SC/67A/HIM/10

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INTERNATIONAL WHALING COMMISSION

Gear modifications reduced whale entanglements in a commercial rock lobster fishery

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ABSTRACT

Entanglement of large whales in fishing gear occurs world-wide and, in regions where whale populations are recovering from past harvesting, it is expected entanglements will increase in frequency. The Western Australian population of humpback whales (*Megaptera novaeangilae*) is recovering rapidly and yet between 1990 and 2010 the reported entanglement rate in gear from the pot-based western rock lobster (*Panulirus cygnus*) fishery was relatively stable at around one per year. However, from 2010, reported entanglements increased dramatically, peaking at 17 in 2013, with this increase linked primarily to the fishery moving from a 7.5 month season to operating all year. To reduce entanglements a series of fishing gear modifications were

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implemented into the commercial rock lobster fishery, eliminating surface rope in waters deeper than 20 metres and minimising float numbers. The utility of these measures has been assessed using entanglements reported between 2000 and 2016. The assessment model incorporated expected changes in whale population size, entanglement sighting probability, commercial fishing effort, inter-annual variation in the timing of the whale migration and the implementation of gear modifications. The analyses suggest gear modifications reduced entanglements by ~65% with two and four entanglements in 2015 and 2016, respectively. The model also highlighted the northward migration and water depths of 37 – 73 m as the times and areas with the greatest rate of entanglements. This is the first assessment that examines the effectiveness of gear modifications to reduce whale entanglements and highlights the importance of incorporating all factors which may impact on entanglement rates to assess the effectiveness of gear modifications.

KEYWORDS

Entanglements, humpback whale, gear modifications

INTRODUCTION

The entanglement of large whales occurs world-wide and in many types of fishing gear including drift/gill nets, long-lines, shark control nets, traps and pots (International Whaling Commission, 2010). Such interactions are recognised as one of the major anthropogenic impacts on whale populations (Van Der Hoop et al. 2013) and have been shown to have a major influence on the viability of some cetacean populations (Johnson et al., 2005; Knowlton & Kraus, 2001). At the individual level, entanglements can cause prolonged periods of suffering before death and as such pose a significant social and ethical concern (Moore et al., 2006). Even in circumstances where entanglements don't jeopardise conservation objectives, there are legislative requirements in Australia to mitigate them due to the ethical issues surrounding large whale entanglement.

Since records began in 1982 entanglements in gear from several fisheries operating off Western Australia have been reported for four large baleen cetacean species (Groom & Coughran, 2012). The most common species (>90%) involved in these entanglements is the humpback whale (*Megaptera novaeangilae*). Like many humpback whale populations worldwide, the two Australian populations of humpback whales are recovering rapidly from whaling activities (Bettridge et al., 2015) and some argue that this species should be down-listed (Bejder et al., 2015), though they remain listed as 'vulnerable' under Australian federal legislation. The Western Australian population of humpback whales (named Breeding Stock D by the International Whaling Commission) migrates along coastal waters of Western Australia during the austral autumn to spring, leaving summer feeding grounds in Antarctica to calve in the warm waters of the Kimberley region (Jenner et al., 2001). This population was severely impacted by commercial whaling from the early 1900s through to the late 1960s, by which time the origin population of around 30,000 had been reduced to fewer than 800 individuals (Chittleborough, 1965; Ross-Gillespie et al., 2014). While absolute abundance estimates are difficult to derive for this population (Hedley et al., 2011b; Jackson et al., 2015), the rate of recovery has been estimated to be as high as 12% per annum (Hedley et al., 2011b) and a recent stock assessment model suggested the population size was approximately 20,000 individuals in 2015 (Ross-Gillespie et al., 2014).

Entanglements and gear modifications

Of the 63 entanglements or encounters (when a whale is recorded as coming into contact with gear but it does not result in an entanglement) recorded off Western Australia between 1982 and 2010, nearly half were attributed to the West Coast Rock Lobster Fishery (WCRLF, Groom & Coughran, 2012). The WCRLF targets the spiny lobster *Panulirus cygnus,* an endemic species to the Western Australian coast and the most valuable single-species fishery in Australia valued at over AUD $400 million. The lobsters are captured with baited pots which are set singularly with a floating rope marked by 2-7 surface buoys. Pots are generally set and retrieved 1-3 days later (de Lestang et al., 2012). Due to a reduction in the settlement of juvenile lobsters (puerulus) caused by unfavourable environmental conditions (Caputi et al., 2014) and a necessity to restrict catch, the fishery transitioned from an effort-based management system to an output (quota) based management regime. The traditional closed season from 1 July to 14 November which existed under the effort-control system, was gradually reduced from the 2010/11 season so that by the 2013/14 season the fishery operated year round.

