# An analysis of catches and fish survival associated with the Modular Harvest System (MHS) and conventional commercial trawl gear

Nokome Bentley, Trophia Ltd

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## 1. Introduction

The Modular Harvest System (MHS) is a trawl technology developed by Precision Seafood Harvesting (PSH) to "catch seafood in a way that maximises fish quality, improves size and species selectivity, and reduces mortality of unintended catch (i.e. undersize fish of target species and unwanted species)." (Black et al 2014). The Ministry for Primary Industry (MPI) requires that any new fishing gear must perform "no worse overall" than existing gears. To test this, PSH conducted sea trials following an experimental design, to collect data on the catches and survival associated with MHS and conventional trawl gear. This report describes an analysis of the data collected in those sea trials.

This analysis was requested by MPI to examine alternative approaches to those taken in previous analyses of the sea trials (Moran et al 2015). Specifically, MPI requested the following,

1. Develop an approach for analysing survivability data to determine whether there is a difference between MHS and conventional trawl gear, while accounting for other variables, and to apply this approach to the existing data.
2. Develop an approach for combining the survivability data with the catch data to determine the overall difference between the two gears, and to apply this approach to the existing data.
3. Determine whether the small number of trials that have been undertaken so far are adequate for addressing 1 and 2.
4. Make recommendations for future data collections and analytical protocols, including collecting information on other variables that might affect the results, given that there is an intention to repeat these experiments one or more times.

## 2. Data

Details of the experimental design are provided by Black et al (2014). Here, brief descriptions of the resulting datasets are provided as an aid to understanding the following analyses.

## 2.1. Tows

The `tows` dataset provides tow-by-tow data (Table 1). The source for this data set was an Excel spreadsheet named "PSH summer survival and CRI data.xlsx" provided by MPI.

The sampling protocol for the sea trials specified that 50 undersized snapper were sampled from each tow. However, for tows where there were not 50 undersized snapper caught, the necesssary additional fish were sampled from the 25-30cm size range.

**Table 1: Variables in the `tows` dataset. This variable descriptions are based on the "Variables description" sheet in the "CRI and survival for MPI July 2015.xlsx" spredsheet.**

| Variable | Description |
|---|---|
| `vessel` | Three letter vessel code. Three vessesl but most tows from two vessels. s 9(2)(b)(ii) [redacted] |
| `voyage` | Alphanumeric voyage code |
| `tow` | Numeric tow number within each voyage. Not necessarily consecutive i.e. some tow numbers missing for some voyages. |
| `gear` | Type of cod end, either `COM` (commercial) or `MHS` (modular harvesting system). |
| `depth` | Maximum depth of seafloor during tow |
| `duration` | Duration of fishing; period from doors away to doors up |
| `catch` | Total weight of the landed catch |
| `snx` | Number of undersized snapper (<250 mm) caught in the tow |
| `sna` | Weight of legal sized snapper caught in the tow. Weights taken from TCEPR. |
| `sampled` | Number of fish sampled from the tow |
| `deaths0` | Number of sampled fish that were dead at 0 h |
| `deaths24` | Number of sampled fish that died between 1 and 24 h |
| `deaths48` | Number of sampled fish that died between 25 and 48 h |
| `cri0` | Average CRI score of live fish at 0 h. This is separate sample to that retained in the live bag. 0 h CRI scores only conducted where numbers permitted. |
| `cri48` | Average CRI score of live fish at 48 h. This is from the fish retained in the live bag and is a separate sample to 0 h CRI scores. |

## 2.2. Fish

The `fish` dataset provides data on survival and condition for each fish sampled. The source was an Excel spreadsheet named "PSH summer survival and CRI data.xlsx". Blank cells were replaced with NA. There was a small amount of data from species other than snapper, these were excluded.

This dataset provides greater detail, at the level of individual fish, related to the `deaths0`, `deaths24`, `deaths48`, `cri0` and `cri48` variables in the `tows` dataset. For each sampled fish, the individual components of the CRI score are recorded as well as if the fish died or not.

## 3. Key variables

From the outset it is important to consider which variable, or variables, should be the focus for determining whether MHS is "no worse overall" than conventional gear. Since the snapper fishery, like most fisheries in New Zealand, is quota managed, the best measure of the impact of trawling is the number of undersized snapper that die per ton of legal sized snapper. This ratio is a better reflection of the impact of a fishing gear than say the absolute number of deaths of undersized snapper per trawl. For example, a new gear may have half the mortality rate of released undersized snapper. But if it also has half the catch rate of legal sized snapper then twice as many tows would be necessary to catch the same total allowable catch (TAC) and there would be no overall benefit.

Furthermore, the mortality rate of undersized snapper is dependent not only on the gear used but also on how that gear is fished and on post capture handling protocols. Because these variables are more difficult to control than the gear used, when used in commercial fishing situations the mortality rate may be higher than recorded in these experiments. For this reason, it is also useful to estimate a separate ratio that is independent of the mortality rate, i.e. the number of undersized snapper that are caught per ton of legal sized snapper.

Thus, this analysis focuses on estimating two variables:

1. the number of undersized snapper that are caught per kilogram of legal sized snapper caught (UCK, undersized caught per kilogram)
2. the number of undersized snapper that die per kilogram of legal sized snapper caught (UDK, undersized deaths per kilogram)

For each tow, the number of undersized caught per kilogram is simply the total number of undersized caught in the tow ( snx) divided by the catch of legal sized snapper ( sna),

$$Y\ VDL\ \frac{TO}{TOB}$$

The probability of mortality of undersized snapper can be calculated as the proportion of sampled undersized snapper that died,

$$NPSUBMJUZ\ \frac{EFBUIT \quad EFBUIT \quad EFBUIT}{TBNQMFE}$$

The mortality rate can then be applied to UCK to calculate UDK:

$$VEL \quad VDL\ NPSUBMJUZ$$

## 4. Descriptive analyses

Figure 1 compares the distribution of UCK and UDK, and the component variables used to calculate them, across all tows for commercial (COM) and MHS gear. Table 2 provides the median of these variables by gear type.

In these sea trials, MHS tows on average caught more snapper, both undersized and legal, per tow. The median number of undersized snapper per tow for MHS was 1.5 times the median from commercial tows. For legal sized catch the same ratio was 1.67. There is less of a difference in the key variable UCK (ie snx/sna) between the two gears (ratio of 1.34, Table 2). The overall mortality rate is substantially lower for MHS gear than for conventional commercial gear (Figure 1, Table 2).

In summary, based on medians of the data only, the MHS gear has slightly higher undersized catch per kilogram (UCK, 0.98/kg v 0.73/kg) and substantially lower mortality of undersized ( mortality, 13% v 71%). The combined effect is that MHS has a median for undersized deaths per kilogram (UDK) that is less than half that for conventional commercial gear (0.14/kg v 0.34/kg).

