bearing six to eight 0.3 m long snoods with hooks, were attached 0.3 m above the terminal ends of each branch/connecting line. As gear was being set, weights were tied to the ends of each branch/connecting line with a 0.5–1 m long snood. By this gear configuration, baited hooks were located no more than 1.5 m from weights, whereas with the Spanish system, weights ranged from a few metres to nearly 40 m from hooks.

For the purposes of the experiment, hooks for both fishing methods were baited with sardines (*Sardina pilchardus*) which are typically used in toothfish fisheries in Chile and in CCAMLR waters.

Line weights

Line weights tested in the experiment were 4, 6 and 8 kg. Streamlined steel weights are likely to sink faster than rock weights, so it was considered unnecessary to use weights heavier than 8 kg. The authors purpose-built the rock weights which were weighed to the nearest 5% on an electronic balance. The steel weights were purpose-built by a steel works company in Valdivia, Chile. The intention was to cast the steel weights from a computer-generated moulded design (torpedo-shaped) identical to those used in the Ross Sea fishery. (Moulded cast iron weights are available from CCIP (China Cast Iron Company – www.china-cast-iron.com). However, after production of about half the 70 required 8 kg weights, the mould broke and time did not permit production of a new mould. Therefore, the remaining 8 kg weights and all the 4 kg and 6 kg weights were cut from round-section steel rod following computer-assisted determination of the weight of the various components (snood attachment loop, weld beads). The difference in shape was minor and not expected to affect the sink-rate relationships recorded in the experiment (Figure 2).

Experimental design

Deployment of the Spanish system followed closely the procedure of Robertson et al. (2008a). Weights were deployed in a single set of the longline, in continuous procession and in systematic order from the lightest weights to the heaviest (4 kg then 6 kg then 8 kg). Within each mass, the rock weights were always set before the steel weights. For each type of weight and each mass of weight, 10 replicates were set in series (Figure 3). A replicate comprised three baskets of gear and seven line weights spaced 40 m apart. Each of the 10 replicates within each weight type/mass replicate was separated by 100 m of connecting line (hookless fishing line), which took 30 s to pay out, to provide independence between the replicates. At the end of each set of 10 replicates within weight mass and weight type, 200 m of connecting line was payed out. This procedure was continued until all combinations of the two weight types and three weight masses were exhausted. To avoid gear being yanked repeatedly from the water, which occurs when weights are allowed to be pulled from the vessel by gear already deployed, all line weights were released by hand before line tension occurred.

The Chilean longline was also set in a single set of the longline in the same order of weight mass and weight type as described above. Similarly, 10 replicates for each weight-type mass within weight type were set, each replicate comprising seven branch/connecting lines with replicates separated by 100 m of connecting line (in this case, hauling line). As for the Spanish system, at the end of each set of 10 replicates, 200 m of connecting line were deployed to separate the weight types.

Sink rates of longlines were recorded with time-depth recorders (TDRs; MK9, Wildlife Computer, USA) programmed to record depth at 0.5 m resolution every second. A total of 60 TDRs was deployed on each set of the line (i.e. two weight types x three weight masses x 10 replicates/weight mass). For both fishing methods, one TDR was deployed in each replicate. For the Spanish system, TDRs were attached midway between line weights at the aft end of the second of the three baskets/replicate. Thus, by the time each TDR was deployed, four line weights of the replicate had already been deployed and three weights were deployed after the TDR. With the Chilean longline, TDRs were attached to the ends of the fourth branch/connecting line of the seven branch/connecting lines in each replicate. Thus, when TDRs entered the water, three weights of the replicate had already been deployed.

Before deployment, the internal TDR clocks were synchronised with a digital watch. The exact water entry time (nearest second) was recorded for each device. On retrieval, data from the TDRs were downloaded to a computer, water entry times noted in the files and files 'corrected' based on the median offset value of the 10 rows of data before the water entry time.