Prior to 2010 the number of recorded entanglements attributed to the WCRLF varied between zero and six annually. Whale entanglements attributed to the WCRLF greatly exceeded previous annual rates in 2012 and 2013 (12 and 17 respectively), which coincided with the reduction in the closed season length and the shift to year-round fishing in the WCRLF. However, given the current estimated size and trend for this population, this higher rate of entanglement is unlikely to impact on the population's rate of recovery (J. Bannister in Bettridge et al., 2015; Stoklosa, 2013). Regardless, under Australia's Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act) there is an obligation to reduce impact on non-target species and, as such, the increase in whale entanglements prompted both federal and state governments to place a series of conditions on the fishery to address the issue. The federal and state governments in concert with the fishing industry have also recognised the ethical and social considerations associated with the entanglement of humpback whales (DSEWPaC, 2013; Western Rock Lobster Council Inc., 2015).

Based on initial trials (How et al., 2015) gear modifications were actively enforced from 1 July 2014. They were based on the principle of limiting likely points of entanglement within the gear and consisted of reducing the amount of slack line on the surface as well as the number of floats used. This gear modification period ended on 15 November 2014. Subsequent seasons (2015 and 2016) have seen the gear modifications implemented again from 1 May, finishing on 15 November (2015) and 30 October (2016).

This study assessed the effectiveness of these gear modifications in reducing whale entanglements using a statistical model that included factors that were likely to affect the probability of a whale being reported as ‘entangled’. These factors included the sighting probability (relative number of people on the water to sight an entangled whale), the amount and location of fishing effort, the number of whales which are migrating through the fishery each season and inter-annual changes in the timing of whale migration.

METHODS

Entanglement Records

Entanglements and interactions of cetacean species have been recorded by the Department of Parks and Wildlife (Western Australia) since 1982. Information includes but is not limited to date, species, gear type, reporter, fate and location. These data were analysed to differentiate between entanglements and other types of interactions, and where possible, the likely time between entanglement and reporting. For the purpose of this assessment, an entanglement involves a whale carrying equipment (generally fishing gear) that it is unable to release itself from. Excluded from the assessment were records of interactions with fishing gear, where the whale only came into contact with fishing gear and released itself almost immediately and reports of entanglement scarring on whales where no gear is present. Analyses of gear modification effectiveness were limited to only those records where the gear was confirmed to be from the WCRLF.

Preliminary indications from entanglement sightings and re-sightings show that an obvious loss of body condition is evident in humpback whales off Western Australia after a period of around 40 days (How, unpublished data). There were several records where it was evident that the entanglement had been present for an extended period of time, either through the whale's body condition or the condition of the wound. As these individuals showed a greater loss of body condition or wound development, they were arbitrarily assigned a date of 90 days prior to the entanglement report to reflect their long-standing nature. The date of the entanglement could however be determined for some records e.g. where the whale was anchored, or from the date when a pot was recorded as lost by a fisher. For the remaining entanglement records, where there was no evidence of a loss of body condition or estimated date of entanglement, sensitivity analyses were undertaken for varying periods between entanglement and reporting (see Sensitivity Analysis).

West Coast Rock Lobster Fishing Effort

Commercial rock lobster fishers submit mandatory catch and effort statistics. Under the effort control system (pre-2011), this was in the form of a monthly report detailing retained catch and effort (no. pots) in 1 x 1 degree blocks. An additional voluntary logbook was completed by approximately 30% of the fleet (de Lestang et al., 2012) and captured more detailed information such as catch and effort by 18.3 m (10 fathom) depth categories for 10 minute latitude blocks, as well as depth, soak time (time between setting and retrieving gear) and other discarded catch and environmental information. These data were used to apportion mandatory monthly effort information into the finer spatial scale captured by logbooks. Under the quota management regime (2011 onwards), fishers have been mandated to record catch and effort for each trip, explicitly stating the soak time (days) and depth range fished along with other variables. The spatial resolution of these data also increased to 10 x 10 minute blocks (de Lestang et al., 2012).

