Agreement on the Conservation of Albatrosses and Petrels

Seventh Meeting of the Seabird Bycatch Working Group

La Serena, Chile, 2 - 4 May 2016

Categorising branch line weighting for pelagic longline fishing according to sink rates

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SUMMARY

Statistical analysis is provided supporting categorisation of branch line weighting for pelagic longline fishing according to sink rates. New information is provided about sink rates of differing branch line weighting configurations including assigning weighting configurations into statistically significant categories. The analysis completes step one of the re-evaluation of branch line weighting configurations for pelagic longline fishing under the three-step research programme endorsed by the Advisory Committee at its eighth meeting (Punta del Este, Uruguay, 15-19 September 2014). The analysis provides further support for adopting short leaders as best practice branch line weighting for pelagic longline fishing.

RECOMMENDATIONS

1. That SBWG recognises categorisation of branch line weighting for pelagic longline fishing according to sink rates is supported by statistical analysis.
2. That SBWG notes statistical analysis strengthens the proposal to amend ACAP's summary advice for reducing impact of pelagic longlines on seabirds to replace existing advice concerning branch line weighting with the following:
    - 40 g or greater attached at the hook; or
    - 60 g or greater attached within 1 m of the hook; or
    - 80 g or greater attached within 2 m of the hook.

    Positioning weight farther from the hook is not recommended.
3. That SBWG also notes these weighting regimes safeguard against any non-compliance to the use of bird scaring lines and night setting, due to much faster sink rates than regimes recommended by ACAP.
4. That SBWG recommends core funding from the Advisory Committee budgetary appropriation be allocated to support research concerning step three of the three-step research programme.

Categorización del lastrado de brazoladas para la pesca con palangre pelágico según las tasas de hundimiento

RESUMEN

Se proporciona un análisis estadístico que respalda la categorización del lastrado de brazoladas para las pesca con palangre pelágico según las tasas de hundimiento. Se brinda nueva información sobre las tasas de hundimiento de las distintas configuraciones del lastrado de brazoladas, incluida la asignación de configuraciones en categorías de relevancia estadística. El análisis completa el primer paso de la reevaluación de las configuraciones del lastrado de brazoladas para pesquerías de palangre pelágico en el marco del programa de investigación de tres pasos aprobado por el Comité Asesor en su octava reunión (Punta del Este, Uruguay, 15-19 de septiembre de 2014). El análisis respalda aún más la implementación de líneas cortas como buena práctica de lastrado de brazoladas para la pesca con palangre pelágico.

RECOMENDACIONES

1. Que el GdTCS reconozca que la categorización del lastrado de brazoladas para la pesca con palangre pelágico según las tasas de hundimiento se apoya en el análisis estadístico.
2. Que el GdTCS observe que el análisis estadístico consolida la propuesta para modificar el resumen de recomendaciones del ACAP para reducir el impacto de la pesca con palangre pelágico sobre las aves marinas, a fin de reemplazar las recomendaciones existentes sobre lastrado de brazoladas de la siguiente manera:
    - 40 g o más colocados en el anzuelo; o
    - 60 g o más colocados a 1 m de distancia del anzuelo; o
    - 80 g o más colocados a 2 m de distancia del anzuelo.

    No se recomienda colocar las pesas a una mayor distancia del anzuelo que las indicadas más arriba.
3. Que el GdTCS también observe que estos regímenes de lastrado constituyen una protección contra cualquier incumplimiento relativo a la implementación de las líneas espantapájaros y al calado nocturno, debido a que las tasas de hundimiento son más rápidas que los regímenes que recomienda el ACAP.
4. Que el GdTCS recomiende los fondos de la partida presupuestaria del Comité Asesor sean destinados para financiar investigaciones sobre el tercer paso del programa de investigación de tres pasos.

Catégorisation du lestage de lignes secondaires pour la pêche palangrière pélagique en fonction de la vitesse d'immersion

RÉSUMÉ

L'analyse statistique est fournie en appui de la catégorisation des lestages de lignes secondaires pour la pêche palangrière pélagique en fonction de la vitesse d'immersion. De nouvelles informations sont fournies concernant la vitesse d'immersion des différentes configurations de lestage de lignes secondaires, y compris l'inclusion des lestages dans des catégories statistiquement représentatives. L'analyse complète la première étape de la réévaluation des configurations de lestage de lignes secondaires pour la pêche palangrière pélagique. Cette étape s'inscrit dans le cadre du programme de recherche en trois étapes adopté par le Comité consultatif lors de sa huitième Réunion (Punta del Este, en Uruguay, 15-19 septembre 2014). L'étude est favorable à l'adoption de lests courts en tant que meilleure pratique en matière de lestage de lignes secondaires pour la pêche palangrière pélagique.

RECOMMANDATIONS

1. Que le GTCA reconnaisse que la catégorisation des lestages de lignes secondaires pour la pêche palangrière pélagique en fonction de la vitesse d'immersion est appuyée par une analyse statistique.
2. Que le GTCA prenne acte du fait que l'analyse statistique renforce la proposition d'amendement des conseils sommaires de l'ACAP visant à réduire l'impact des palangres pélagiques sur les oiseaux marins, afin de remplacer les conseils existants relatifs au lestage de lignes secondaires par les conseils suivants :
    - 40 g ou plus attaché à l'hameçon ; ou
    - 60 g ou plus attaché à moins de 1 mètre de l'hameçon ; ou
    - 80 g ou plus attaché à moins de 2 mètres de l'hameçon.

    Placer le lest plus loin de l'hameçon n'est pas recommandé.
3. Que le GTCA prenne également acte du fait que ces méthodes de lestage préviennent toute non-conformité dans l'utilisation de lignes d'effarouchement des oiseaux et de pose nocturne, en raison de vitesses d'immersion bien plus rapides que les méthodes recommandées par l'ACAP.
4. Que le GTCA recommande que des financements de base du budget du Comité consultatif soient alloués au soutien de la recherche concernant l'étape trois du programme de recherche en trois étapes.

1. INTRODUCTION

Consideration is being given within the Seabird Bycatch Working Group (SBWG) concerning whether to adopt short leaders as best practice branch line weighting for pelagic longline fishing, and also to adopt line weighting as a single best practice measure within ACAP's best practice advice for pelagic longline fisheries. Such consideration ensures that ACAP's best practice measures take account of new research in a timely manner to benefit seabird conservation.

