# A general catch comparison method for multi-gear trials: application to a quad-rig trawling fishery for *Nephrops*

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## Abstract

Expeditious uptake of quad-rig trawling in the economically important Irish fishery for *Nephrops norvegicus* outpaced understanding of the catch implications of this new gear technology. The main driver for increased use of this gear is increased catch rates of *Nephrops*. However, discarding of demersal species is likely to have negative impacts on the economics of quad-rig trawling for *Nephrops* unless species and size-selectivity can be improved. Catch comparison methods are suitable for assessing the performance of fishing gear modifications to reduce fisheries bycatch. Utilising a quad-rig potentially increases the number of gears that can be included in a catch comparison study to four but current modeling methods which include error measurements are limited to two gears. Our study provides a statistical framework that: can be applied when two or more gears are used, elucidates how case-specific and choice-specific covariates may influence catch composition, and facilitates discussion on gear specific management measures. We provide a new general multinomial modelling framework that includes multivariate normal random effects to account for clustering of observations at the haul level. Application of the method to catches from four quad-rig cod-ends with different mesh sizes revealed significant effects of net position, total cod-end weight and carapace length on the numbers of *Nephrops* retained in each cod-end. Results suggest that management measures which specifically address different catch profiles associated with different numbers of trawling rigs are required to optimise bycatch reduction in *Nephrops* fisheries.

*Keywords*

## *Catch comparison; gear technology; multinomial mixed effects; mixed logit; landing obligation.*

## Introduction

*Nephrops norvegicus* is a commercially important species distributed throughout the North East Atlantic and Mediterranean Sea. Total landings of 66,500 tonnes in 2010 were predominantly attributed to the United Kingdom (58.1%) followed by Ireland (11.7%) and various other European Union (EU) countries operating in Atlantic and Mediterranean waters (FAO, 2010). More than 95% of EU *Nephrops* landings are taken using single or multi-rig trawlers which target *Nephrops* in mixed species fisheries (Ungfors *et al.*, 2013). The high value of Irish *Nephrops* landings at the first point of sale (estimated at €44.5M in 2014) make it the most commercially important demersal species in Ireland (Cosgrove *et al.*, 2015). The use of four rigs known as quad-rig trawling (Figure 1) commenced in October 2012. By the end of 2014 quad-rigs accounted for ~ 80% of *Nephrops* landings by the Irish fleet (unpublished data, Marine Institute Ireland).

The main driver for increased uptake of the quad-rig trawling is increased catch rates of *Nephrops* which are likely to result from a wider swept area of seabed without increasing the drag of the gear compared with the more traditional single or twin-rig trawling, (Montgomerie, 2015). *Nephrops* catch weights were observed to increase by at least 50% in the North Sea and Celtic Sea in studies comparing quad with twin-rig trawling (BIM, 2014; Revill *et al.*, 2009). Such increases in catching efficiency may be beneficial in terms of improving operational performance but could lead to increases in the 15% discard rate of *Nephrops* below minimum landing or market size in Irish waters (MI, 2014). By-catch of undersized and non-targeted fish species is also a major issue in *Nephrops* trawl fisheries (e.g. Catchpole *et al.*, 2005; Catchpole and Revill, 2008; Nikolic *et al.*, 2015; Ungfors *et al.*, 2013). New requirements to restrict discarding of demersal species under Article 15 of EU regulation 1380/2013, the landing obligation, are likely to have negative impacts on the economics of *Nephrops* fisheries unless species and size-selectivity can be improved.

Gear modifications to reduce bycatch are generally assessed using either selectivity (e.g. McClanahan and Mangi, 2004; Millar, 1992; Millar and Fryer, 1999; Millar and Walsh, 1992) or catch comparison (e.g. Holst and Revill, 2009; Krag *et al.*, 2014; Sangster and Breen, 1998; van Marlen *et al.*, 2014). Practical advantages of the catch comparison method include commercial-like performance and handling of the gear. In addition, the ease with which results of catch comparison experiments can be reported and interpreted (Holst and Revill, 2009) is likely to be of particular assistance to the fishing industry in addressing challenges posed by regulation of their catch composition, for example the EU landing obligation. Whilst catch comparisons can only compare the gears included in particular experiments (Frandsen, 2010), utilising a quad-rig increases the number of gears that can be evaluated in the experiment to four. This potentially allows assessment of more concurrent experimental settings and provides substantially more information than twin or single-rig catch comparisons. Development of a Generalized Linear Mixed Model (GLMM) approach to catch comparison provided a statistical and graphical comparison of fish catch at length by two fishing gears with associated error measurements, improving the power of catch comparison analyses (Holst and Revill, 2009). Binomial GLMMs are, however, limited to experiments with two response categories. Multinomial models can generalise logistic regression to multi-category response problems (McCullagh and Nelder, 1989), i.e. those with two or more fishing gears.