A metric was established from these effort data to describe the number of vertical lines that whales could encounter in each depth band and month. The number of pot retrievals was multiplied by the soak time to provide the total number of days when ropes and floats were present in the water column (rope days). The total number of rope days was determined for each 18.3 m (10 fathom) depth category, month and year combination.

Gear Modifications

The regulated gear modifications, first enforced on 1 July 2014, stipulated that fishing gear in waters greater than 20 m be set so that:

(1) the rope is no longer than two times the water depth;

(2) the top third of the rope be negatively-buoyant such that there is no surface rope;

(3) the float rig be no longer than 9.3 m;

(4) no more than three floats to be used;

(5) only two floats to be used in waters shallower than 54.9 m; and

(6) pots are to be pulled at least every seven days.

Commercial Whale Watching Returns

These data were used to incorporate annual variation in the timing of the whale migration into the model. Commercial whale watching vessels access either the northerly or southerly migration of humpback whales off the Western Australian coast depending on the region they are operating in. Vessels licenced to undertake commercial whale watching activities in Western Australia are required to provide a daily return of all encounters with large cetaceans. These vessels undertake multiple trips per day with each trip consisting of a number of encounters. For each encounter, operators record the number and species of whales encountered and the location (GPS) and environmental conditions for each contact. Four regions were identified that produced consistent sighting information from 2000 – 2016, two accessed the northerly migration (Albany and Augusta) and two accessed southerly migrating whales (Perth and Geographe Bay).

Model Description

To examine the effect of the gear modifications on the entanglement rate of whales in the WCRLF an integrated modelling approach was employed. This approach was chosen over simpler GLM-based approaches to deal with the high parameterisation of the model and the combination of two likelihood components. The rate of reported entanglements of whales was considered to be a function of water depth, month, fishing gear construction, fishing effort levels, sighting probability, direction and timing of whale migration and the size of the whale population migrating along the coast. This represented a large number of coefficients to be estimated (53 parameters) and was therefore reduced where possible. Thus, since some of these factors were considered auto-correlated, i.e. the abundance of whales in successive months of migration, these relationships were generalised using a normal distribution to reduce parameterisation of the model. In order to reduce the number of parameters being estimated and incorporate the assumed relationships, normal probability distributions (NPD; implemented via the difference in two cumulative distribution functions [CDF]) were employed to account for variation in some parameter groups. For example, rather than estimate 12 parameters, each representing a unique month for the northward whale migration, the monthly distribution of migration was represented by a NPD with only two parameters (mean and standard deviation). These modifications were made to three of the parameter groups (monthly timing of the northerly and southerly migration and depth distribution) which reduced the number of parameters being estimated from 53 to 30. The proportion at a given point (either month or depth zone) was determined by the difference in probability between two CDF functions ($F(x) = \nu \le x < \nu + 1$). For example, the probability of whales migrating in the 20 – 30 fathom depth range was determined by the cumulative probability of them being in 30 fathom depth minus the probability in 20 fathom depth.

The model was split into two main components; inter-annual variation in the timing of migration and the number of whales reported to be entangled in each month (*m*) and depth zone (*d*) of each year (*y*), with each component having its own log-likelihood function.

The inter-annual variation in the timing of migration was determined using a weighted linear model approach. This assumed that the timing of migration followed a normal distribution each season, and could be determined from commercial whale watching logbook data. The mean day (Julian from January 1) weighted by the number of whales observed on that day represented the mean timing of migration at that location for that season (i.e. the day when the peak number of whales would be expected). The difference in the timing at each of the four locations (Albany, Augusta, Perth and Geographe Bay) was also considered to be consistent between years, i.e. a later timing of migration seen at Albany would be reflected in a later timing of the same magnitude at the other three locations). The timing of migration for each year was estimated as a temporal offset (O_y) from the start year of the model, i.e. the difference in the timing of migration from the timing of migration in year 2000.