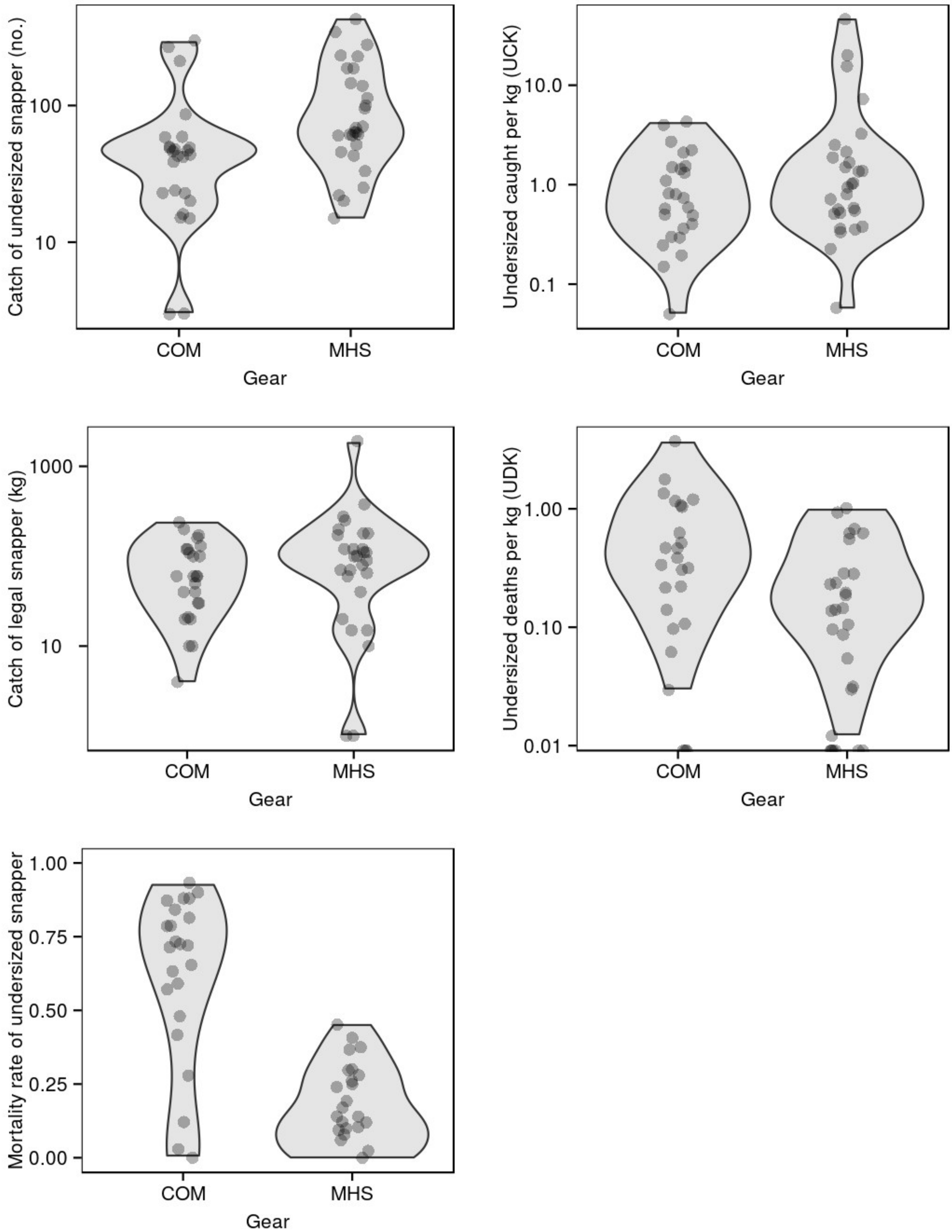


**Figure 1: Distributions of variables (left) and derived key variables (right) in the `tow` dataset by gear type. Each point represents an individual tow and have been jittered (small random movements added) so that individuals points can be more easily discerned. Distributions represent kernel density estimates of each variable. Note that a log scale is used for most of these plots and in these cases points on the x-axis represent zeros.**

**Table 2: Median values of key variables in the `tow` dataset for COM and MHS gears. The**

**"MHS/COM" column is the ratio of the median value for MHS over the median value for COM.** no./kg)

| Variable | COM | MHS | MHS/COM |
|---|---|---|---|
| Catch of undersized snapper ( `snx`, no.) | 44 | 66 | 1.5 |
| Catch of legal snapper ( `sna`; kg) | 60 | 100 | 1.67 |
| Undersized caught per kilogram of legal snapper (UCK, no./kg) | 0.73 | 0.98 | 1.34 |
| Mortality rate of undersized snapper ( `mortality`, proportion) | 0.71 | 0.13 | 0.18 |
| Undersized deaths per kilogram of legal snapper (UDK, | 0.34 | 0.14 | 0.41 |

## 5. Statistical analyses

Generalized linear models (GLMs) were used to test for a significant difference between UCK and UDK for commercial (COM) and MHS gears. The experimental design was not completely balanced (for example, all of the tows on the s 9(2)(b)(ii) were in depths less than 30 m). GLMs provide a means for standardising for other factors (e.g depth, tow duration) so that the underlying differences between gear types can be better estimated.

Both of the independent variables are approximately lognormally distributed (Figure 2). As such, the following GLMs were performed on MPH Z (where Z is the independent variable) and a Guassian error distribution. The additional small constant allows tows with zero deaths to be included in the analysis. A potentially better alternative would be to use a GLM with an error distribution that allows for zeros (e.g. negative binomial or Weibull) but this was not investigated in this study given the small dataset and the time available.