Here, we develop and test the potential benefits of applying a multinomial modelling approach to a comparison of *Nephrops* catches in a trawl fishery with four simultaneously deployed test gears. Our goals are to provide a general statistical framework that incorporates the multivariate response, elucidates how covariates may influence catch composition, and facilitates discussion on gear specific management measures.

## **Materials and Methods**

Addressing the particular requirements of catch comparison in quad-rig trials required a modified trial design and modelling framework.

### Trial design

Data were collected from a catch comparison experiment conducted in the western Irish Sea, ICES sub-area VIIa, between 18 -21 July 2015. The trial vessel carried out multi-rig trawling using a triple warp and centre clump arrangement with 4 identical nets each fitted with a diamond mesh cod-end with nominal mesh sizes of 70, 80, 90 or 100 mm (mesh size descriptors used henceforth) (Table 1). Cod-ends were constructed with single 6 mm, polyethylene twine, with mean omega mesh gauge measurements of 70.8, 80.8, 92.6 and 103.0 mm. Mesh size in the top and bottom panels behind the head-line and in the lower wing ends of the net was 80 mm, while mesh size in the upper wing ends was 160 mm. Corresponding to normal fishing practices in the area, square mesh panels of 120 mm mesh size were mounted 9 to 12 m from the cod-line. Here, ‘net’ describes the whole trawl body. Net positions in relation to the vessel were fixed while cod-end positions were rotated daily to account for potential differences in fishing power without confounding cod-end mesh and net position effects (Figure 1). Described as ‘net configuration’, each cod-end was deployed on each net for 3 hauls which equates to one out of four fishing days, with the data from 12 consecutive hauls analysed. Further information on the vessel and gear used in the trial is presented in Table 1. Operations approximating normal commercial fishing practice were carried out with haul duration, towing speed and depth of ground fished averaging: 04:47 h, 3.1 knots and 48 m respectively. Catches of fish and *Nephrops* were weighed and random representative subsamples were selected. *Nephrops* carapace length was recorded to the nearest mm below using digital callipers connected to a wireless recording system (Cosgrove *et al.*, 2015).

### Model development

In a quad-rig trial the response was a matrix of *Nephrops* counts per observation () and cod-end (). Each row contained four counts (one for each cod-end) for length-bin in haul . For example, for the 30mm length bin in haul 5, the response might be denoting that 10 *Nephrops* were counted in the first cod-end, 20 in the second, etc.

The response data are multivariate counts for which interest lies in describing how the relative proportions retained per length-class in each of the cod-ends varies as a function of the cod-end design (predominantly mesh size) and other explanatory variables. When trials consist of counts per category (cod-end), a starting distribution is the multinomial (Agresti, 2002) with probability mass function

(1)

where: is the count in the th cod-end and ; and is the probability of outcome , , implying 3 parameters in the basic model.

#### Covariates

A common model when explanatory variables are included (such as carapace length) is the multinomial logit model, where the probability of a given outcome depends on values of the explanatory variables for the th observation (row):

, (2)

where is a () row vector of case/row-specific explanatory variables for the th observation and is a () column vector of parameters for the th category. Note that so that the first cod-end is set to the baseline, assuring that the probabilities sum to unity across the categories (Greene, 2000). The explanatory variables included were: carapace length, net configuration (the cod-end positions were changed each night to account for position effects, as highlighted above, thus 4 net configurations were tested) and total weight per cod-end. The total weight per cod-end covariate deserves special attention as it requires different treatment to the case-specific variables such as carapace length. Cod-end bulk weights vary by cod-end and can thus be considered a choice-specific attributes. Choice-specific variables in a multinomial setting are typically modelled as conditional logit models (McFadden, 1973), which remove the subscript *k* from the parameter for that covariate, thus for weight the effect is so at equal weights in the cod-end the effect is cancelled. We thus use a mixture of case-specific and choice-specific covariates leading to the fixed effects model

(3)

#### Subsampling offset

As the counts are sub-sampled, it is also necessary to include an offset for the proportion of the catch in each cod-end sampled . In a twin-rig (two category) trial the offset is given by where and are the proportions of the catch sampled in the test and control, respectively (Holst and Revill, 2009).In the quad-rig trial with the proportion of the th net in the th observation sampled, the vector of offsets for this is given by , where the first zero comes from . The offset is incorporated as

, (4)

*Multinomial random effects*

Counts for category in a multinomial have an expected mean and variance , however, there is often more variability in the counts than the mean-variance (and covariance) allows for, which is termed overdispersion (Hinde and Demétrio, 1998). This may reflect uncaptured variability or clustering, in particular haul-level variability not accounted for when the observations are treated as independent multinomial. Overdispersion was indicated for in the best fitting multinomial model by testing the residual deviance (-2 (log-likelihood best model – log-likelihood of the saturated model)) on a chi-squared distribution with the residual degrees of freedom.