The linear model used to estimate the mean Julian day of migration for each year contained two factors, location (with four levels, representing each location) and year (with 17 levels, representing 2000 - 2016), which combined, equated to 20 parameters plus one additional parameter for the standard deviation of the error term ($\hat{\sigma}_1$) of the linear model used in the fitting process by the negative log-likelihood (λ_1) equation:

$$\lambda_1 = -\sum_{i=1}^{n} 1/(\hat{\sigma}_1\sqrt{(2\pi)})\mathrm{e}^{(-((J_i - \hat{J}_i)^2/(2\hat{\sigma}_1^2)))} W_i ,$$

where J_i is the observed Julian day of the ith observation, when W_i whales were sighted and $\hat{J}_i$ is the model's estimated mean Julian day for that observation.

The number of whales reported to be entangled in each month and depth zone of each year was estimated in the second component of the model. This component utilised the first component's estimates of the offset in the timing of migration (O_y) as well as an additional nine parameters: the mean and sd for the northerly [N(N,Nsd)], southerly [N(S,Ssd)] and depth of migration [N(D,Dsd)]); fishing effort ($E_{d,m,y}$) , the catchability of the fishing gear (q) and the impact of the gear modifications on q (qm). The second component also contained a standard deviation associated with its likelihood component ($\hat{\sigma}_2$). Sighting probability ($R_{d,m,y}$) and the size of the whale population (W_y) were not estimated, rather they were varied in a range of sensitivity trials around plausible values (see Sensitivity Analysis below). In the model, the depth distribution did not vary between years, whereas that of northerly and southerly migration timing did.

The equation used to estimate the number of whales reported entangled in depth d, month m and year y, ($I_{d,,m,,y}$) was estimated as:

$$I_{d,m,y} = W_y \mathrm{N}\left(NO_y, Nsd\right)_m \mathrm{N}\left(SO_y, Ssd\right)_m \mathrm{N}\left(D, Dsd\right)_d \, q \, E_{d,m,y} qm \, R_{d,m,y} ,$$

. The negative log-likelihood of the second component (λ_2) was determined using the equation:

$$\lambda_2 \; = \; -\sum_{i=1}^{n} 1/(\hat{\sigma}_2 \sqrt{(2\pi)}) \mathrm{e}^{(-((A_{d,m,y} - I_{d,m,y})^2 /(2\hat{\sigma}_2^2)))} ,$$

where $A_{d,m,y}$ is the reported number of entangled whales. The two negative log-likelihoods ($\lambda_1 + \lambda_2$) were combined and minimised using the "optim" routine in R with the standard errors of coefficients being derived by calculating the inverse of the square root of the diagonal elements of the Hessian matrix.

Sensitivity Analysis

Not all factors in the model could be directly estimated as information did not exist that allowed for the determination of sighting probability, whale population size or lag between entanglement and reporting. Uncertainty around the magnitude of these factors was therefore investigated via a sensitivity analysis approach, a technique easily incorporated into the integrated model framework. Annual whale abundances (W_y), relative depth adjusted and inter-annual sighting probability ($R_{d,m,y}$) and the lag between entanglement and reporting, were each systematically varied through a range of sensible values. The outcomes of these models were then summarised to show the extent to which the estimated parameters were influenced by these three factors.

Aerial surveys of western Australian humpback whales have delivered relative abundance estimates for this population (Paxton et al. 2011, Hedley et al. 2012, Salgado Kent et al. 2012). However in attempting to estimate absolute abundance, each of these studies made assumptions regarding the duration and distribution of the migration, the amount of milling or mixed migration in the survey region and importantly each of these studies lacked an effective means to estimate availability bias which is required to estimate the total abundance (Hedley et al., 2011a). The northerly migration off Western Australia tends to be further offshore than off eastern Australia and there are few high cliffs suitable for land-based observations. Thus, options to estimate availability bias are limited (Hedley et al., 2011a). The Scientific Committee of the International Whaling Commission (IWC-SC) recognised this constraint and thus only used relative abundance estimates for the Western Australian population (‘Breeding Stock D’) in its stock assessment models (International Whaling Commission, 2014, 2015). As such, the sensitivity analyses for this assessment were conducted using the lower, median and upper annual estimates of absolute abundance for the duration of the study from the IWC-SC's recent single stock assessment model (Ross-Gillespie et al., 2014).