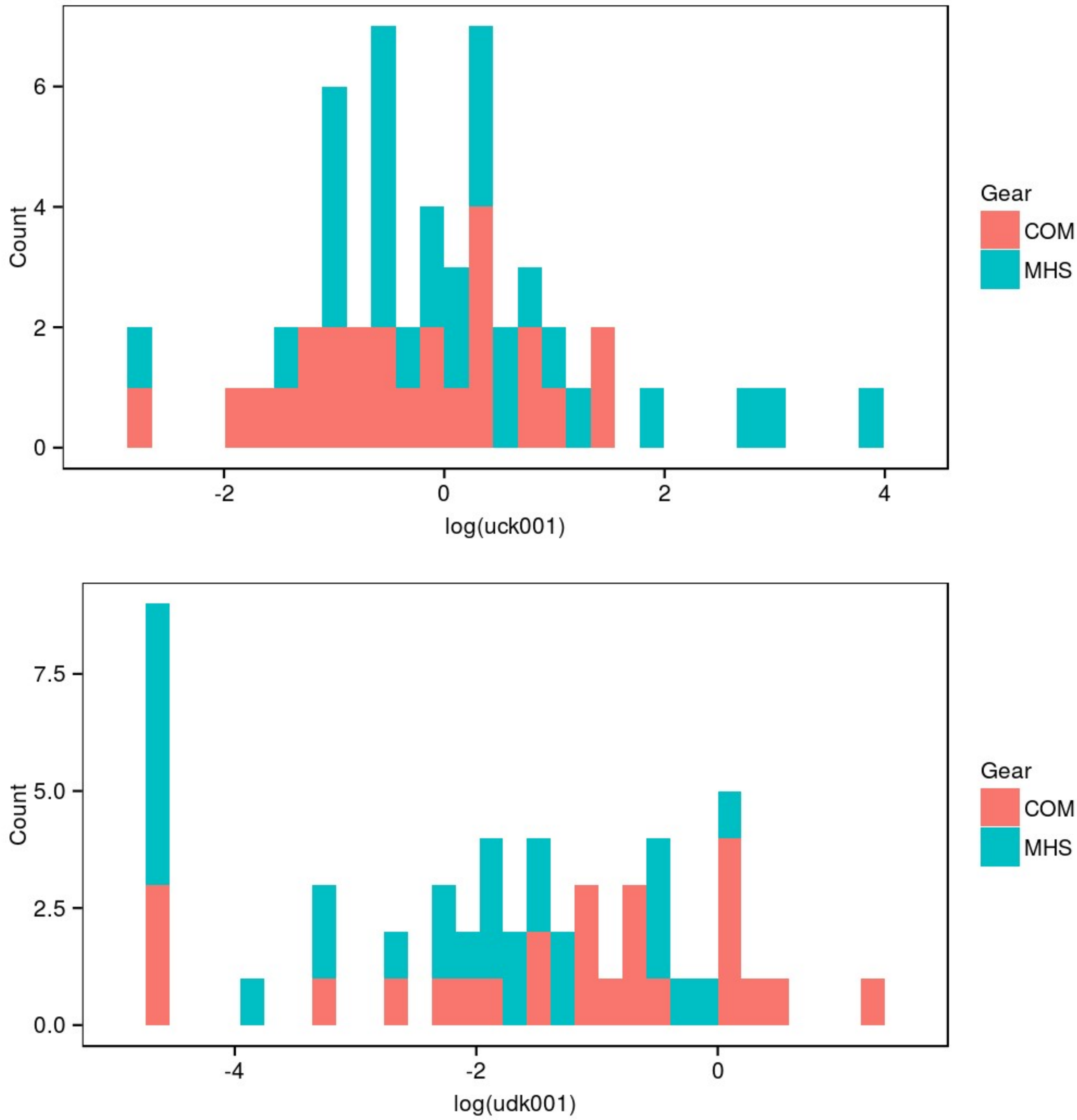


**Figure 2: Distribution of `log(uck+0.01)` and `log(udk+0.01)` by gear type.**

Diagnostics plots from preliminary GLMs indicated that one tow had very high leverage (Cook distance greater than 1). This tow, using the MHS cod end, had a total catch of 2449 kg (431 undersized snapper and 1900 kg of legal snapper catch) which was more than ten times the median catch for all other tows (230 kg). Given the large leverage of this tow and its exceptionally high catch this tow was excluded from further analyses.

Stepwise selection of GLM terms was performed using the initial null models `log(uck+001)~1` and `log(udk+001)~1`, and offering the terms `vessel`, `gear`, `poly(depth,3)`, `poly(duration,3)`, `poly(catch,3)` as well as interaction terms between the polynomial terms and gear. AIC was used as the selection criterion. The variables, `depth`, `duration` and `catch` were offered as continuous variables with third order polynomials to allow for effects that were not simple straight lines. A potentially better alternative to using polynomial terms for continuous variables would be to use generalised additive models (GAMs). Preliminary investigations using GAMs suggested results differed little and given that the dataset is currently quite small using the somewhat simpler and more commonly used GLMs was preferred.

GLMs were also done on the subset of 38 tows from the s 9(2)(b)(ii) . This vessel accounted for 72% of the tows and had tows in all depth strata (the s 9(2)(b)(ii) had only four tows none of which were in greater than 60 m and the s 9(2)(b)(ii) had 11 tows all in less than 30 m). These GLMs were performed in the same manner except that `vessel` was not offered as a term.

## 5.1. Undersized catch per kilogram (UCK)

The variables selected through stepwise selection were, in order, `poly(catch,3)`, `gear`, `vessel` and the interaction term `poly(catch,3):gear` (Table 3). The magnitude of the catch explained most of the variation in UCK with a decreasing UDK as overall catch weight increased. This may simply due to the fact that heavier catches are positively correlated with the average size of snapper in the catch and thus negatively correlated with the proportion of undersize snapper. Of note was the fact that MHS appears to have higher UCK at lower catch magnitudes than the commercial gear (bottom panel, Figure 3). Residuals diagnostics are provided in Figure 4.

The standardised UCK (ie. taking the other factors into account) was higher for MHS than for COM (Figure 3). The GLM coefficient for MHS was 0.9 which is equivalent to a multiplier of 2.46. This multiplier was significantly different from 1 with a p-value of 0.003. This implies a large standardisation effect of the model because the difference is substantially greater than seen in the unstandardised geometric means or medians for the two gear types (top panel, Figure 3; Table 2).

There was concern that the large standardisation effect may have been an artifact of the inclusion of overall catch (the `catch` variable) and in particular the `poly(catch,3):gear` interaction. There is some circularity in standardising UCK using a variable that it is correlated with - as noted already, we might expect UCK to be correlated with catch due the effect of average fish size on both these variables. To examine the sensitivity of the standardisation effect to this, several more models were fitted with the removal of various terms (-). This indicates that the inclusion of catch in the model causes a large apparent UCK for MHS gear. When catch was removed as an independent variable the estimated UCK for MHS gear was still 1.7 times that of commercial gear but no longer statistically different.

When the GLM fitting procedure was repeated using only data from the s 9(2)(b)(ii) only tow `duration` was selected as a model term (Table 3). Notably, `gear` was not selected suggesting that there was no significant difference in UCK for this data subset. This was checked by forcing the gear term into the model. In the resulting model, the coefficient for the difference between MHS and commercial gear was not significantly different from zero (p-value>0.25).