Given that the observations are clustered by hauls, the approach we focus on for accounting for extra-multinomial variability is to include random effects in the model . Multinomial random effects include the baseline category logit random effects model (Hartzel *et al.*, 2001). This model has a multinomial response distribution with the addition of random effects that more explicitly capture the variability attributable to hauls, as opposed to the more general additional variability unattributed to specific grouping but included in, for example, the Dirichlet-multinomial model. The random effects multinomial model we test is an extension of Equation (4) given by

, (7)

where the random effects per haul have a multivariate normal distribution . The baseline category random effect is again set to zero, resulting in a trivariate normal distribution for . An arbitrary (6 parameter) covariance matrix structure, as recommended in Hartzel et al. (2001) was implemented.

The model contained conditional logit, multinomial logit and random effects, which does not facilitate model naming. For simplicity, we refer to the model as a “multinomial mixed effects model”.

#### Inference

We use likelihood ratio tests of nested models to test the significance of each of the fixed effects. As the models are estimated via maximum likelihood we also report Akaike’s Information Criterion for each model. Overall predictions in the presence of a categorical variable (net configuration) were obtained by setting the net configuration values in the predicted model matrix to 1/3 (Fox and John, 2003); total haul weight in the overall predictions was set to the mean.

#### Estimation

Estimation of the multinomial random effects model necessitates integrating over the random effects to estimate the marginal likelihood. We did not find readily available software to fit Equation (7) we therefore wrote an estimation routines in AD Model Builder (ADMB) (Fournier *et al.*, 2012). The ADMB-RE module (Skaug and Fournier, 2006) was used to estimate the multinomial mixed effects model with the variance-covariance matrix specified via a Cholesky-decomposition. ADMB and ADMB-RE also allow for estimates of uncertainty on the linear predictor scale via the delta-method approximation. All pre- and post-processing code was run in R 3.2.0 (R\_Core\_Team, 2015). ADMB code for running the multinomial mixed effects model is stored at (http://www.github.com/mintoc/epif/multinomial).

## Results

A total of 15,443 *Nephrops* were measured during the 12 hauls of the trial. Most of the carapace length measurements were in the range of 20-45mm (Figure 2). Considerable between-haul variability was observed in the proportions retained at length with some hauls displaying consistently lower or higher retention across carapace lengths (Figure 2). The observed proportions at the extremes of the length distribution were more variable as they were derived from fewer observations (e.g., zero or unity proportions in Figure 2).

An estimated deviance of 1448.73 on 998 residual degrees of freedom (338 rows of data x (4-1) cod-ends – 16 parameters) indicated significant overdispersion relative to the baseline multinomial assumption. Our results therefore focus on the multinomial mixed effects models. Separate inclusion of each of the main effects (carapace length, net configuration and bulk weight) resulted in large decreases in the AIC relative to a model with fixed proportions (Table 2). Net configuration was important with inner port position typically fishing worst, and the outer starboard or port fishing better. These likely reflect differences in fishing power of the nets. Higher-order carapace length effects (allowing more curvature in the proportions over length) did not improve the model fit (Table 2). Combining carapace length and total cod-end weight or net configuration resulted in further decreases in the AIC and the model including the three main effects fit best overall (Table 2). Note that higher-order interactions of the explanatory variables were not included in the models, as with 12 hauls and 4 test gears there are 36 independent cells from which to estimate the factor parameters and the models can quickly become overfit (exact predictions at the factor level).

From the best fitting model the estimated covariance and correlation matrices of the random effects were:

and , respectively.

Note that the variance of the random effects was similar across the three log-odds ratios (diagonal of ) and strong correlation exists between the random effects (Figure 3). The magnitude of the variance of the random effects (e.g., ) implies that having accounted for the fixed effects of carapace length, net configuration and total cod-end weight (Table 2), the expected proportions vary in extremes by +/- 12% by haul (inverse logit of 95% intervals -0.5, +0.5). Typically the variability will be lower than this (Figure 3). The relatively low inter-haul variability estimated together with the model comparisons (Table 2) highlight that a considerable amount of between-haul variability is captured by the fixed effects of net configuration and bulk weight though some inter-haul variability remains, which was captured by the random effects (Figures 3 and 4).

The by-haul predictions fit the data well in both the fixed effects and random effects models (Figure 4), though the random effects models expectedly fit some haul and mesh combinations better (e.g., 70mm and 80mm in hauls 3 and 5). Overall predictions show a higher proportion of small *Nephrops* retained in the 70mm, the proportion of smaller *Nephrops* decreases as cod-end mesh size increases (Figure 5). In addition, the slope of the proportion retained over length classes goes from negative in the 70mm and 80mm to positive in the 90mm and 100mm (Figure 5). A higher proportion of larger *Nephrops* were retained in the 90mm and 100mm cod-ends (Figure 5).

The estimated confidence intervals on the mean proportions are narrow reflecting the number of observations contributing to the mean with the considerable between-haul variability accounted for via the fixed and random effects (Figure 4). Note that confidence intervals on proportions should not be interpreted separately as the proportions at a given length across the four meshes sum to one.