The number of reported entanglements will be influenced by the number of opportunities for an entangled whale to be seen. While there has been a decline in commercial WCRLF fishing effort during the study period, there has also been an increase in recreational vessel registrations (Department of Transport, unpublished data) and commercial whale watching activities. With reports coming from commercial fishers, commercial eco-tour operators and members of the public, a range of relative sighting probabilities were assessed. Annual variation in relative sighting probabilities was considered to be either zero, or increasing at 2%, 4%, 6%, 8% and 10% per annum. Relative sighting probability was also then assessed as either being uniform across depth categories, or adjusted by decreasing the likelihood of sighting further offshore by 0.5 of the previous depth category. This was based on the assumption that greater vessel usage was likely in shallower water depths than further offshore.

The timing of entanglements could be determined for nine reports (12%) involving rock lobster gear. For those where the specific date of the entanglement could not be determined, seven different lag periods between entanglement and reporting were assessed. These lags were 0, 1, 7, 14, 21, 28 and 35 days prior to the entanglement report.

RESULTS

Entanglement Records

There have been 145 entanglements reported off the Western Australian coast between 1982 and 2016: 137 (94%) involved humpback whales, six (4%) involved southern right whales (*Eubalena* *australis*) and single entanglements of a Bryde's (*Balaenoptera brydei*) and minke (*Balaenoptera acutorostrata*) whale.

Entanglements rose from between zero and eight in the period 1990 to 2010 to a peak of 31 entanglements in 2013. Entanglements declined to 13, eight and five in 2014, 2015 and 2016, respectively (Figure 1). Over half of all entanglements (*n*=75) were associated with WCRLF gear, though gear from a number of other sources including, octopus, deep sea crustacean and crab fisheries, as well as aquaculture activities has been involved in whale entanglements off Western Australia (Figure 1a). Approximately 34% (*n*=49) of all entanglements could not be ascribed to a particular fishery, although 48 of these entanglements involved ropes with or without floats that were similar to those used in the WCRLF but lacked identifying marks or configurations. Entanglements in 'unknown ropes and floats' followed a similar pattern to entanglements in WCRLF gear, peaking with ten entanglements in 2013, and three, five and one entanglements in 2014-16, respectively (Figure 1a).

Prior to quota management in 2011, entanglements in WCRLF gear averaged 1.3 (range 0-6) per year (Figure 1b). From 2010, when there were no reported entanglements in identified WCRLF gear, entanglements rose with five in 2011, 12 in 2012 and peaked at 17 in 2013 (Figure 1b). Recent seasons have seen a decline with seven reported entanglements linked to the WCRLF in 2014, two in 2015 and four in 2016.

Western Rock Lobster Fishing Effort

Annual rope days remained relatively constant at around 12 million until 2005 after which time they decreased gradually due to a series of effort control measures introduced into the fishery (Figure 2a). Rope days declined markedly in 2009 and have remained at a low level in subsequent years resulting in the post quota period (2011+) having markedly less rope days than under the effort-control management system.

While there has been an overall reduction in rope days since 2008 the changes have not been uniform in relation to the depths fished during the whale migration period (May-October) (Figure 2b). All depth categories less than 30 fathoms (54.8 m) had a reduction in rope days prior to the introduction of quota in 2011, while rope days in deeper water remained at consistently low levels. The reduction in rope days was most noticeable in shallow water (<10 fathoms, <18.3 m), which accounted for much of the overall effort reduction. Rope days in the 10-19 fathom (18.3-36.5 m) and 20-29 fathom (36.6-54.8 m) ranges were at minima in 2010 before increasing over the next 2 years, before gradually declining from their peak in 2012 (Figure 2b).

Changes in fishers' behaviour resulted in a progressive increase in the proportion of rope days in 36.6-54.8 m range from 2008. Since the introduction of gear modifications in 2014, the proportion of effort has declined in the 18.3-36.5 m and increased in the 36.6-54.8 m strata. There has been a slight increase in the deep water fishing (>54.9 m), while shallow water fishing (<18.3 m) has remained relatively constant (Figure 2b).