SBWG6 (Punta del Este, Uruguay, 10-12 September 2014) recommended re-evaluation of branch line weighting configurations for pelagic longline fishing through a three-step research programme:

1. statistical analysis of existing sink rate data to categorise various weighting configurations according to their sink rates
2. review of the papers underpinning the existing ACAP advice, including taking account of the criteria for best practice and the type of bird assemblages within which the previous studies were conducted
3. carrying out further collaborative field research on the relationship between sink rate configurations, identified in step 1, and resulting seabird mortalities and/or attack rates (AC8 Doc 12 Rev 1).

This three-step research programme was endorsed by the Advisory Committee at its eighth meeting (Punta del Este, Uruguay, 15-19 September 2014) (AC8 Final Report, para 12.1.3).

The re-evaluation has been prompted by research into the sink rates of various weighting regimes highlighting the benefits of adopting short leaders as best practice branch line weighting for pelagic longline fishing (SBWG6 Doc 13; SBWG5 Doc 31; Robertson et al., 2013). The catalyst for that research was the finding, albeit preliminary, in the Uruguayan swordfish fishery where a reduction in leader length from 4.5 m (75 g) to 1 m (65 g) reduced seabird mortality by about 50 per cent in the absence of other mitigation (night setting, bird scaring lines) (SBWG5 Doc 49). The re-evaluation has also been prompted by proposals recommending that line weighting be assessed as if it is a single best practice measure within ACAP's best practice advice for pelagic longline fisheries as a safeguard against any non-compliance to the use of bird scaring lines and night setting.(SBWG6 Doc 13; SBWG5 Doc 31).

SBWG5 (La Rochelle, France, 6-10 May 2013) recommended line weighting be given priority over night setting and using bird scaring lines, as part of the best practice advice (AC7 Doc 14 Rev 1). This prioritisation helps in monitoring compliance, as line weighting is integral to the fishing gear, and is more likely to be consistently implemented, even in the absence of independent monitoring of fishing operations. This prioritisation helps safeguard against any non-compliance by fishing operators with night setting and/or bird scaring line measures, and in addressing problems with current low levels of onboard observers, and lack of uptake of electronic monitoring systems.

This paper addresses the requirements of step one of the three-step research programme, by providing a statistical analysis of existing sink rate data to categorise various weighting configurations according to their sink rates.

2. SINK PROFILES AND SINK RATES

The way a branch line in a pelagic longline fishery sinks matters. A sharper, steeper sink rate and sink profile, reduces the risk of seabird bycatch by reducing the time that baited hooks will be available to diving seabirds.

Line weighting, and the distance of the added weight from the baited hook, affect the sink rate and sink profile (Robertson et al., 2013). This means that as the amount of added weight that is attached at an identical distance from the baited hook increases, the overall sink rate of the baited hook increases, and as the distance of the added weight from the baited hook increases, the sink profile of the baited hook changes. Typically, a baited hook sinks in two stages: (a) slowly at first until the length of line connecting the baited hook to the lead weight becomes taut, and (b) more quickly thereafter, as the lead weight engages fully on the baited hook pulling it down, resulting in a curved sink profile (see Figure 1 below; Robertson et al., 2010b).

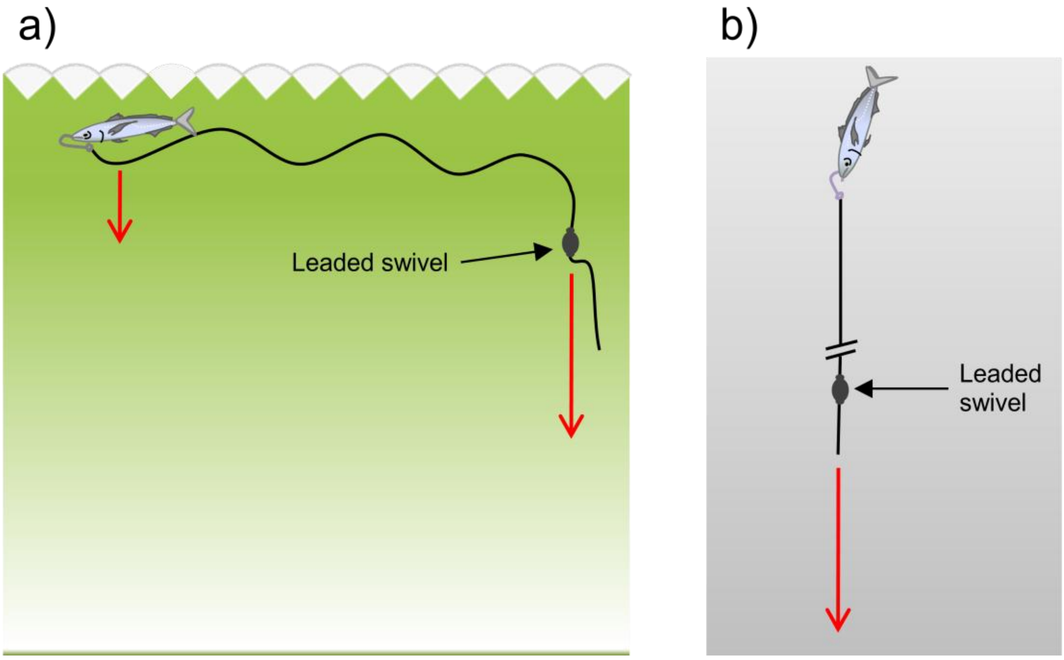

Figure 1. Sink profile of a baited hook: a baited hook sinks in two stages: (a) slowly at first until the length of line connecting the baited hook to the lead weight becomes taut, and (b) more quickly thereafter, as the lead weight engages fully on the baited hook pulling it down, resulting in a curved sink profile.

Placing the weight at the hook eliminates the time lag at the surface associated with long leaders (Robertson et al., 2010b). Shortening the length of the leader by moving the added lead weight closer to the hook, and/or increasing the mass of the added weight, will result in a steeper sink rate and sink profile (SBWG6 Doc 13). Long leaders greatly accentuate the time lag at the surface and virtually negate the benefit of line weighting (Robertson et al., 2010b).

In studies of comparative sink rates, the sink rate of the baited hook should be ignored as soon as the branch line becomes taut on the mainline (Robertson et al., 2013). This is because the sink rate of the branch line is, thereafter, subject to confounding mainline effects including, among other things, wave action (Robertson et al., 2013, cf. Pierre et al., 2015). Ideally, when the branch line becomes taut baited hooks would be beneath seabird dive depth.