## Discussion

Our study developed a multinomial random effects model that included: case-specific and choice-specific covariates, cod-end specific sub-sampling, and multivariate random haul effects. The method is generally applicable to multi-gear catch-comparison studies, as demonstrated in our analyses of a quad-rig trawling *Nephrops* fishery. Here we discuss the model developments, main findings of the quad-rig application and fishery implications.

Model developments

Examples of the application of multinomial models to fisheries include analysis of egg stages (Ibaibarriaga *et al.*, 2007; Stratoudakis *et al.*, 2006), comparisons of age-length keys (Gerritsen *et al.*, 2006), fleet behaviour (Ward and Sutinen, 1994) and discard survivability (Benoit *et al.*, 2010). We extended the traditional multinomial logit model to include the specific requirements of a catch-comparison trial such as choice-specific covariates (e.g., cod-end total catch weight), multiple sub-sampling ratios, and haul-level random effects (to account for over-dispersion). The method is applicable to other catch comparison situations where multiple gears are tested concurrently. By incorporating these effects we have developed a general multinomial modelling framework with applications beyond the field of fisheries science. Hartzel et al. (2001), conceptually develop the baseline logit multinomial random effects model but, to our knowledge, no readily available open source code exists for fitting this model. Use of ADMB-RE greatly facilitated model development and further work linking to R for ease of application would prove useful. .

Using a Dirichlet-multinomial distribution (Thorsén, 2014) offers an alternative method for modelling count data with a response with two or more categories. The Dirichlet-multinomial model is a multivariate extension of the beta-binomial distribution and is used in cases where data exhibits variance greater than expected in a multinomial. Over dispersion in the Dirichlet-multinomial is accounted for by an additional set of parameters for the baseline category, allowing for an additional variability in the response counts (Thorsén, 2014). We chose to develop the multinomial mixed effects model over applying the Dirichlet-multinomial model, as a key component of over-dispersion here is likely at the haul-levelA combined Dirichlet-multinomial mixed effects model could be developed in the future.

Covariate effects

Net position, total cod-end weight and carapace length significantly affected the numbers of *Nephrops* retained in the different cod-end mesh sizes (Table 2). Similar to a previous study conducted in the Irish Sea (Briggs *et al.*, 1999) and a study in the Bay of Biscay (Nikolic *et al.*, 2015), proportionally less smaller *Nephrops* were retained as mesh size increased (Figures 3 & 4). This can be explained by the fact that larger mesh opening angles are known to influence *Nephrops* selectivity (Frandsen *et al.*, 2010).

Total catch weight is known to affect mesh openings and cod-end size selection for a range of fish species (Campos *et al.*, 2003; Herrmann and O’Neill, 2005) and the crustacean Aristeus antennatus (Campos *et al.*, 2003). The significant effect of total catch weight on the proportion of *Nephrops* caught in the current study confirms the influence of this parameter on an additional crustacean species (*Nephrops norvegicus*).

Net position was an important variable explaining a considerable amount of inter-haul variability (Table 2). Position effects within a quad-rig likely result from differences in fishing power caused by variable net geometry associated with asymmetry of warps, sweeps and doors. Net geometry is assumed to govern gear performance and fishing mortality for *Nephrops* (Eigaard *et al.*, 2011; Sangster and Breen, 1998). Failure to deal with this issue could result in confounding mesh effects with position effects. We found that the simplest way to mitigate for these effects is to rotate the gears so that each gear has multiple opportunities to fish in each position. Logistical constraints limit the number of rotations but we found a rotation each night to be a feasible compromise between logistics and position mitigation. Assessment of position effects on quad-rigs using data from gear monitoring sensors (Sangster and Breen, 1998) or side-scan sonar (Lucchetti and Sala, 2012) could further assist in understanding this issue.

The model allows for additional covariates to be included. Variables we did not incorporate in the model include: haul duration, depth, time of day, tidal effects, weather, and data from gear monitoring sensors, among others. The effects of these variables will be captured to some extent by the random effects estimated in the model (Figure 4). They could also be included as fixed effects but the number of covariates that can be included is limited by the number of tows and meshes in the trial (i.e., available degrees of freedom).

Fishery implications

The finding that total cod-end catch weight influences the proportion of *Nephrops* retained has important implications for the development of gear specific management measures in *Nephrops* fisheries. Reductions in total catches of up to 61% of cod, 38% of haddock, and 59% of whiting were observed in trials which compared catches in quad and twin-rig trawls in the Celtic and North Seas. These reductions are thought to be associated with lower headline height and altered sweep arrangements (BIM, 2014; Revill *et al.*, 2009). . Furthermore, significantly increased proportions of small *Nephrops* and cod were retained in the quad-rig compared with the twin-rig in the Celtic Sea study (BIM, 2014). Results of the current and latter studies suggest that lower total catch weights associated with reduced fish catches in quad-rig trawling are likely to reduce cod-end selectivity compared with single or twin-rig trawling. Hence, management measures which specifically address the different catch profiles of different numbers of rigs used in *Nephrops* fisheries are required to optimise bycatch reduction and quota utilisation under the EU landing obligation.