Model Outputs

The best model fit ($r^2 = 0.92$) to the observed data was for a one day lag, lower population estimate of absolute whale abundance and a 10% p.a. increase in sighting probability unadjusted for depth. This combination of parameters was able to replicate the high entanglement numbers recorded in 2013 (Figure 3) and resulting model estimates fitted the observed data well (Figure 4). As these parameters resulted in the optimum fit, they were then used to examine the impact of an increasing whale population on entanglement numbers. This represented an estimated timeline of entanglements for a scenario in which effort reductions for stock management had not been implemented. By maintaining the mean effort distribution of 2000-2004, which included the seasonal closure from 1 July – 14 November, the model predicted that reported whale entanglements would have generally increased through time due to the increasing whale population (Figure 3). This scenario would have led to almost 13 entanglements being recorded in 2016 (Figure 3).

The residuals from the model do not show any biases although, as expected, variance is greater towards the end of the time series, reflecting the higher entanglement rates recorded in 2012 and 2013 (Figure 4).

Model outputs were generally robust to changes in humpback whale population size assumptions (Figure 5a, Figure 6 a), and for reporting lag times of a week or less (Figure 5b, Figure 6 b). Longer lag times slightly reduced model fit and estimates of gear modification effectiveness, while a depth adjusted sighting probability slightly improved model fit and estimates of gear modification effectiveness (Figure 5c, Figure 6 c). Higher inter-annual sighting probability increases improved model fit and estimates of gear modifications effectiveness, though there was little difference between 8-10% p.a. (Figure 5d, Figure 6 d). Higher inter-annual sighting probabilities were not examined as they would represent and unrealistic increase in sighting probability.