3. CATEGORISING SINK PROFILES AND SINK RATES

Research into categorising sink profiles and sink rates benefits from dedicated at-sea experimental trials under controlled conditions. Dedicated at-sea experimental trials under controlled conditions reduce the likelihood of (i) sampling bias, (ii) confounding of average effects of experimental configurations with nuisance variables, (iii) insufficient statistical power to detect differences due to uncontrolled variability. Experiments have been undertaken in Australia's pelagic longline fishery to establish a scientific basis for branch line weighting in pelagic longline fisheries (Robertson et al., 2010a; Robertson et al., 2010b; Robertson et al., 2013; Robertson & Candy, 2014). Australian research using chartered longline fishing vessels into factors affecting branch line weighting sink rates and sink profiles in pelagic longline fishing have sought to strictly control the experimental design to avoid confounding factors (Robertson et al., 2010; Robertson et al., 2013; SBWG6 Doc 13; cf. Pierre et al., 2015).

SBWG6 Doc 13 provided information about the sink rates and sink profiles of 11 branch line weighting regimes. Data collection occurred during dedicated at-sea trials on a chartered vessel (*FV Samurai*) in the Australian pelagic longline fishery using time depth recorders. The 11 branch line weighting regimes comprised:

- unweighted
- 40 g at 0 m, 1 m, and 2 m from the hook
- 60 g at 0 m, 1 m, 2 m, and 3.5 m from the hook
- 80 g at 0 m, 1 m, and 2 m from the hook

Branch line weighting of 40 g, 60 g and 80 g are currently used by pelagic longline fishing vessels operating in coastal fisheries of the southern hemisphere. The branch line weighting regime of 40 g, 60 g and 80 g at 1 m approximates or exceeds existing ACAP best practice branch line weighting (of 45 or greater at 1 m from the hook), and the regime of 60 g at 2 m and 80 g at 2m corresponds with or exceeds existing ACAP best practice branch line weighting (of 60 or greater at 2 m from the hook).

Further analysis has now been undertaken of these data to categorise various branch line weighting configurations according to their sink rates and sink profiles.

4. STATISTICAL ANALYSES

4.1 Average depth-at-time sink profiles

Figure 2 shows average depth versus time sink profiles for all 11 branch line weighting regimes. At the bottom of the figure is a 'tuning fork' that allows a formal comparison of the significance of the difference in mean depths for any time between any pair of regimes. If the difference between mean sink profiles in a pair exceeds the width of the tuning fork for a given time point, then the difference can be considered statistically significant at the 95 per cent confidence level. Additional comparisons of depth versus time sink profiles by regime factors are presented in Figures A1.1 and A1.2 in Annex 1. These present the depth versus time sink profiles in Figure 1 by separating out the common leader lengths and weights, respectively, to simplify comparisons.

Categorisation is problematic when based only on visual comparisons of average depth versus time sink profiles. There are some obviously significant differences (e.g. between unweighted and weighted with short leader lengths). There are other pairwise comparisons that are not as clear. Also, even though the analyses present the relevant proportion of the sink profile, trying to follow these mean profiles visually in order to evaluate a 'categorisation' that shows clearly significantly different categories is difficult.