**Table 3: Analysis of variance table for the GLM of UCK.**

| | Df | Deviance | Resid. Df | Resid. Dev |
|---|---|---|---|---|
| NULL | NA | NA | 51 | 80.8 |
| poly(catch, 3) | 3 | 19.68 | 48 | 61.2 |
| gear | 1 | 8.21 | 47 | 53.0 |
| vessel | 2 | 7.64 | 45 | 45.3 |
| poly(catch, 3):gear | 3 | 8.10 | 42 | 37.2 |

**Table 4: Analysis of variance table for the GLM of UCK using only data from the vessel s 9(2)(b)(ii) .**

| | Df | Deviance | Resid. Df | Resid. Dev |
|---|---|---|---|---|
| NULL | NA | NA | 36 | 40.7 |
| poly(duration, 3) | 3 | 14.66 | 33 | 26.1 |

| | | | | |
|---|---|---|---|---|
| gear | 1 | 1.49 | 32 | 24.6 |

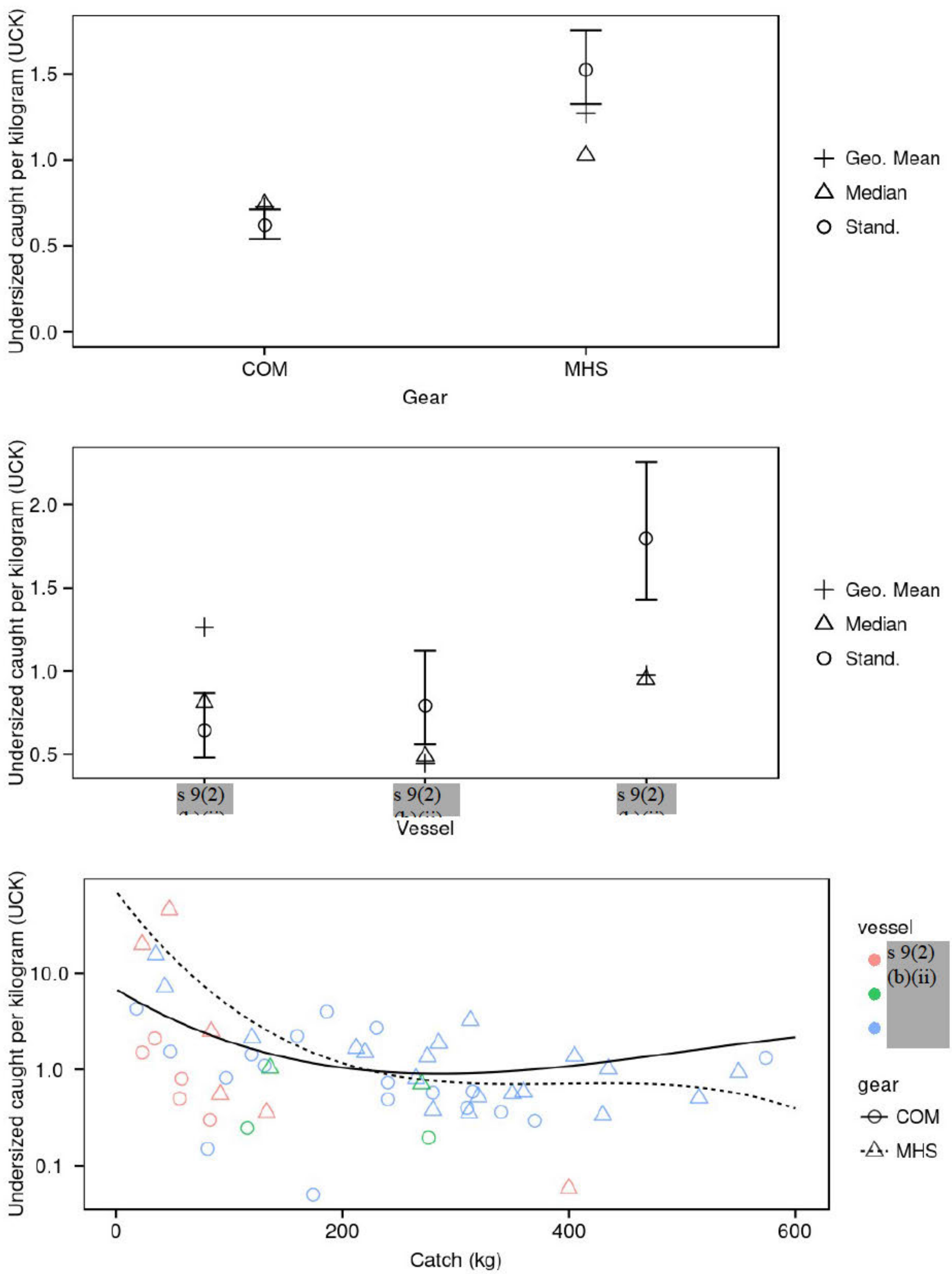


**Figure 3: Effect of GLM terms on expected undersized caught per kilogram (UCK). For the categorical variables, `vessel` and `gear` the canonicalized model coefficients (i.e. having a geometric mean of 1) have been scaled to the overall UDK and the mean and median of the data are shown for comparison. For, the continuous variable, `duration`, the model's coefficients have been scaled so that the expected UDK at the mean catch of 225 is the same as the overall mean UDK. The observed values are shown for each tow.**