Data analysis

In previous studies of the sink rates of Spanish-system longlines (Robertson et al., 2008a) and autolines (Robertson et al., 2008b), data were analysed using 'time to target depths' as the response variable. In the current study the data were analysed using 'depth at given time intervals of 1 s' (rather than time-to-depth) as the response variable for both fishing methods. This latter approach allows finer-scale data to be used in the analysis which requires depth as the response variable if autocorrelation in the depth data with time is to be modelled. However, this approach does not allow sink rates to be obtained by direct application of the fitted model, but requires an iterative search to be carried out, as described below.

The repeated observations of depth were modelled for 1 s intervals for times of 1–17 s using a linear mixed model (LMM). The LMM incorporated cubic smoothing splines (Verbyla et al., 1999), fitted using the ASREML library (Gilmour et al., 1995, 1999) within the R software package (R Development Core Team, 2006). The limit of 17 s was the maximum time for which all replicates yielded a complete set of depths (i.e. for the fastest sinking lines the maximum depth recorded was reached in 17 s). The fixed effects in the LMM were the 12 combinations of the three factors: fishing method (Spanish, Chilean), weight type (rocks, steel) and masses of the weights (4, 6 and 8 kg). In the non-parametric form of the LMM, 'time' was included as a factor with 17 levels (i.e. times 1–17) to examine the depth trend with time without smoothing using the spline. In the parametric form of the LMM, time was fitted as a linear trend along with nonlinear cubic spline terms. The random terms in both LMMs (apart from spline terms in the parametric LMM) were 'TDR' (individual TDRs were used repeatedly) and the replicate-within-treatment combination. To account for increasing variance of depth with time given the treatment combination, data were log transformed so that the response variable fitted by the LMM was y = log(Depth + 1) and predictions on this scale, $\hat{y}$, could be back-transformed to give a predicted depth of $\exp(\hat{y})-1$. The autocorrelations between depths within a replicate were modelled using a continuous-time exponential decay correlation (equivalent for unit changes in time to a first-order autoregressive error model). This model corresponds to that of Diggle et al. (1994, p. 79) with experimental units (i.e. replicate-within-treatment combination) as random effects plus residual variance with autocorrelation but no measurement error. Generalising this model, the need to specify separate variances for each time point, in case the log transform over-corrected for heterogeneous variances, was also investigated.

Sink rates to 5 s and between 5 and 10 s were predicted using the parametric LMM. The parametric (i.e. cubic spline) LMM gives predictions that 'gain strength' from considering the profile as a sequence of values that follow a clear trend, rather than simply a set of means as with the non-parametric LMM. To predict sink rates to 2 m and 5 m depth (see below for the reasons for the choice of these two depths), the parametric spline model was used to search for predictions of depth given time that were, to a close approximation, equal to 2 m and 5 m (i.e. using 0.1 s time intervals) respectively, so these depths could be divided by the corresponding time to give sink rates.

Approximate standard errors of predicted depths used to obtain sink rates were obtained as $SE(\hat{y})\{\exp(\hat{y})-1\}$ where $SE(\hat{y})$ is the standard error on the transformed scale. The approximate widths of the 95% confidence bounds for the difference between the predicted average depth-versus-time profile between mass treatments for each combination of weight type and fishing method were obtained as $2.101\sqrt{2}SE(\hat{y})\{\exp(\hat{y})-1\}$, where $\hat{y}$ was averaged across mass treatments and 2.101 is the 95% probability two-sided t-statistic with 18 degrees of freedom (this is a conservative value corresponding to 10 replicates/treatment combination). The zero depth:zero time data points were excluded from the analysis because they have zero variance.

In analysis of data for the Spanish system, sink rates in the 0–2 m and 2–5 m depth ranges were emphasised. The former provides a measure of the

Table 1: Mean masses and coefficients of variation (SD ÷ mean) of 20 randomly selected weights of each weight type built for the experiment. The 4 kg and 6 kg steel weights were cut from steel rod (see text).