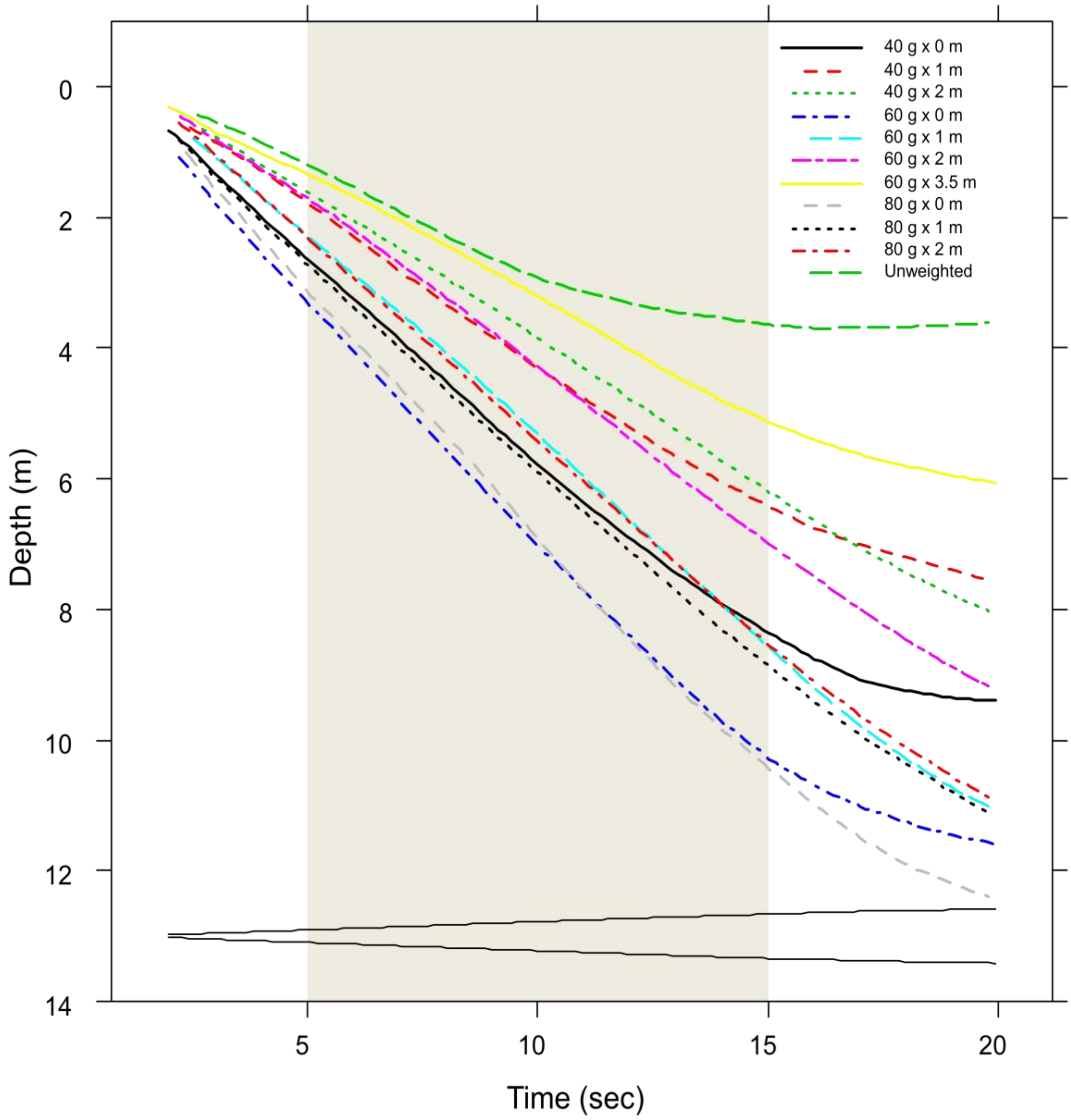

Figure 2. Mean depth-time profiles for 11 line weighting regimes using at-sea Trials on *FV Samurai* during November 2013. The "tuning fork" at bottom of graph shows approximate 95 per cent confidence limits for any pair of differences between means (see Robertson et al., 2010b). If the difference between mean sink profiles in a pair exceeds the width of the tuning fork for a given time point, then the difference can be considered statistically significant at the 95 per cent confidence level. Shaded area corresponds to the range of data used in the Canonical Variates Analysis. The depth-time profiles without the tuning fork correspond to Figure 1 of SBWG6 Doc 13.

4.2 Categorisation of average depth-at-time sink profiles using Canonical Variates Analysis

Canonical Variates Analyses outputs simplify the process of categorisation to something much more manageable for visual assessment. The outputs allow formal statistical hypothesis testing.

To provide a statistical categorisation of the branch line weighting regimes, Canonical Variates Analysis (CVA) was applied to the 11 different branch line weighting regimes: unweighted; 40 g at 0 m, 1 m, and 2 m from the hook; 60 g at 0 m, 1 m, 2 m, and 3.5 m from the hook; and 80 g at 0 m, 1 m, and 2 m from the hook — across 11 time points: 5 sec to 15 sec. This generates a total of 11 canonical variates for statistical comparison with a total of 218 scores for each canonical variate representing the total number of branch lines deployed across the 11 branch line weighting regimes. The methodology, as implemented using the CANDISC package (Visualizing Generalized Canonical Discriminant and Canonical Correlation Analysis: Available at http://cran.r-project.org/) within the R-software (R Development Team, 2006) is described in Gittins (1985) and is summarised in Annex 2.

Figure 3 shows a two-dimensional plot of the canonical variate scores using canonical variates (Can) 1 and 2 (i.e. CV1 and CV2, respectively). CV1 explains 82.9 per cent of the inter-centroid Euclidean distances in the 11-dimensional space in a single dimension. CV2 explains seven per cent (see Annex 2 for further explanation of Figure 3). The nine lower order canonical variates explain the remainder of 10.1 per cent. Graphical presentation of the lower order canonical variates did not show any additional categorisation compared to that seen in Figure 3.

Statistically significant average depth-at-time sink profile categories are evident from Figure 3. Most of the information on categorisation occurs on the scale of the first canonical variate, CV1 as seen in Figure 3, which shows group (i.e. regime) centroids and their 95 per cent confidence circles for the first two canonical variates. It can be seen from Figure 3 that from the top of the graph to the bottom, the branch line weighting regimes are ordered from fastest to slowest sinking, respectively. The scale is reversed to present the fastest sinking regimes at the top, but this is arbitrary as it is the ordering that is important.

Seven statistically discrete categories are evident on the vertical axis of Figure 3. CV1 alone provides a categorisation of basically seven groups starting from the top of Figure 3:

1. 80 g x 0 m, 60 g x 0 m
2. 80 g x 1 m, 40 g x 0 m
3. 60 g x 1 m, 80 g x 2 m
4. 60 g x 2 m
5. 40 g x 1 m, 40 g x 2 m
6. 60 g x 3.5 m
7. Unweighted.

The horizontal axis of Figure 3 provides some refinement to the above categories. CV2 provides some refinement of categorisation based on CV1 alone by separating 80 g x 0 m from 60 g x 0 m and separating 80 g x 1 m from 40 g x 0 m.