An increase in minimum cod-end mesh size would be a relatively simple, inexpensive and practical new management measure in the *Nephrops* fishery. Although different diamond cod-end mesh sizes do not generally affect the selection range, they do affect the quantities of *Nephrops* retained (Catchpole and Revill, 2008). Our finding that larger cod-end mesh sizes retained significantly lower proportions of small *Nephrops* (Figures 3 and 4) bodes well for the development of a management measure in relation to increased minimum cod-end mesh size. The reasons why higher proportions of larger *Nephrops* were retained in the larger cod-end mesh sizes of the quad-rig (Figures 3 & 4) are unknown but may, if confirmed, be an additional potential benefit of increase in minimum cod-end mesh size in the quad-rig trawling fishery for *Nephrops*. The current minimum cod-end mesh size in Irish waters is 70 mm. In the context of the landing obligation, economic modelling of an increase in minimum cod-end mesh size demonstrated that reduced catches of small *Nephrops* in an 80 mm cod-end can provide more opportunity to catch increased quantities of larger more valuable *Nephrops,* leading to marginal increases in vessel profitability over the course of a fishing season (Cosgrove *et al.*, 2015). Results of the current study suggest that*, ceteris parabis*, a larger increase in minimum cod-end mesh size would be required in quad-rig trawling compared with operations which employ fewer rigs to optimise bycatch reduction in *Nephrops* fisheries.

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Table 1. Details of fishing vessel and gear

|  |  |
| --- | --- |
| Vessel | Our Lass II (DA261) |
| Vessel Length Overall (m) | 21.7 |
| Engine power (kW) | 484 |
| Home port | Howth, Ireland |
| Trawl type | Quad-rig for *Nephrops* |
| Trawl manufacturer | Pepe Trawls Ltd., Ireland |
| Otter board manufacturer/ type | Dunbar 7’6” |
| Fishing circle (m) | 380 x 80 |
| Door weight (kg) | 492 |
| Clump weight type/ weight (kg) | Roller/ 680 |
| Average door to clump spread (m) | 34.4 |
| Sweep length (m) | 50 + 20 |

Table 2. Multi-rig catch comparison. Multinomial random effects model fit summary. Explanatory variables are abbreviated: carapace length (CL), net configuration (NC) and cod-end total weight (W). The model degrees of freedom (df) includes 6 parameters parameterising the trivariate covariance matrix of the random effects.

|  |  |  |  |
| --- | --- | --- | --- |
| Explanatory variables | Log-likelihood | Model df | AIC |
| None | -2084.79 | 9 | 4187.58 |
| CL | -2062.56 | 12 | 4149.12 |
| NC | -2049.41 | 18 | 4134.82 |
| W | -2058.52 | 10 | 4137.04 |
| CL + NC | -2027.31 | 21 | 4096.62 |
| CL + W | -2036.2 | 13 | 4098.4 |
| NC + W | -2039.81 | 19 | 4117.62 |
| CL + NC + W | -2017.17 | 22 | 4078.34 |
| CL + CL2 + NC + W | -2016.79 | 25 | 4083.58 |



Figure 1. Outline of quad-rig gear including net position in relation to the vessel. Reproduced and edited from Seafish (2010) with permission from Seafish.