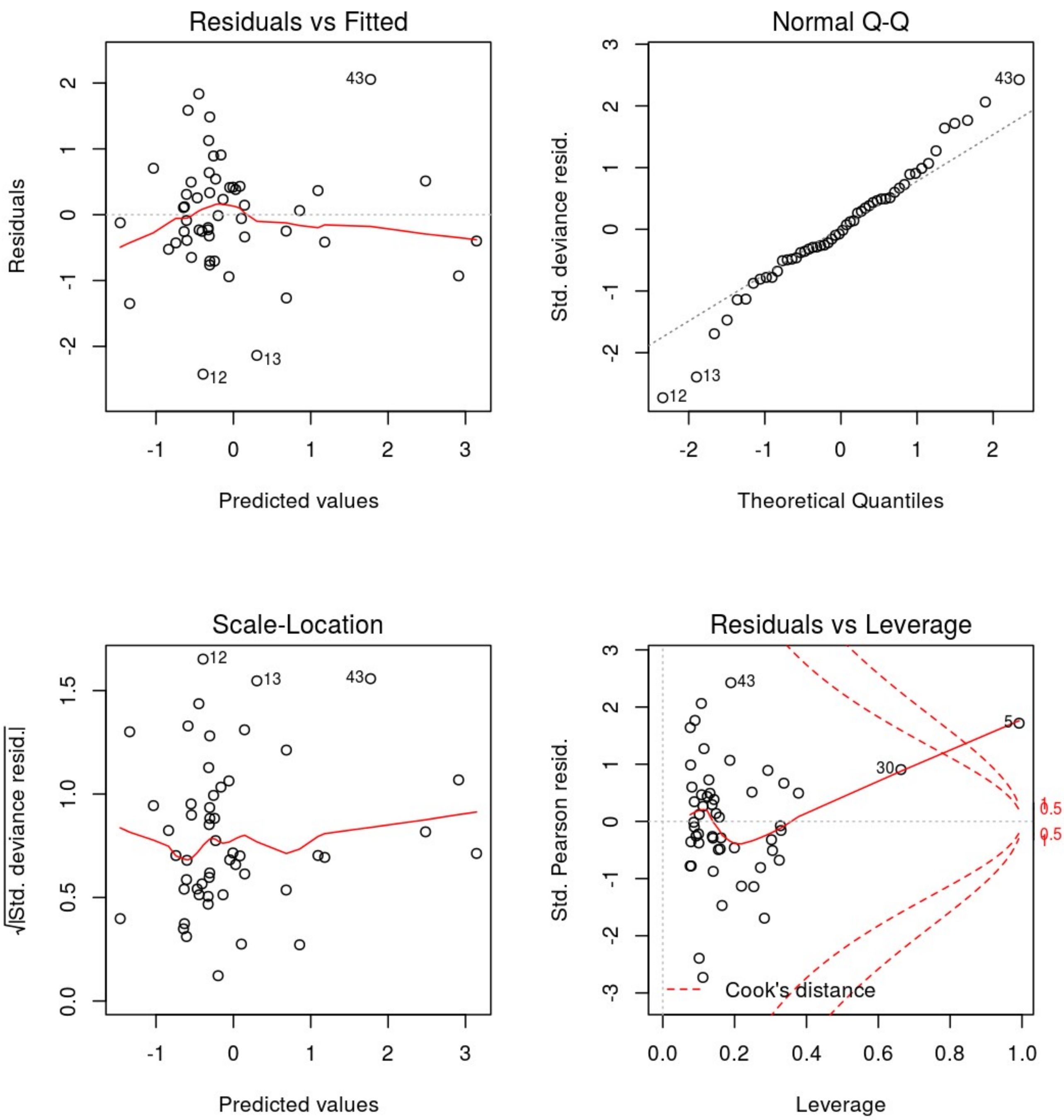


**Figure 4: Residual diagnostic plots for the GLM on UDK.**

**Table 5: Sensitivity of the estimated difference between MHS and commercial (COM) gear in UCK given alternative GLM model formula. "Coefficient" is the estimated difference between MHS and COM gear in log space, "SE" is the standard error for the coefficient, "Multiplier" is the exponent of "Coefficient" (i.e. a multiplier of 1.5 says that MHS has a UCK that is 1.5 times that of commercial gear), "t" is the t-test statistic and "p" is it's associated probability value.**

| **Model** log(uck001) ~ | **Coefficient** | **SE** | **Multiplier** | **t** | **p** |
|---|---|---|---|---|---|
| poly(catch, 3) + gear + vessel + poly(catch, 3):gear | 0.899 | 0.281 | 2.46 | 3.20 | 0.00259 |

| | | | | | |
|---|---|---|---|---|---|
| log(uck001) ~ vessel + gear + poly(catch, 3) | 0.963 | 0.298 | 2.62 | 3.24 | 0.00228 |
| log(uck001) ~ vessel + gear | 0.546 | 0.344 | 1.73 | 1.59 | 0.11910 |
| log(uck001) ~ gear | 0.556 | 0.344 | 1.74 | 1.62 | 0.11223 |

## 5.2. Undersized deaths per kilogram (UDK)

The variables selected through stepwise selection were, in order, `vessel`, `gear`, and `poly(duration,3)` (Table 6). Residuals diagnostics are provided in Figure 6.
Previous analyses by Moran et al (2015) had shown a potential relationship between survival (i.e. `1-mortality` in this analysis) and `depth`, particularly for commercial gear. This was confirmed in a separate GLM fitting procedure for `mortality` (using a binomial distribution) in which and `depth` was selected as a model term. However, depth was not selected in the current GLM of UDK. This appears to be the case because although mortality was generally greater at greater depths, the proportion of undersized snapper (UCK) is lower at greater depths and the two trends cancel each other out in UDK (Figure 7).

The standardised UDK for MHS is substantially lower than for commercial gear (Figure 3). There was little standardisation effect with respect to gear (then mean and the standardised mean are similar for each gear). There was a large standardisation effect for the vessel s 9(2)(b)(ii) (middle panel) which appear to be due to the fact that this vessel had on average longer tows (bottom panel). Note that the vessel s 9(2)(b)(ii) had many tows with zero mortality and thus zero UDK (this may due to the fact that this vessel only made tows in shallow water less than 30 m).

The difference in UDK between MHS and commercial gear was robust to alternative model specification (-). In all models, MHS is expected to have a UDK that is about 40% of the UDK for commercial gear. This difference was statistically significant (-) and similar to that estimated from medians of unstandardised data (Table 2).

When the GLM fitting procedure was repeated using only data from the s 9(2)(b)(ii) tow `poly(catch,3)` and `gear` were selected as a model terms (Table 7). The coefficient for the difference between MHS and commercial gear was significantly different from zero (pvalue<0.001).

**Table 6: Analysis of variance table for the GLM of UDK.**

| | Df | Deviance | Resid. Df | Resid. Dev |
|---|---|---|---|---|
| NULL | NA | NA | 51 | 139.5 |
| vessel | 2 | 83.34 | 49 | 56.1 |
| gear | 1 | 9.57 | 48 | 46.5 |
| poly(duration, 3) | 3 | 9.97 | 45 | 36.6 |

**Table 7: Analysis of variance table for the GLM of UDK using only data from the vessel s 9(2)(b)(ii)**

| | Df | Deviance | Resid. Df | Resid. Dev |
|---|---|---|---|---|
| NULL | NA | NA | 36 | 47.9 |
| poly(catch, 3) | 3 | 13.44 | 33 | 34.5 |
| gear | 1 | 2.44 | 32 | 32.1 |