Weight type	Nominal mass (kg)	$\bar{x}$ mass (kg)	SD	CV (%)	$\bar{x}$ minus nominal mass (kg)
Rocks	4	4.42	0.09	2.0	+0.42
Steel	4	3.94	0.22	5.6	–0.05
Rocks	6	6.37	0.08	1.3	+0.64
Steel	6	5.97	0.35	5.9	–0.03
Rocks	8	8.45	0.11	1.4	+0.45
Steel (steel rod)	8	8.00	0.04	0.05	0.00
Steel (moulded)	8	7.97	0.11	1.4	–0.03

Table 2: Average sink rates (m s^{-1}) (± SE) of longlines to target depths and, after prescribed time intervals, predicted from the fitted parametric linear mixed model, for longlines equipped with weights of different type and mass. The emboldened categories represent sink rates in water most likely to be affected by propeller turbulence. The other categories represent sink rates in the linear phases of sink profiles and are included for comparison.

Spanish system	Target depth		Elapsed time	
	0–2 m	2–5 m	**0–5 s**	5–10 s
Rocks 4 kg	0.17 ± 0.01	0.50 ± 0.03	0.05 ± 0.00	0.22 ± 0.03
Steel 4 kg	0.23 ± 0.02	0.45 ± 0.03	0.13 ± 0.01	0.39 ± 0.04
Rocks 6 kg	0.21 ± 0.01	0.55 ± 0.03	0.12 ± 0.01	0.31 ± 0.03
Steel 6 kg	0.29 ± 0.02	0.75 ± 0.05	0.21 ± 0.02	0.65 ± 0.04
Rocks 8 kg	0.22 ± 0.02	0.58 ± 0.03	0.15 ± 0.01	0.31 ± 0.04
Steel 8 kg	0.33 ± 0.03	0.80 ± 0.06	0.28 ± 0.02	0.74 ± 0.05

Chilean longline	Target depth	Elapsed time	
	2–5 m	**0–5 s**	5–10 s
Rocks 4 kg	0.51 ± 0.06	0.68 ± 0.06	0.49 ± 0.06
Steel 4 kg	1.06 ± 0.11	1.10 ± 0.09	0.58 ± 0.09
Rocks 6 kg	0.64 ± 0.07	0.77 ± 0.06	0.58 ± 0.07
Steel 6 kg	1.47 ± 0.13	1.34 ± 0.11	0.73 ± 0.10
Rocks 8 kg	0.64 ± 0.08	0.80 ± 0.07	0.52 ± 0.07
Steel 8 kg	1.36 ± 0.32	1.31 ± 0.11	0.82 ± 0.10

degree of lofting in propeller turbulence, which slows sink rates and increases exposure of seabirds to baited hooks, and the latter provides an estimate of the linear phases of the sink profiles. With the Chilean longline, because the initial sink rates were very fast, especially for gear with steel weights, sink rates in the 0–5 s and 5–10 s ranges were emphasised to provide sufficient time for the TDRs to record accurately. The former variable is consistent with Moreno et al. (2008) and provides an estimate of the initial rapid sink rates when gear free-falls in the water column, and the latter provides an estimate of sink rates in the linear phases of the sink profiles.

Results

Variation in weights

The masses of the steel weights more closely approximated nominal weight than the rock weights. The rock weights were consistently heavier than nominal mass (Table 1).

LMM analyses

For both parametric and non-parametric LMMs, the extra residual variance (in addition to the experimental unit variance) associated with time for the