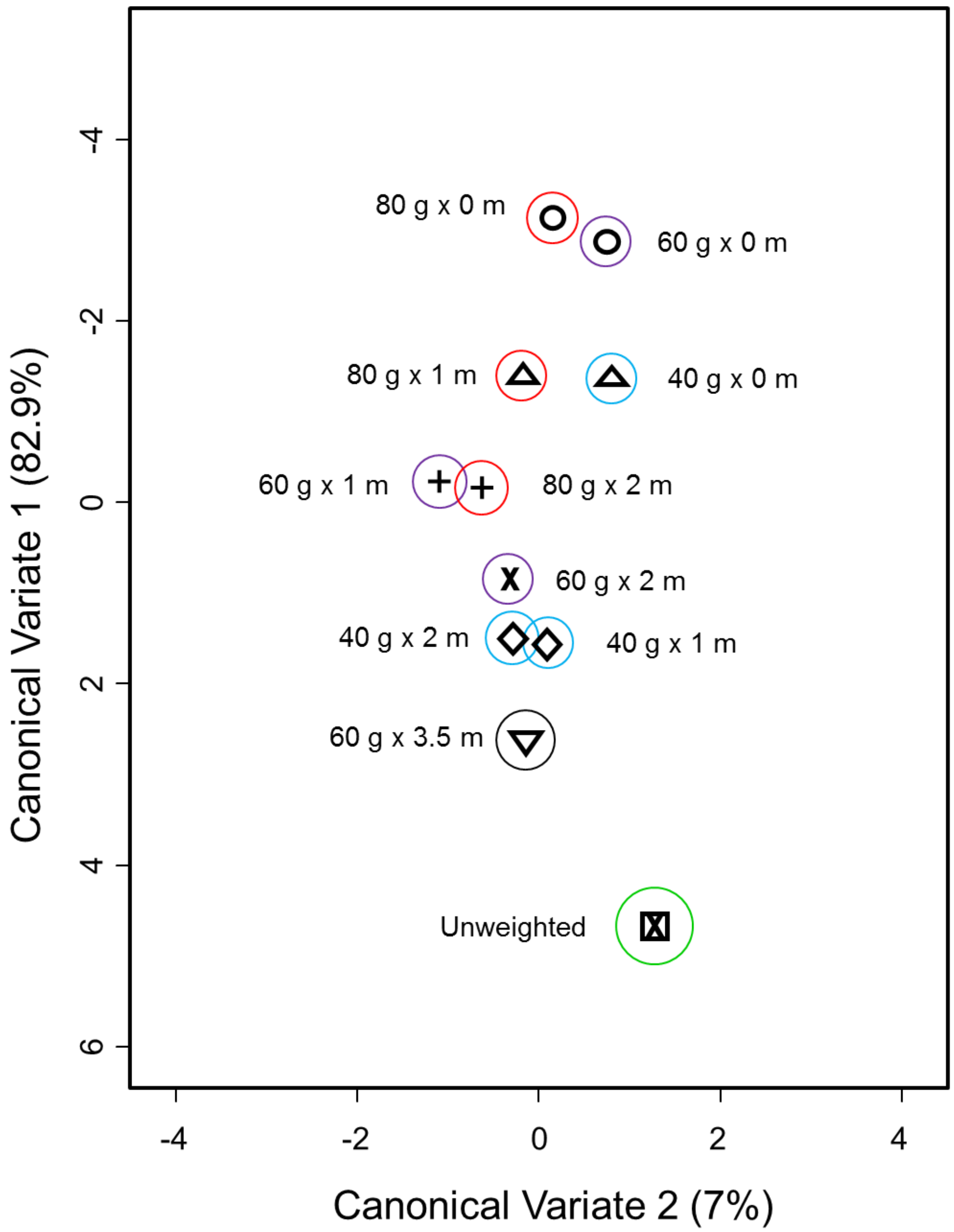

Figure 3. Line weighting regime centroids for the first two canonical variates showing approximate 95 per cent confidence circles using 11 depth-time values for 5 sec to 15 sec (inclusive) from at-sea trials on *FV Samurai* during November 2013. Symbols represent the categorisation based on the vertical axis (i.e. Canonical Variate 1). Seven categories are evident: 1: “80 g x 0 m", "60 g x 0 m"; 2: "80 g x 1 m", "40 g x 0 m"; 3: "60 g x 1 m", "80 g x 2 m"; 4: "60 g x 2 m"; 5: “40 g x 1 m", "40 g x 2 m"; 6: "60 g x 3.5 m"; 7: "Unweighted").

The order is basically defined by weight and leader length, with short leader lengths with a zero leader length being very effective in improving sink rate (e.g. a 40 g weight at the hook had a very similar sink rate to twice that weight with just one metre longer leader length).

Figure 4 shows results for only canonical variate 1 (CV1). Instead of means (i.e. two-dimensional centroids) as shown in Figure 3, box and whisker plots are shown, based on the CV1 score for each replicate within each regime. The centre of the box shows the median while lower and upper limits of the box are the 1st and 3rd quartiles, respectively. The upper whisker extends from the upper limit to the largest value that is less than this limit plus 1.5 times the inter-quartile range (i.e. 3rd minus 1st quartile). The lower whisker extends from the lower limit down to the smallest value that is greater than this limit minus 1.5 times the inter-quartile range. Beyond the whiskers individual data points (potential outliers) are shown. The right hand panel shows the relative contribution of each of the dimensions (i.e. the 11 time points from 5 sec to 15 sec inclusive) to the CV1 score (i.e. a linear combination of the depth values for each time).

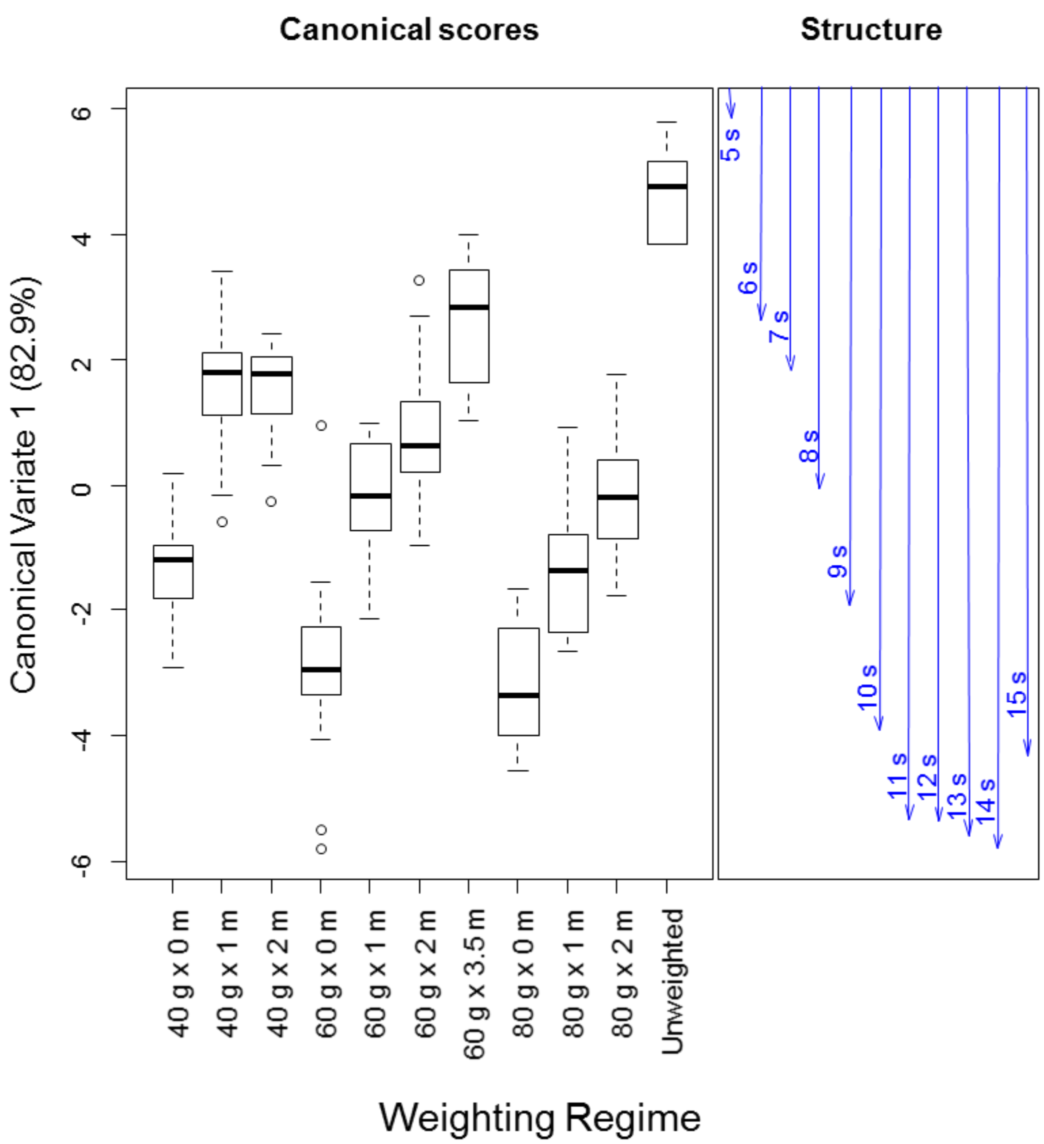

Figure 4. Line weighting regime box and whisker plots (left panel) for canonical variate 1 scores and contribution of each time point to score (right panel) using 11 depth-time values for 5 sec to 15 sec (inclusive) from at-sea trials on *FV Samurai* during November 2013.