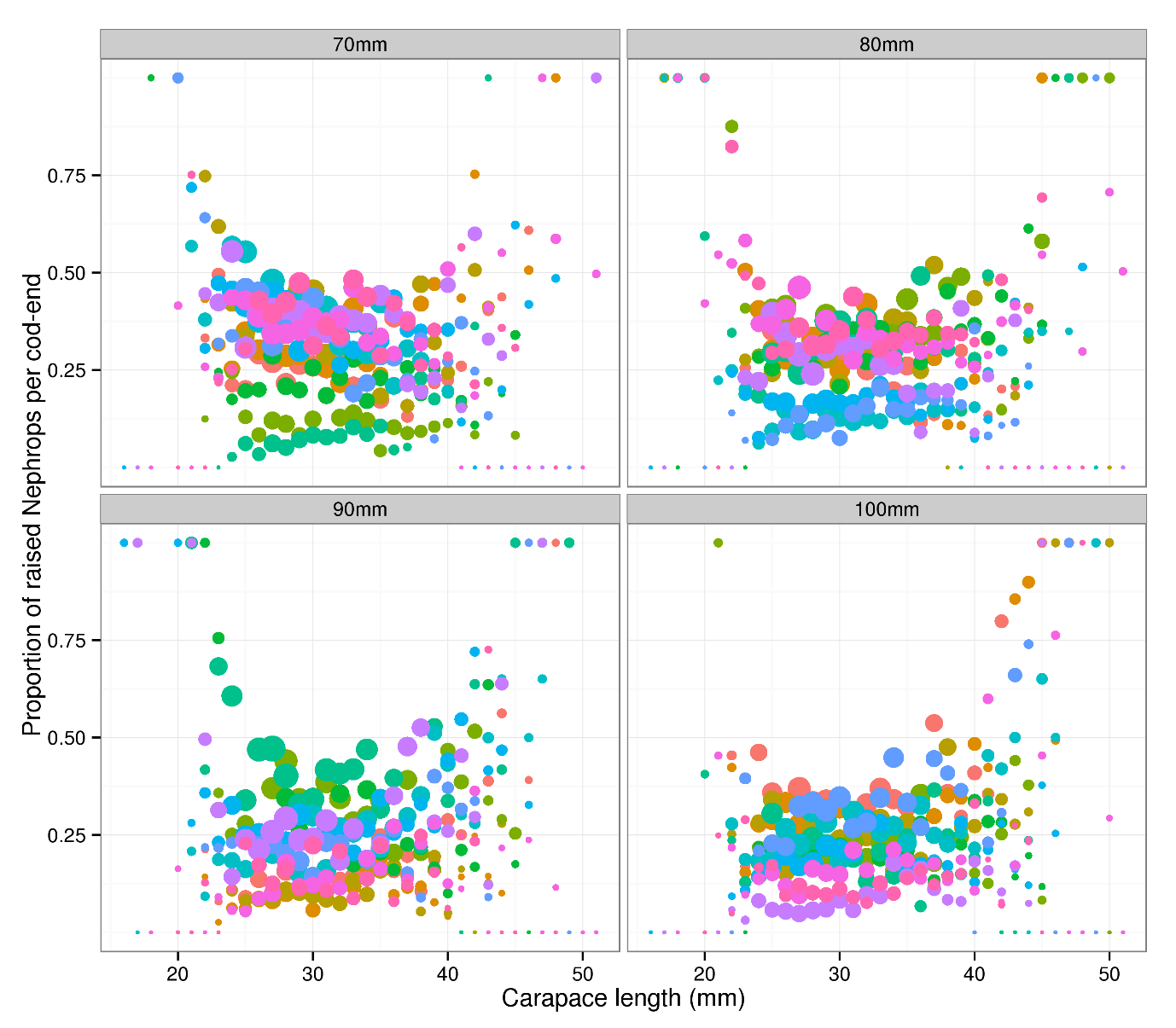


Figure 2. Multi-rig catch-comparison. Proportion of Nephrops retained per length-class by diamond mesh size. Hauls are coloured to demonstrate the haul effects. The diameter of the points is proportional to the log base 10 of the raised counts to illustrate where the distribution of the counts.