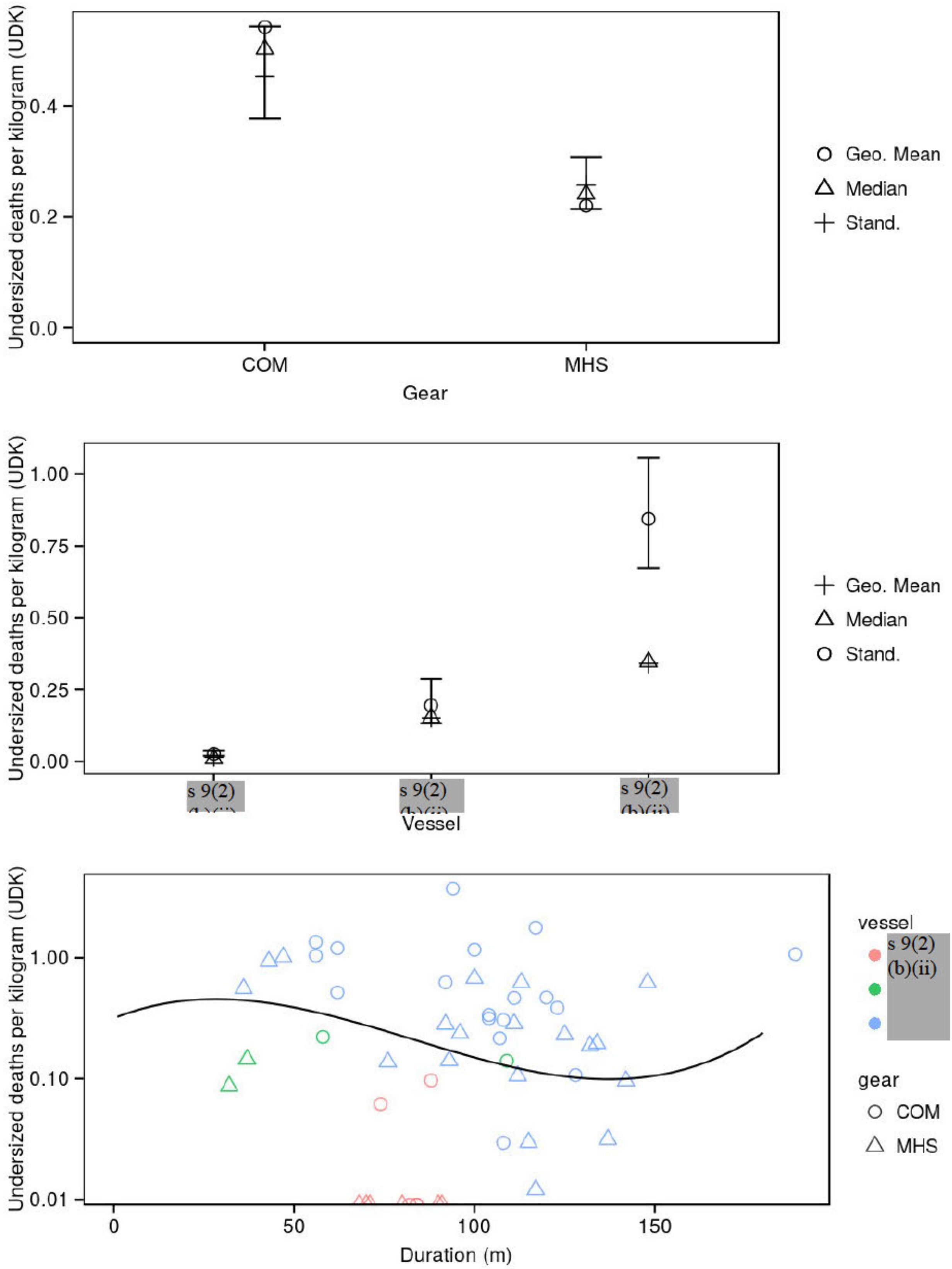


**Figure 5: Effect of GLM terms on expected undersized deaths per kilogram (UDK). For the categorical variables, `vessel` and `gear` the canonicalized model coefficients (i.e. having a geometric mean of 1) have been scaled to the overall UDK and the mean and median of the data are shown for comparison. For, the continuous variable, `duration`, the model's coefficients have been scaled so that the expected UDK at the mean duration of 95m is the same as the overall mean UDK. The observed values are shown for each tow.**