Note that canonical variate analysis is a multivariate technique which does not account for the time ordering of the depth values directly (i.e. theoretically), but in this case it has empirically recovered the progressive time order of the depths up to 14 sec after which the depth-time profiles demonstrate some nonlinearity (i.e. slow-down of sink rates).

Since all profiles start from zero-zero, regimes with the fastest velocity will, on average, progressively separate, in terms of depth given time, from those with slower sink rates. The velocity is close to constant, on average, within a regime for the 5 sec to 14 sec time range giving linear profiles. The canonical variates analysis is thus well-suited to categorisation of the 11 regimes for this range.

4.3 Average sink rates

Figure 5 shows line weighting regime mean sink rates over the depth range from zero to target depths of 4, 6, and 8 m showing single SE bars and common symbols representing the categorisation of weighting regimes using mean Canonical Variate 1 (CV1) scores and their 95 per cent confidence bounds (see Figure 4) (i.e. common symbols represent the same category). Mean sink rates are based on mean depth-time profile (see Figure 2). Missing means for the slowest sinking regimes are missing if, on average, the target depth was not reached.

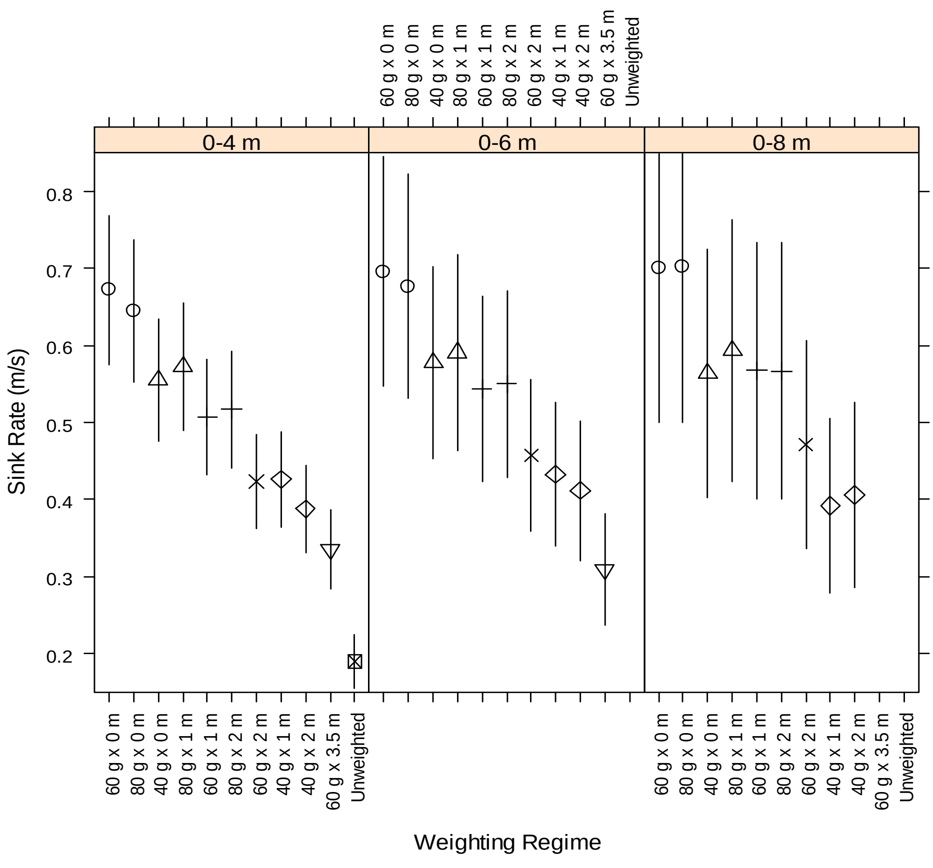

Figure 5. Line weighting regime mean sink rates over the depth range from zero to target depths of 4, 6, and 8 m showing single SE bars and common symbols representing the categorisation of weighting regimes using mean Canonical Variate 1 scores and their 95 per cent confidence bounds (see Figure 3) (i.e. common symbols represent the same category). Mean sink rates are based on mean depth-time profile (see Figure 2). Missing means for the slowest sinking regimes are missing if, on average, the target depth was not reached.

5. DISCUSSION

Branch line weighting regimes in pelagic longline fisheries are able to be categorised according to their sink profiles, and these categories are statistically significant. No existing studies have compared the sink rates of different line weighting treatments across the sink rate profile, and accounted for variability between initial fast sink rates with slower sink rates as depth increases. Statistical analysis confirms physical observations that line weighting, and the distance of the added weight from the baited hook, affect the sink rate and sink profile. The analysis completes step one of the re-evaluation of branch line weighting configurations for pelagic longline fishing under the three-step research programme endorsed by AC8.

The analysis provides further evidence that there is demonstrable practical significance, as well as statistical significance, that using short leaders is better. The analysis reveals seven distinct sink profile categories:

1. 60 g and 80 g at 0 m
2. 40 g at 0 m and 80 g at 1 m
3. 60 g at 1 m and 80 g at 2 m
4. 60 g at 2 m
5. 40 g at 1 m and 40 g at 2 m
6. 60 g at 3.5 m
7. unweighted

The findings are not directly related to biological significance, which is to be addressed under step three of the three-step research programme. It may well be possible however, that the biological significance of improved line weighting options may not be determinable, due to a reluctance to carry out studies that have mortality impacts.