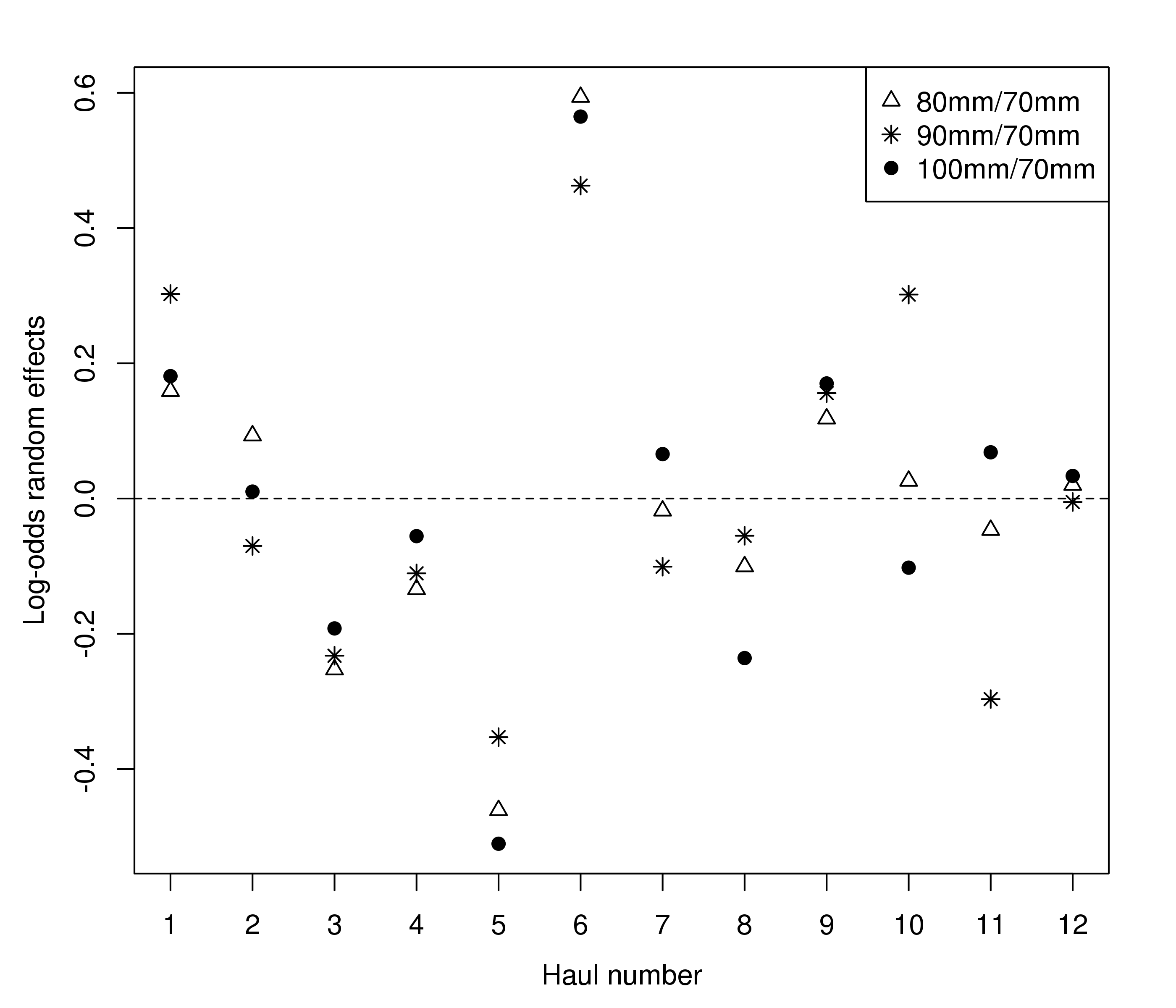


Figure 3. Multi-rig catch comparison. Estimated trivariate random effects (log-odds ratios to the baseline 70mm case: in Equation 6) by haul.