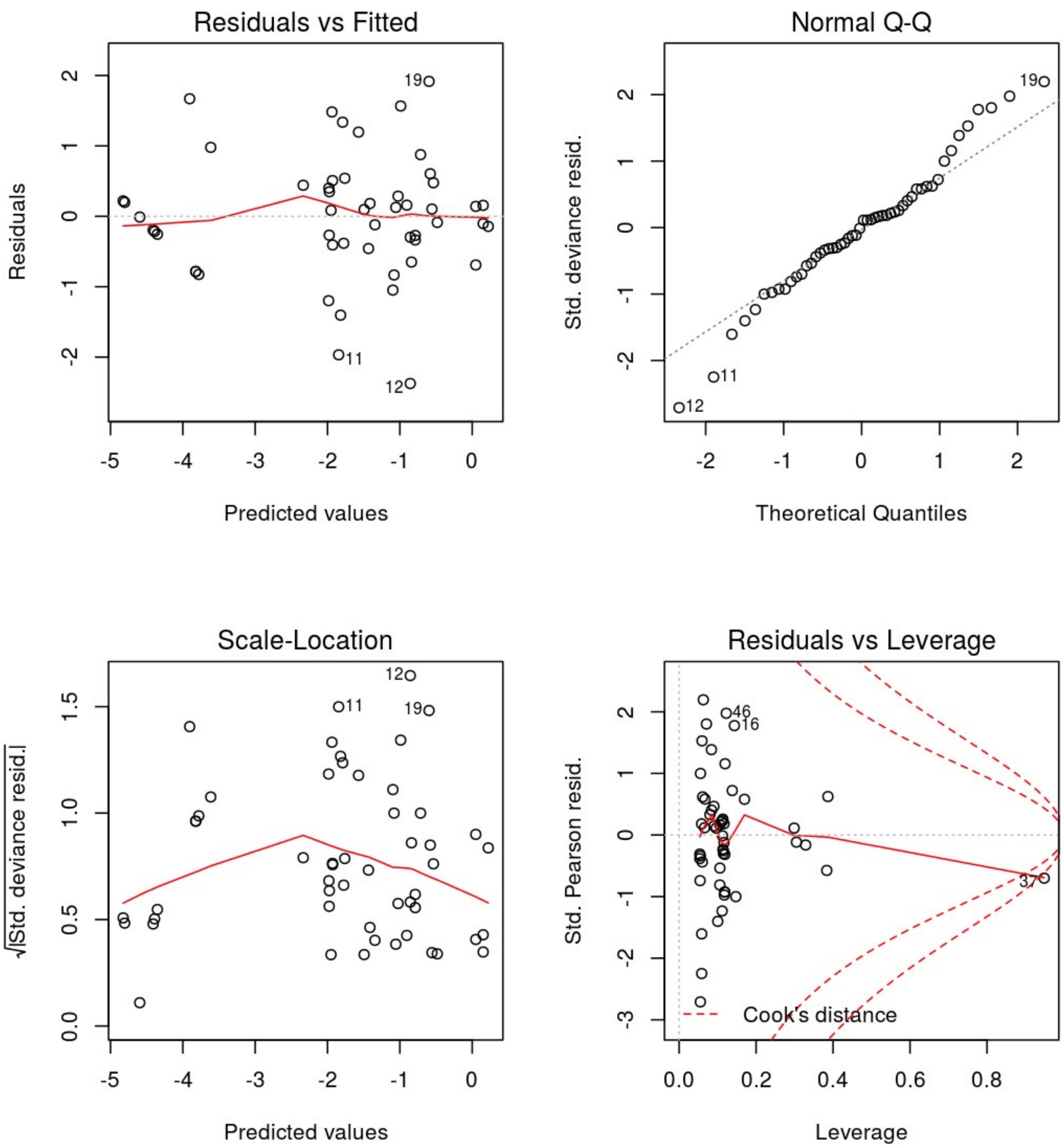


**Figure 6: Residual diagnostic plots for the GLM on UDK.**

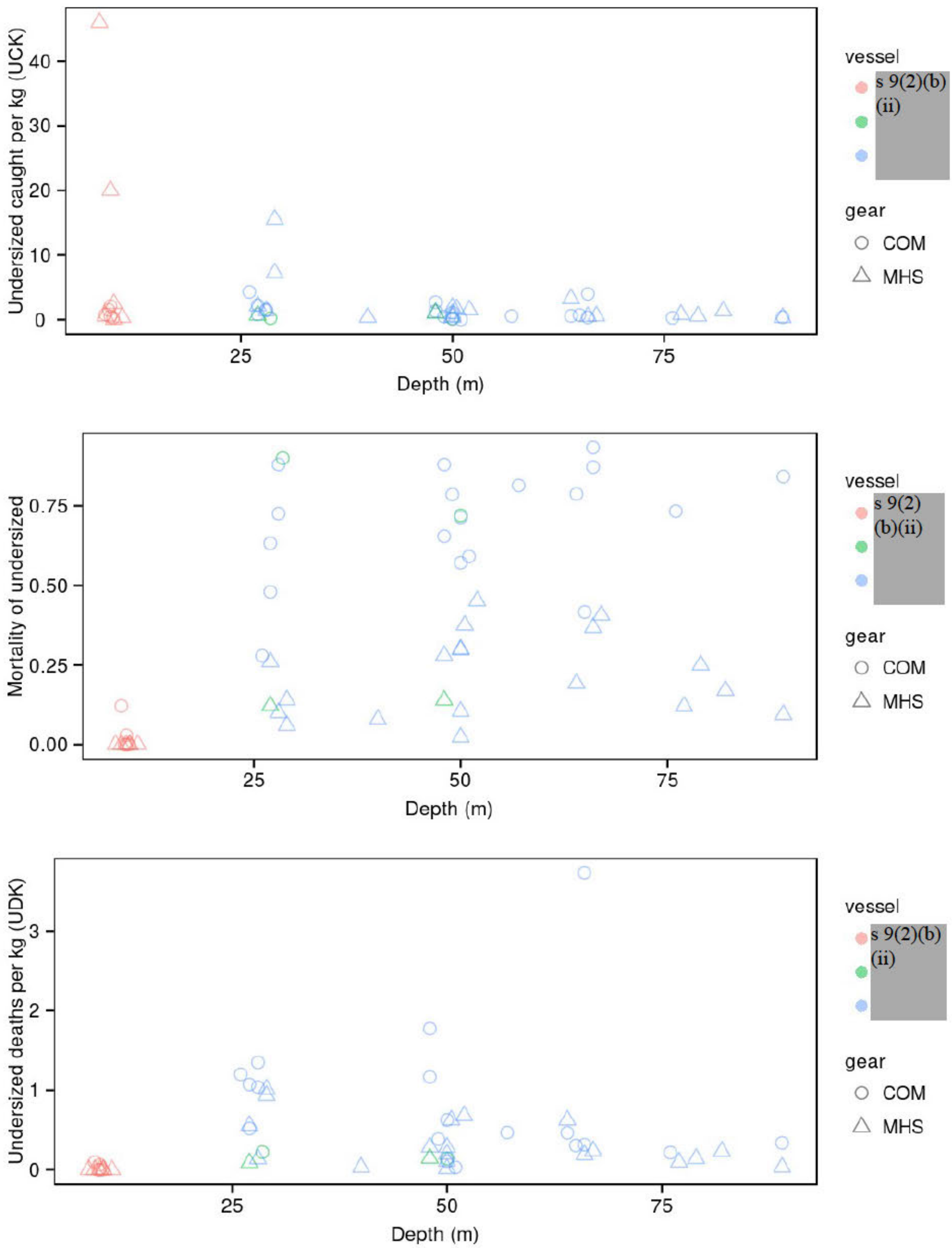


**Figure 7: Relation between undersized caught per kg (UCK), mortality of undersized, and undersized deaths per kg (UCK), and the depth of tow.**

**Table 8: Sensitivity of the estimated difference between MHS and commercial (COM) gear in UDK given alternative GLM model formula. "Coefficient" is the estimated difference between MHS and COM gear in log space, "SE" is the standard error for the coefficient, "Multiplier" is the exponent of "Coefficient" (i.e. a multiplier of 1.5 says that MHS has a UCK that is 1.5 times that of commercial gear), "t" is the t-test statistic and "p" is it's associated probability value.**

| Model | Coefficient | SE | Multiplier | t | p |
|---|---|---|---|---|---|
| log(udk001) ~ vessel + gear + poly(duration, 3) | -0.857 | 0.278 | 0.424 | -3.08 | 0.00349 |
| log(udk001) ~ vessel + gear | -0.859 | 0.273 | 0.424 | -3.14 | 0.00288 |
| log(udk001) ~ gear | -0.923 | 0.445 | 0.397 | -2.08 | 0.04314 |

## 6. Relation between CRI and survival

The relation between the Condition Reflex Index (CRI) and mortality rates was examined. The CRI was measured on a subsample of fish at time 0 and all surviving fish at 48 h (Moran et al 2015). If CRI at 0 h is sufficiently correlated with mortality at 48 h then there is potential to use CRI at 0 h as a proxy for mortality. Given a high enough correlation, and a sufficient sample size, this could potentially mean that fish would not need to be retained on board in tanks. Conversely, if the CRI at 0 h is not a good predictor of mortality then it may be little use collecting this data, and for logistical and costs reasons it may be appropriate to discontinue this aspect of the experimental design.

The mean CRI at 0 h and 48 h and the mortality rate at 48 h was calculated for all tows and correlations between these variables examined (Figure 8). There was a poor correlation between the CRI score at 0 h and CRI score at 48 h (top panel) and between CRI score at 0 h and mortality rate at 48 h (middle panel). Further work could be done to see whether an alternative score, calculated from a subset of the CRI indicators instead of all 13 of them, may provide a better predictor of mortality. However, care would have to be taken to avoid spurious correlations obtained by trialling many candidate combinations.