Further research concerning step three of the three-step research programme would benefit by comparing: (i) unweighted branch lines (with a mean sink rate of about 0.2 m.sec^{-1}; the 'control') (Category 7 above); (ii) existing ACAP best practice advice about branch line weighting (e.g. 60 g at 3.5 m that has a mean sink rate of about 0.3 m.sec^{-1}) (Category 6 above); and (iii) a line weighting regime with an average sink rate equal to or above 0.5 m.sec^{-1} (Categories 1-3 above; mean sink rates drawn from Figure 5). This research design would help ensure that meaningful comparisons can be made about whether improved branch line weighting is biologically significant, when compared to existing best practice advice about branch line weighting. Such experiments should include real-time stoppage rules to ensure seabird mortality is kept to a minimum. The experiments should be conducted in daylight without the use of bird scaring lines, as a key reason for improved line weighting is to safeguard against any non-compliance to the use of bird scaring lines and night setting.

The findings reinforce proposed amendments to ACAP's summary advice for reducing impact of pelagic longlines on seabirds concerning minimum standards for branch line weighting configurations, as follows, which encompass the first three categories identified above:

- 40 g or greater attached at the hook; or
- 60 g or greater attached within 1 m of the hook; or
- 80 g or greater attached within 2 m of the hook.

Priority should be afforded to conducting research concerning step three of the three-step research programme. Consideration should be given to allocation of core funds from the Advisory Committee's budgetary appropriation to support action against this priority.

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ANNEX 1

Comparison of Depth-Time profiles by regime factors

Figure A1.1 exploits the commonality of branch line weighting regimes that have the same leader length (i.e. for the 40 g, 60 g, and 80 g weights). Controlling for leader length, these leader length specific panels allow for comparison across these branch line weighting regimes. These graphs are useful to see the effect of branch line weighting while holding leader length constant. However, this does not allow an overall categorisation of the 11 branch line weighting regimes.

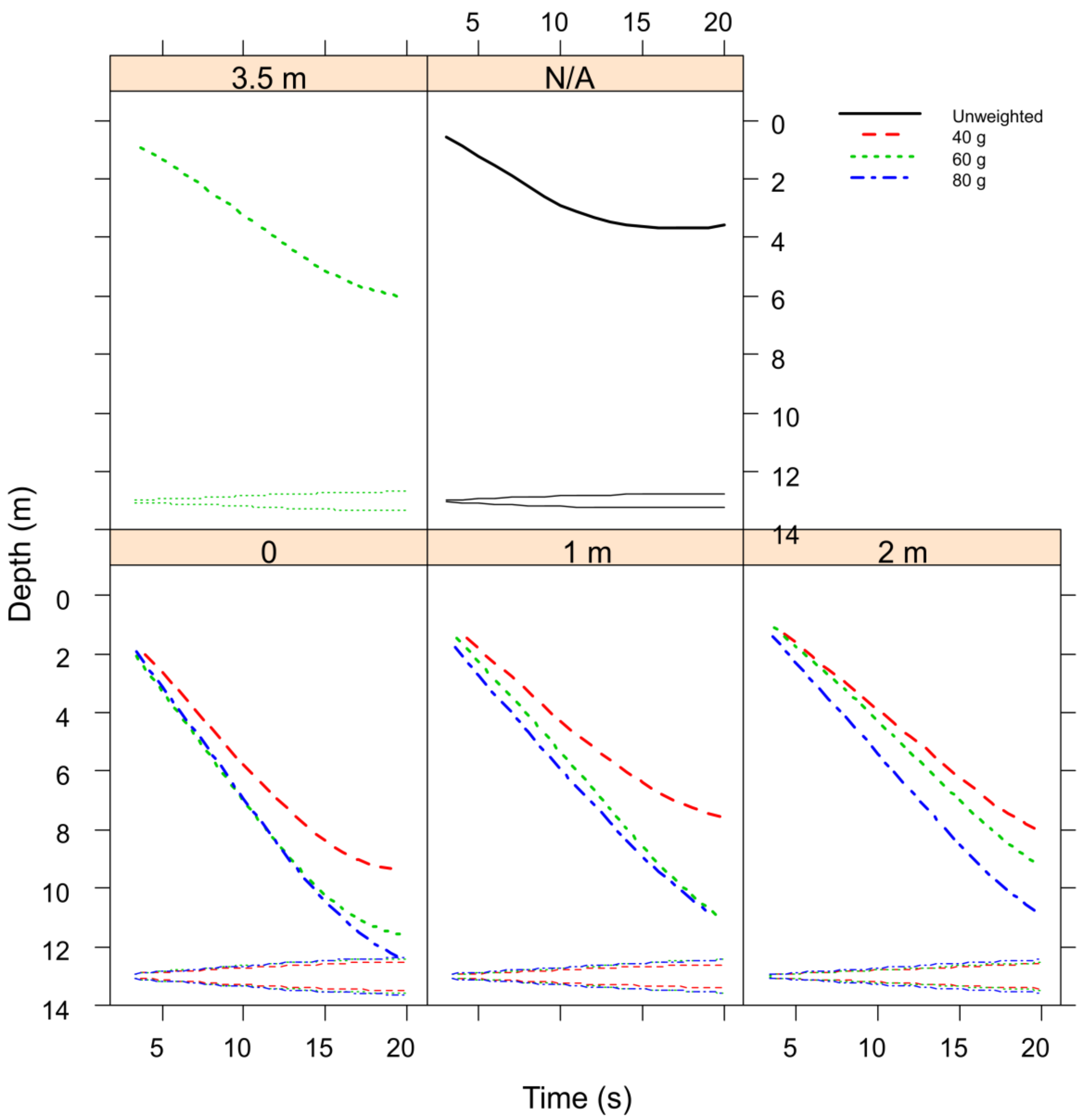

Figure A1.1. Mean depth-time profiles for 11 line weighting regimes using at-sea trials on *FV Samurai* during November 2013 with separate panels for each leader length. Note that there is no logical leader length for the "Unweighted" regime. There are separate tuning forks for each regime (see Robertson et al., 2010a, 2010b). If differences between sink profiles exceed the distance between the upper bound of the tuning fork for one regime in the pair and the lower bound of the other regime in the comparison, then the difference can be considered statistically significant at the 95 per cent confidence level.

Figure A1.2 also exploits the commonality of regimes that have the same weight (i.e. for the 0 m, 1 m and 2 m leader lengths). These graphs are useful to see the effect of leader length holding branch line weighting constant, but again it does not allow an overall categorisation of all 11 branch line weighting regimes.