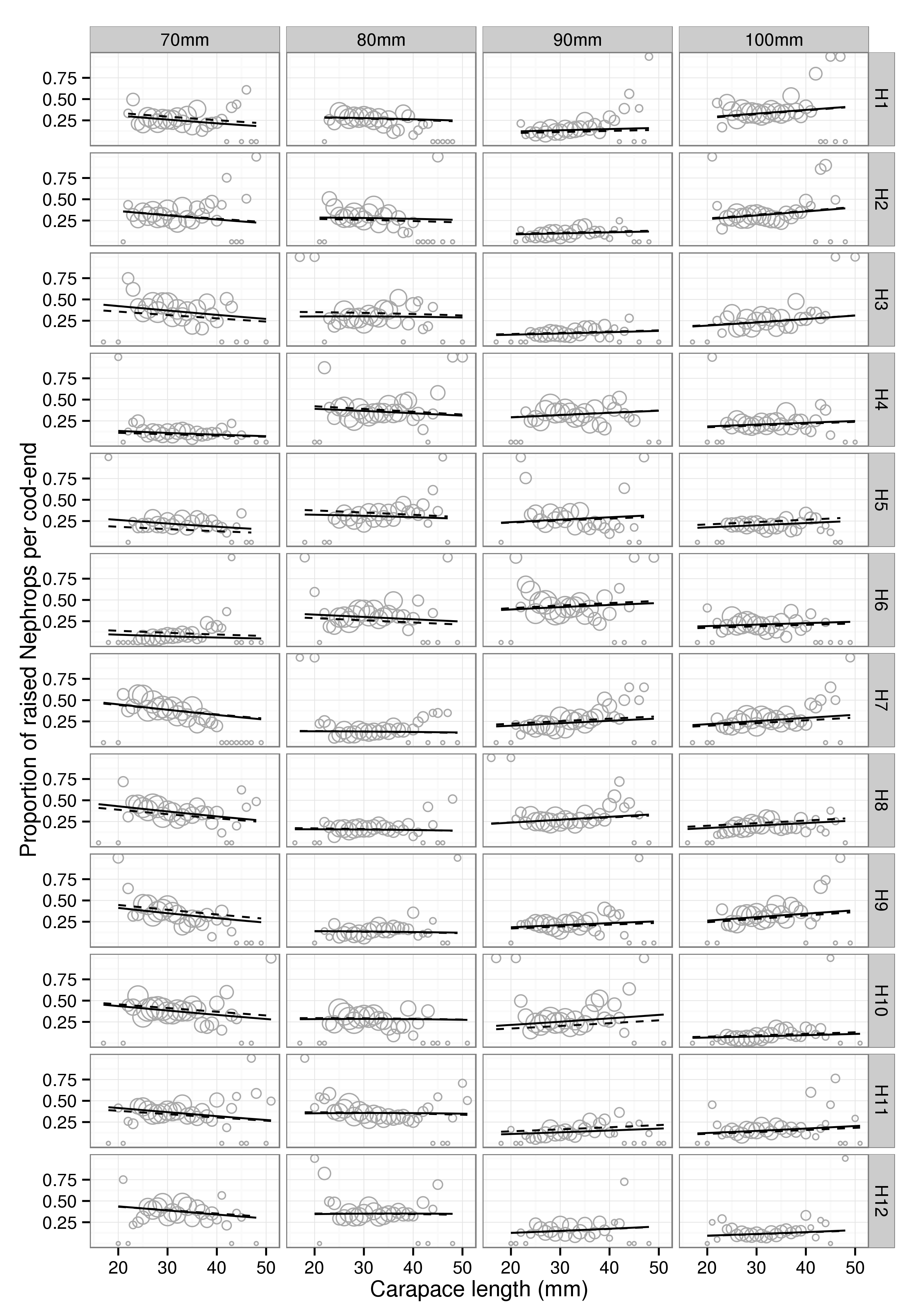


Figure 4. Multi-rig catch comparison. Fitted multinomial mixed effects proportions by haul. Solid and dashed lines represent the predictions from the best fitting model with and without random effects

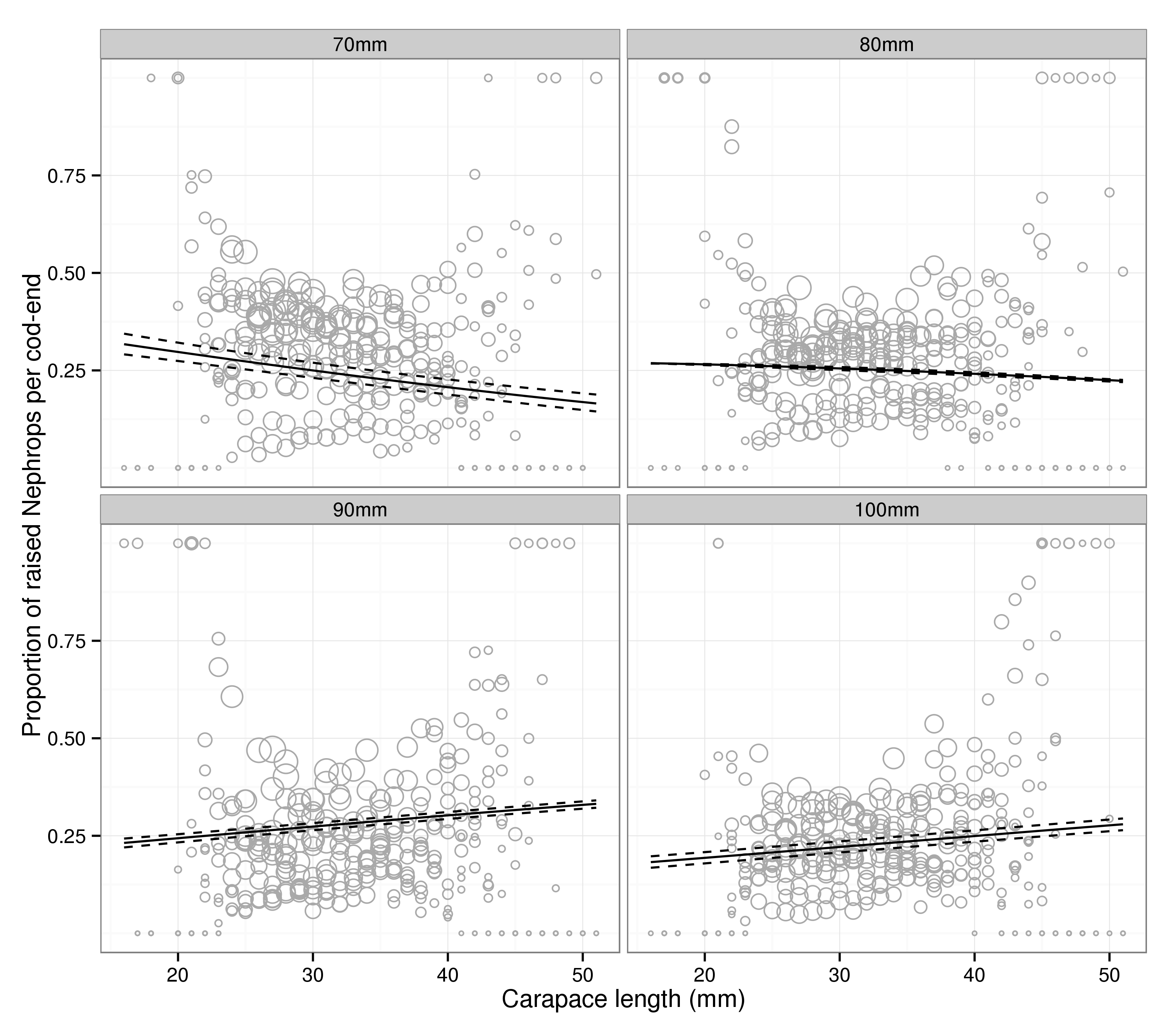


Figure 5. Multi-rig catch comparison. Overall predicted proportions at length. Solid and dashed lines represent the mean and 95% confidence intervals on the mean (see text for discussion on confidence intervals in this setting).