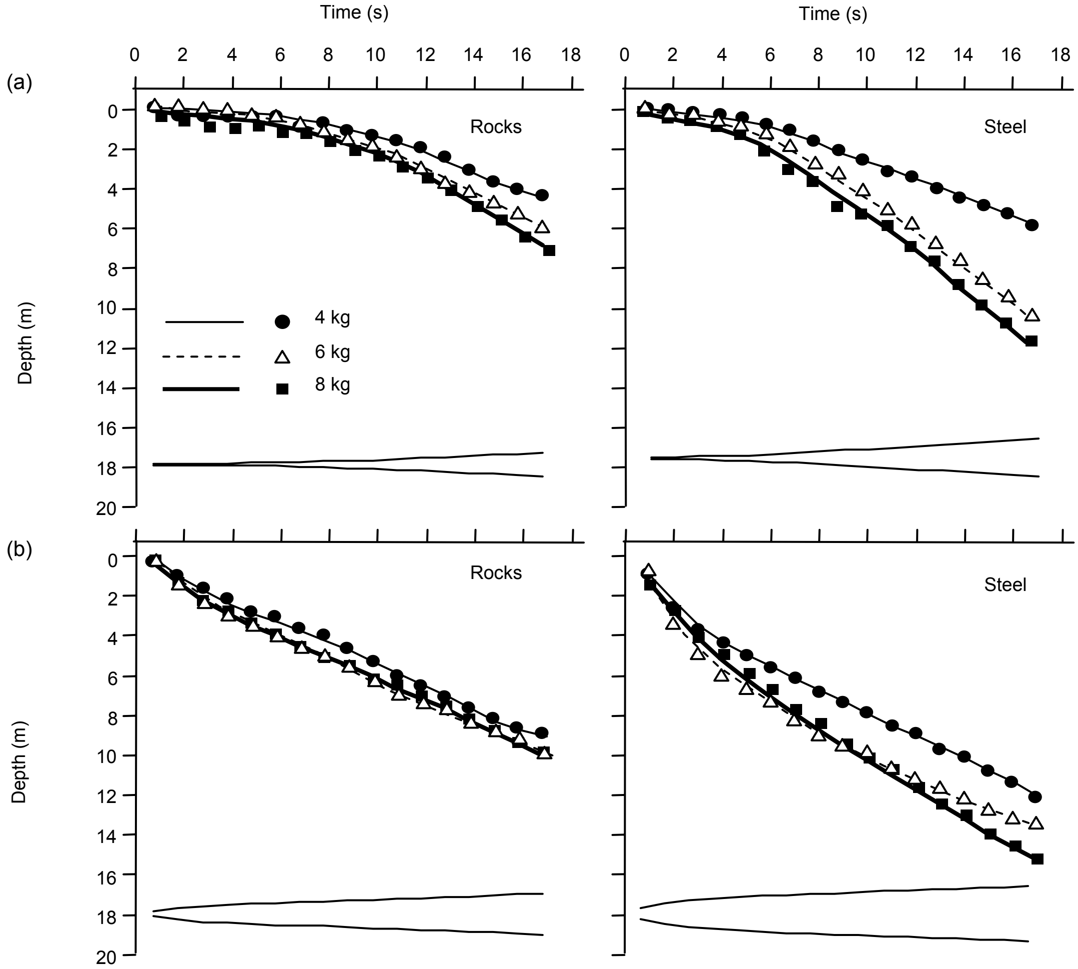

Figure 4: Predicted (see text) sink profiles for: (a) Spanish-system, and (b) Chilean longlines fitted with rock weights or steel weights of nominated mass. Shown are the mean depths predicted from the LMMs and presented as points (non-parametric) and spline curves (parametric). Approximate 95% confidence bounds (see bottom of graphs) for differences between depth-versus-time profiles have been centred on a depth of 18 m to improve clarity (see 'Methods' for calculation of confidence bounds). For a given time, differences between curves that are greater than the width of the bounds can be considered significantly different.

response variable log(Depth + 1) was estimated using the heterogeneous variance form of these LMMs. These variance estimates were similar for both forms of the LMM and decreased smoothly from approximately 0.13 (SE = 0.02) down to approximately 0.003 (i.e. close to zero; SE = 0.001) as time increased from 1 to 17 s. Therefore, these forms of the LMMs were required to adequately model the errors since the log transform over-corrects for the heterogeneous variances on the natural scale. The TDR variance component was very close to zero, so this random term was dropped. As expected, the estimated autocorrelation was very high and positive for both LMMs with values of 0.765 (SE = 0.020) and 0.756 (SE = 0.019) with corresponding estimates of experimental variance of 0.0352 (SE = 0.0053) and 0.0355 (SE = 0.0053) for the parametric and non-parametric LMMs respectively.