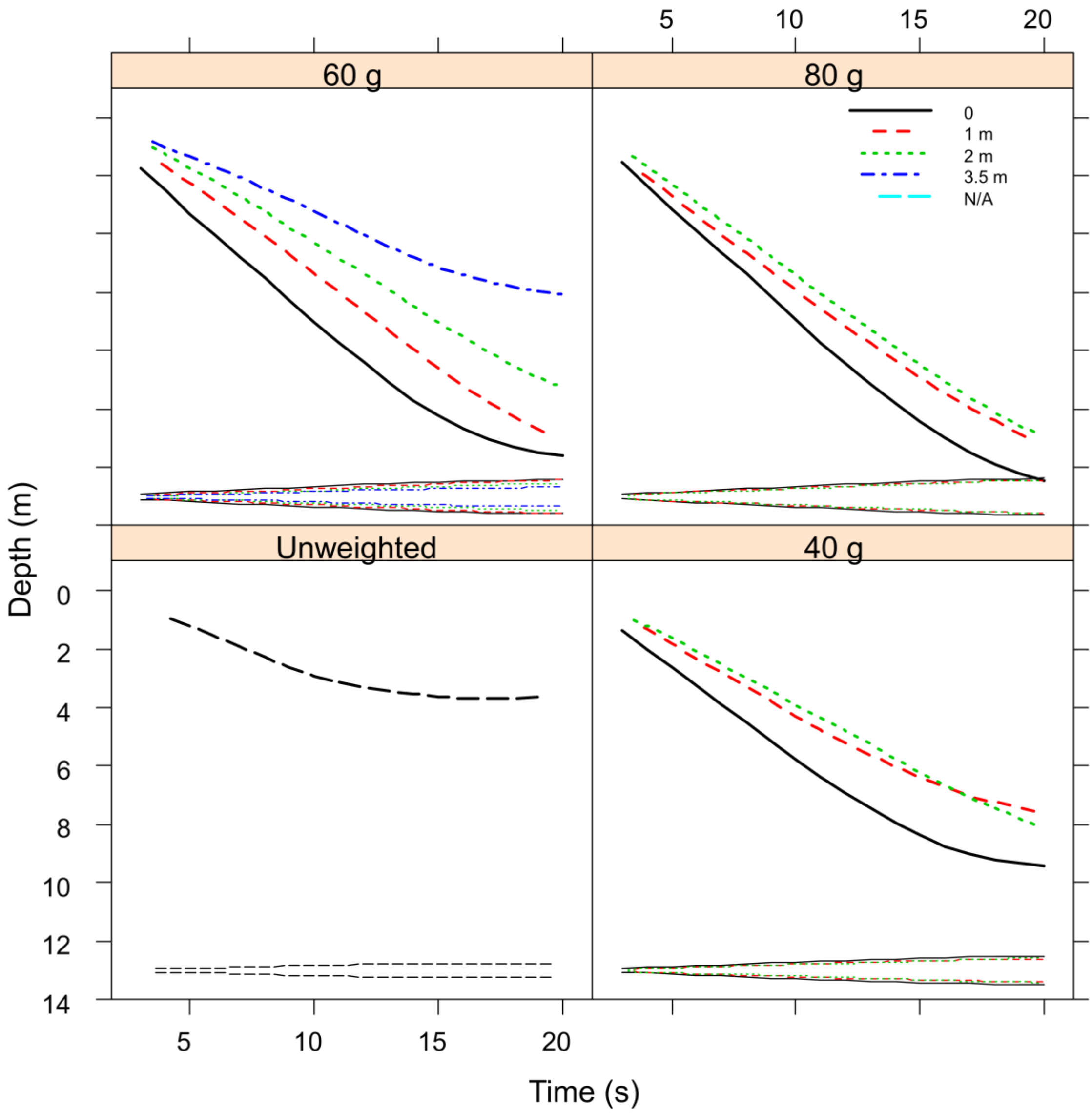

Figure A1.2. Mean depth-time profiles for 11 line weighting regimes using at-sea trials on *FV Samurai* during November 2013 with separate panels for each weight. Note that there is no logical leader length for the "Unweighted" regime. There are separate tuning forks for each regime (see Robertson et al., 2010a, 2010b). If differences between sink profiles exceed the distance between the upper bound of the tuning fork for one regime in the pair and the lower bound of the other regime in the comparison, then the difference can be considered statistically significant at the 95 per cent confidence level.

ANNEX 2

Canonical Variates Analysis: description and additional explanation of results

Canonical Variates Analysis is a useful multivariate data analysis technique. Canonical Variates Analysis serves a similar role as post-hoc comparison of treatment (i.e. group) means in Analysis of Variance (ANOVA) for a univariate response by allowing comparison of means, but in the case of Canonical Variates Analysis these means are represented in more than one dimension. Additionally, in the multivariate response case, Canonical Variates Analysis provides a dimension-reducing technique so that most of the variability between group (i.e. branch line weighting regime here) centroids in the full p-dimensional space (p=11 in this case) is ideally contained in one or two canonical variate dimensions. The first to last canonical variate account for a corresponding ordered decrease in the proportion of the total of the Euclidean distances between the centroids in the p-dimensional space when represented by the first orthogonal rotation of the original p-dimensional space. This first rotation is calculated from the eigen vectors of the within-group sums of squares and products matrix for the multivariate response. A second rotation then is applied which is calculated from the eigen vectors of the between-group sums of squares and products matrix of the scores obtained from the first rotation. There are (k-1) non-zero eigen vectors in this last case (where k is the number of groups and p>k-1) and these are ordered from largest to smallest eigen value corresponding to canonical variate 1 to k-1. Although these rotations are each orthogonal their final (k-1) dimensional canonical variate space is not orthogonal to the original p-dimensional space. Evenso, the (k-1) canonical variates are independent as a result of the first rotation.

In Figure 3 where the 95 per cent confidence circles do not overlap for a pair of regimes, then this can be taken as indicating a small probability of incorrectly rejecting the null hypothesis (Type I error) that true means for the theoretical population of branch lines for each regime (from which the observed samples were drawn) in the pair are the same. Note that the confidence probability for comparing regimes is less than 0.05 since the 0.05 refers to the confidence interval for each regime centroid considered independently. When pairwise comparisons are made the confidence interval for the difference between a pair of means is reduced by a factor of $1.96\sqrt{2}/3.92$ relative to double confidence bounds for individual regime means to give the probability of a Type I error of approximately 0.006 [i.e. 2 times the standard normal cumulative probability for the $-1.96(2\sqrt{2})$ quantile]. The size of the circles reflect different amounts of replication since after removing unrepresentative branch lines there were 20 or 21 replicates of all the weighted regimes except the 60 g at 3.5 m which had 18 replicates while the unweighted regime had only 14 replicate branch lines.