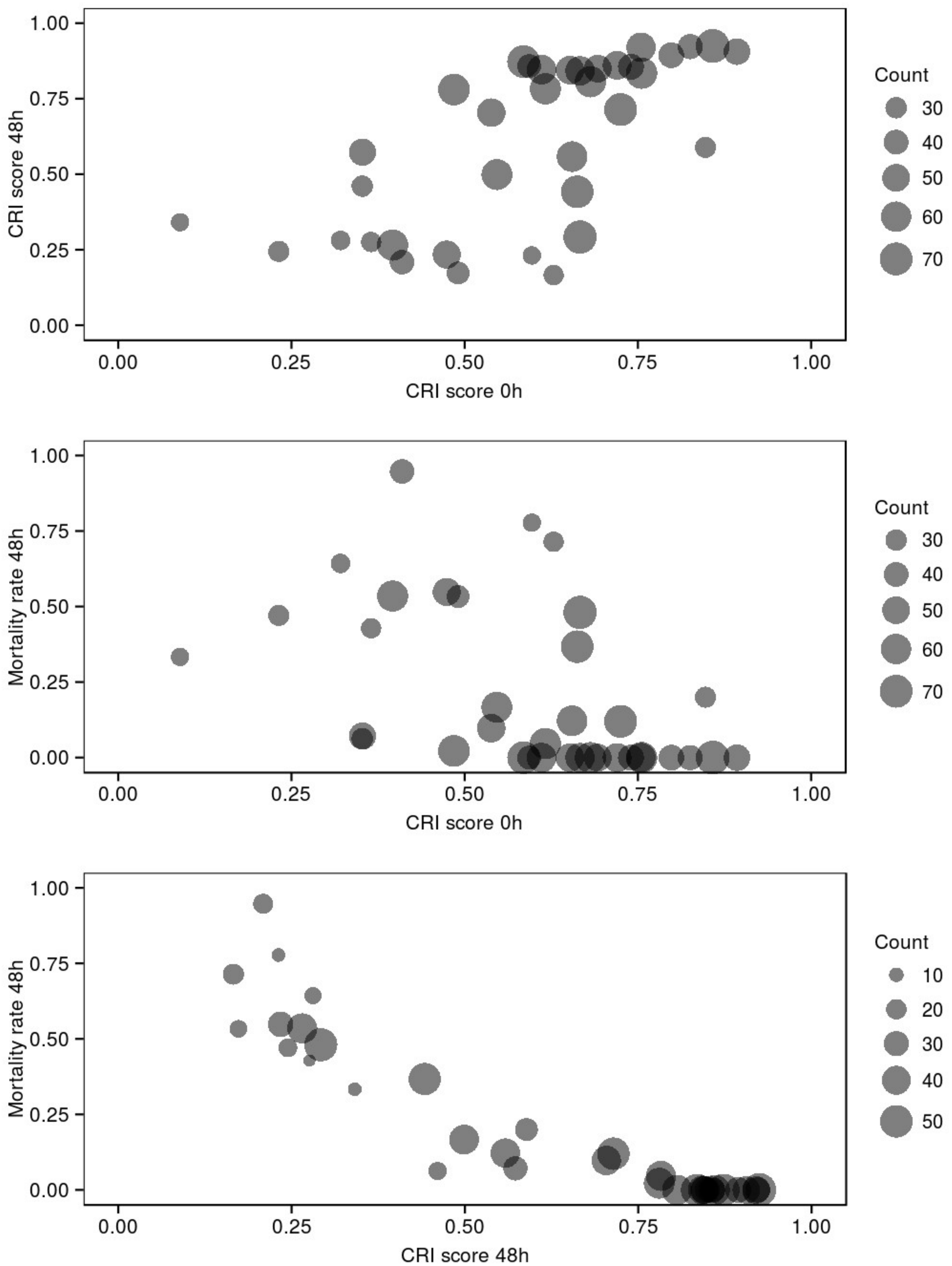


**Figure 8: Relations between the mean CRI at 0 h and at 48 h, and the mortality rate at 48 h. For the top two panels the count is the combined count of fish sampled at 0 h and 48 h. For the bottom panel the count is the count of fish sampled at 48 h only.**

## 7. Summary and recommendations

This work suggests that analysis of the MHS sea trial data focus on two calculated variables, the number of undersized snapper caught per kilogram of legal sized snapper (UCK) and the number of undersized snapper deaths per kilogram of legal sized snapper (UDK). In the context of the quota management system, these variables have most relevance to assessing the question of whether MHS is "no worse overall" than conventional gear.

Of these two variables UDK is the most relevant if it is assumed (a) that the handling of fish on commercial vessels using MHS will be similar to that during the sea trials and (b) that the mortality rate of fish released immediately is similar to those retained in a tank for 48 h. During these sea trials, UDK for MHS was about 40% of that for commercial gear (i.e. more than twice as good). This difference was statistically significant and robust to the formulation of the statistical model used.

However, if those assumptions are violated, that is if handling on commercial vessels is worse, or the mortality of fish released immediately is higher, then the real difference in UDK between MHS and commercial gear may be less. At the extreme, if all undersized fish were to die, then UCK forms a basis for comparison. The median UCK for the MHS gear was 1.34 times that for commercial gear and up to 2.62 times in some of the standardisation models. However, that difference was not robust to the formulation of the statistical model used and for the simplest model (one that amounts to a t-test of differences between gears), and when only data from the main vessel was used, was not significantly different. Thus, there is greater uncertainty in the difference in UCK between MHS and commercial gear.

When deployed on commercial vessels the actual deaths of undersized snapper per kilogram of legal snapper is likely to be somewhere between the estimates of UDK and UCK estimated from these sea trials. Caution needs to be applied in assuming the UDKs achieved in these sea trials would be achieved in commercial situations. But it seems unrealistic to assume that mortality of undersized snapper would be 100% and that UCK should be used as a sole basis of evaluation. Mortality rates for MHS would have to be several times worse than that estimated in this analysis for the overall effect of MHS gear to be worse than conventional gear. Using the medians presented in Table 2 we can roughly calculate that for MHS to have a UDK similar to commercial gear its mortality rate would need to be about 48% ((0.34/0.73)/0.98). In other words, mortality rates for MHS during commercial fishing operations would have to be 3.7 times higher (0.48/0.13) than those observed in sea trials for the overall effect of to be worse than conventional gear.

Note that these conclusions are based on the relatively small amount of data from initial sea trials. Results and conclusions could change when more data is collected.

MPI requested discussion on whether the "the small number of trials that have been undertaken so far are adequate" for determining if the PSH gear is "no worse than" the conventional trawl gear. The existing data was sufficient to demonstrate a statistically significant difference in UDK between MHS and commercial gear. However, the results for UCK were less robust. Furthermore, although statistically significant results can be obtained from the current data set, given the large variability often observed in fish catchability and size composition, it would be highly advisable to conduct more sea trials.

MPI also requested "recommendations for future data collection and analytical protocols, including collecting information on other variables that might affect the results, given that there is an intention to repeat these experiments one or more times". The existing experimental design appears to be appropriate although it is recommended that more effort be made to ensure a balanced distribution of tows by individual vessels across the experimental strata (i.e. depth, season) and to standardise trawl duration. The brief analysis of the Condition Reflex Index (CRI) score suggested that the sample collected at 0 h is of little use as a proxy for mortality rates at 48 h. If the marginal cost of collecting this data is high then it may be worthwhile excluding it from the experimental design. It would appear worthwhile recording CRI on fish at 48 h as it may provide useful additional information on long term survival after release.

The analyses, tables, graphs and analyses provided in this report were produced using R and the source code is available from the author.

## 8. References

Black, S., Chambers, B., Janssen, G. (2014) Postharvest survival assessment of juvenile snapper (*Pagrus auratus*). Unpublished report produced by Plant and Food Research. PSH Standard Method 16.

Moran D., Janssen G., Jacksons, P., Black S. (2015) MPI Update 3 Postharvest survival assessment of juvenile snapper (*Chrysophrys auratus*). Data summary for summer trawl sampling. 22 June 2015