For the non-parametric LMM, the four-way interaction was not significant ($P > 0.1$) but the three-way interactions of fishing method x weight type x time and weight type x weight mass x time were both significant ($P < 0.001$). Sink profiles of Spanish-system and Chilean longlines differed markedly, being curvilinear in opposite directions (Figure 4). Within weight type and mass, Spanish-system longlines sank slowly initially, then faster, whereas the reverse applied with Chilean longline.

Sink rates

Initial sink rates for the Chilean longlines were about three times those of Spanish-system longlines (Table 2). Mean sink rates ranged from 0.68 m s^{-1} (4 kg rocks) to 1.31 m s^{-1} (8 kg steel) in the shallow depth ranges. Within fishing method, initial sink rates of longlines with steel weights were substantially faster than gear with rock weights, although differences were reduced in the linear phase of the sink profiles. For both fishing methods and weight types, the proportional increase in sink rates from 4–6 kg was greater than from 6–8 kg. These differences were most pronounced in the linear phases of the sink profiles.

Spanish-system longlines with 8 kg rock weights averaged 0.22 ± 0.02 m s^{-1} to 2 m depth. The equivalent rates for steel weights of 4 kg and 6 kg were 0.23 ± 0.02 and 0.29 ± 0.02 respectively. This suggests that longlines with 5 kg steel weights would be expected to average about 0.26 m s^{-1} to 2 m depth.

Discussion

Consistency of weights

The steel weights more closely approximated nominal mass than rock weights, which were all overweight. This occurred because the rock weights were built by weighing collections of rocks to within 5% of nominal mass and then adding the netting bags, which average 0.4–0.6 kg (see Table 1). It is not known how the extra weight and drag of the netting bags affected the sink rates.

In fishing operations the effect of small differences in weight and the bulk from the netting bags would be minor compared to loss of rocks from the bags. Each 8.5 kg weight typically comprises several rocks of different sizes and shapes which are frequently lost from their netting enclosures. The number of weights on vessels (hundreds), the difficulty of keeping track of them in fishing operations and the difficulty of weighing and repairing them at sea suggests that weights can easily be underweight and go undetected. This would result in longlines, or sections of longlines, being set that fail to meet CCAMLR line-weighting requirements.

Spanish system versus Chilean longlines

The sink profiles of both gear types differed markedly. Spanish-system longlines initially sank slowly then faster, whereas Chilean longlines initially sank rapidly, then slowed. In general, for the first 10 s or so after deployment, Chilean longlines sank about three times faster than Spanish-system lines, but thereafter sink rates (with weights of the same mass and type) were similar. The contrasting results in the shallow depth ranges are due to different gear configurations and deployment methods. Weights on Spanish-system longlines are connected by a continuous length of hook line which is joined to the hauling line by the branch/connecting lines (see Figure 1). Longlines enter the water horizontal to the sea surface, causing line between weights to float in propeller turbulence: once clear of propeller upwellings, sink rates increase. The weights on Chilean longlines are not connected by the conventional hook line and are suspended from one end of the branch/connecting lines, the other end being attached to the hauling line. When set, about 15 m of the 20 m length of each branch/connecting line is payed out (to avoid tangles) and weights are dropped from the height of the setting window above sea level (2.5 m on the *Tierra del Fuego*). Because there is no horizontal link between adjacent branch/connecting lines, the weights are free to sink vertically until the slack in the branch/connecting lines is taken up, at which point gear starts to drag on the hauling line and slows down.