Entanglements and gear modifications

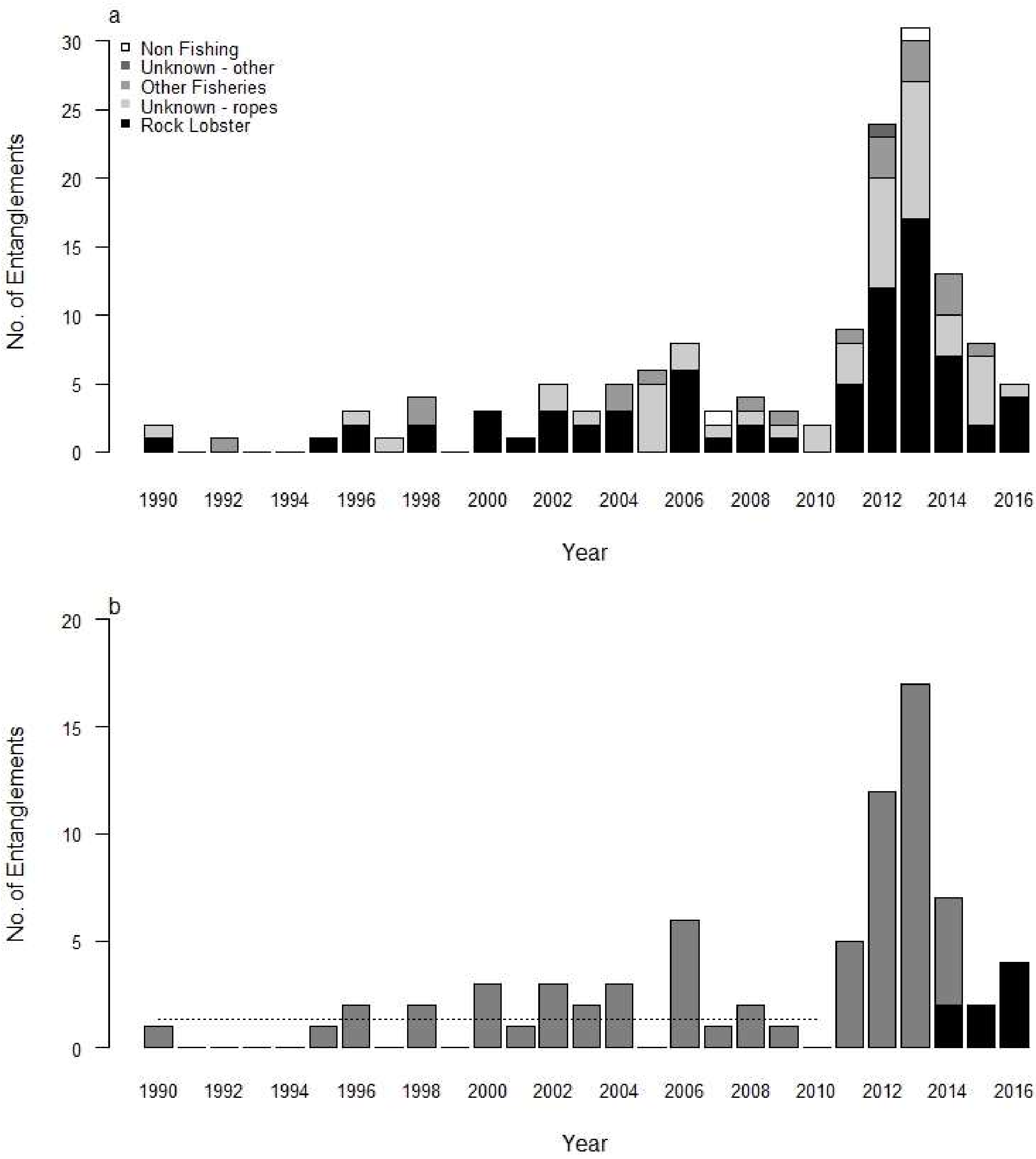

Figure 1 Annual number of whale entanglements a) by fishery/s or, if fishery was unknown, then gear type and b) western rock lobster fishery entanglements without (grey) and with (black) gear modifications and mean annual entanglement rate (1990-2010; dotted line)

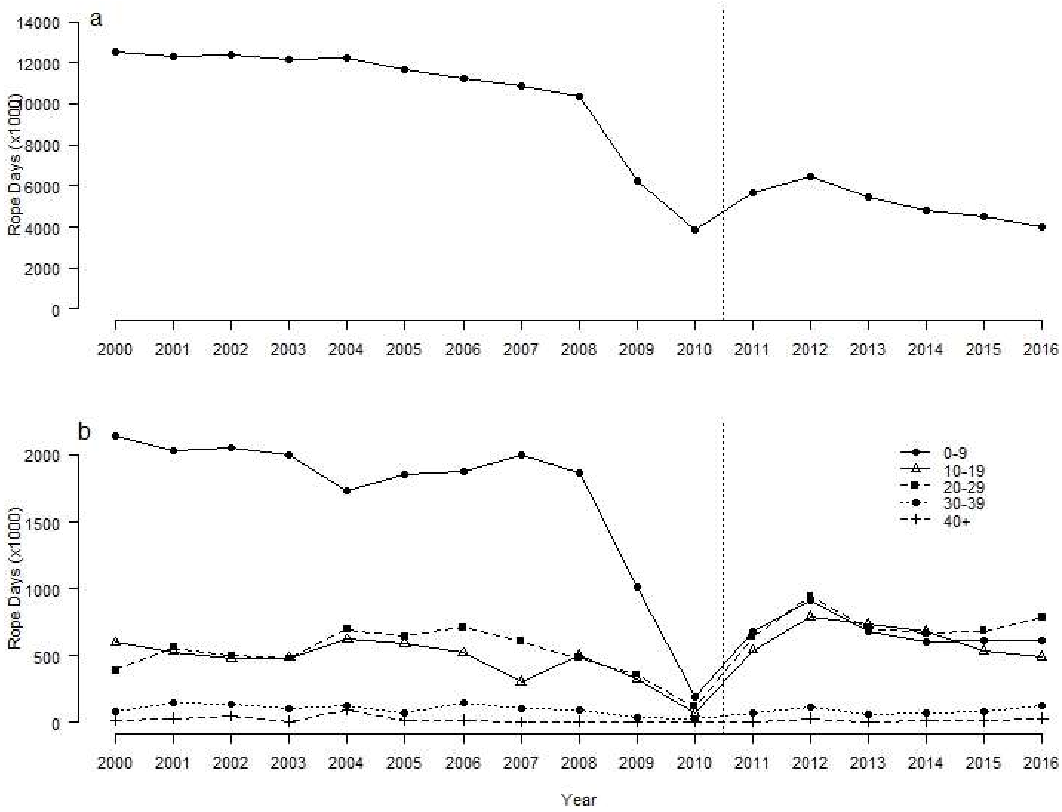

Figure 2 a) Annual rope days (x1000) for the western rock lobster fishery (WCRLF), b) rope days by 10 fathom depth category during the gear modification period (May-October) Vertical dashed line represents when the WCRFL transitioned to a quota management system