Steel versus rocks

Spanish-system longlines with 8 kg at 40 m (approximates the 8.5 kg at 40 m required by CCAMLR) averaged 0.22 ± 0.02 m s^{-1} to 2 m depth. The average is slightly higher than the 0.20 m s^{-1} reported by Robertson et al. (2008a) for similarly configured gear set from a similar vessel to the *Tierra del Fuego*. The difference is possibly due to better control on the *Tierra del Fuego* in releasing weights without tension astern. Since the sink rates for the Chilean longlines greatly exceed those for the Spanish system, and since it is preferable that one weight mass be used for both fishing methods, the results for the Spanish system will be used to compare weight types. In the 0–2 m range, mean sink rates were considerably faster for steel weights than rock weights within each weight class. The average sink rates of gear with 4 kg steel weights (0.23 ± 0.02 m s^{-1}) was virtually identical to the average for the CCAMLR regime (see above), and the rate for gear with 6 kg steel weights (0.29 ± 0.02 m s^{-1}) was higher, suggesting that 5 kg steel weights would be an appropriate substitute for 8.5 kg rock weights. Longlines with 5 kg steel weights would on average equal or exceed the mean sink rates associated with the line-weighting regime currently required by CCAMLR.

Advantages of steel weights

There are a number of advantages associated with the use of steel weights. Once acquired, no labour is required to build the steel weights and they require virtually no maintenance at sea. They are also more robust than the concrete weights

Table 3: Comparative differences in time taken (in minutes) for longlines equipped with weights of different type and mass to reach fishing depth. Estimates are based on sink rates from the linear phases of sink profiles taken 20 s after deployment and are derived for a water depth of 1 000 m.

Fishing method	Weight type and mass					
	Rocks (kg)			Steel (kg)		
	4	6	8	4	6	8
Spanish	49	35	32	37	19	17
Chilean	25	24	23	20	18	17

(used by some operators) which degrade in seawater and are prone to break when handled on vessels (Otley, 2005). The 5 kg steel weights would reduce substantially the total amount of weight that must be hauled on board and handled by crews. A 10 km longline, to CCAMLR line-weighting specifications, would hold 250 weights weighing 2.125 tonnes if made from rocks or 1.250 tonnes if made from steel, a difference of 40%. In summary, steel weights are much smaller than rock weights of equivalent mass, are more easily stored on vessels and handled more easily by crews.

Because of their large size, angular shape and netting enclosures, rock weights potentially increase the incidence of gear snagging on the seabed, especially with the Spanish system. Gear caught on the seabed increases the incidence of line breakages, the amount of gear lost and incidence of ghost fishing (fish caught but not landed). Torpedo-shaped steel weights are smaller, smooth sided and contain no netting bags, features that may reduce the frequency of fowling on the seabed and the amount of gear lost in benthic habitats.

By virtue of their faster sink rates it is possible that gear with steel weights will improve fish catch rates. The chemical attractants in mackerel bait are strongest in the first two hours following deployment, after which time the attractants decay exponentially (Bjordal and Løkkeborg, 1996). Thus, time taken to reach target depths is an important component of fishing strategy. Based on a nominal fishing depth of 1 000 m, and mean sink rates 20 s after deployment, Spanish-system longlines with steel weights would reach fishing depth much sooner than longlines equipped with rock weights of equivalent mass (Table 3). Although Chilean longlines with steel weights attached were faster to the seabed than their rock weight counterparts (most evident with the 4 kg comparison), overall the most important single determinant of fast sink times to fishing depth was the use of steel weights. Thus, both Spanish-system and Chilean longlines with steel weights attached could potentially result in higher fish catch rates.

Conclusion

The sink rates of longlines equipped with 5 kg streamlined steel weights at 40 m intervals on longlines will, on average, equal or exceed those of longlines equipped with 8.5 kg at 40 m rock weights typically used by Spanish-system vessels. Therefore, the use of longlines with 5 kg steel weights attached will not result in an increased risk to seabirds. These two weighting regimes are interchangeable and are suitable for both the Spanish system and Chilean longlines.

Note: at the Twenty-sixth Meeting of CCAMLR (October 2007), Conservation Measure 25-02 was updated to permit Spanish-system vessels to substitute 5 kg shaped steel weights for rock weights that maintain the longline sink rates associated with the 8.5 kg at 40 m weighting regime. Steel weights must be hydrodynamically shaped (not chain links) designed to sink rapidly, and be deployed as single 5 kg units, not several lighter weights tied together. The modification applied to both the Spanish system and the Chilean longlines.

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