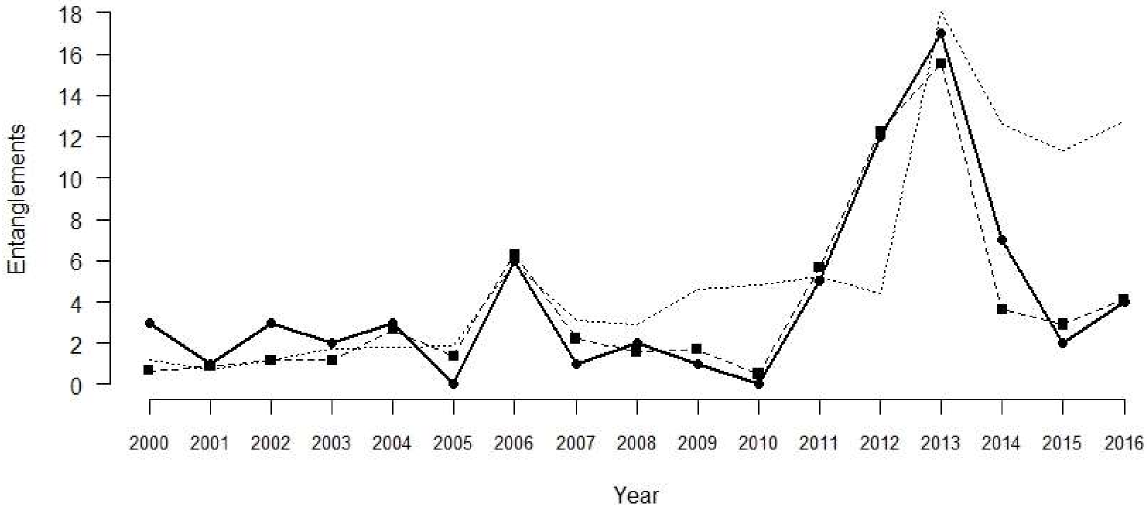

Figure 3 Annual entanglements in western rock lobster gear (full circles), estimated entanglements from best-fitting model (filled square dashed line) and estimated entanglements with no gear modifications and no effort changes from 2000-2004 (dotted line)

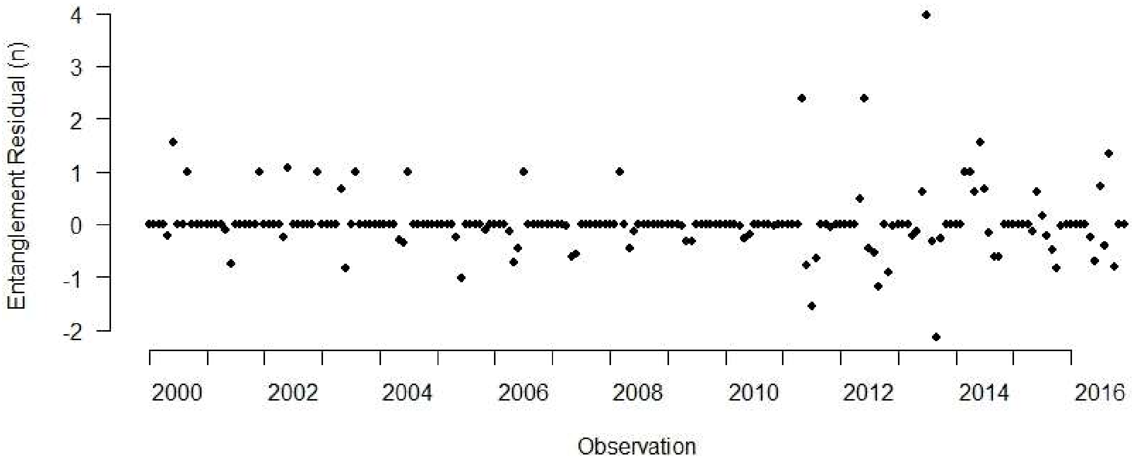

Figure 4 Variance of monthly model-estimated whale entanglements from observed entanglements

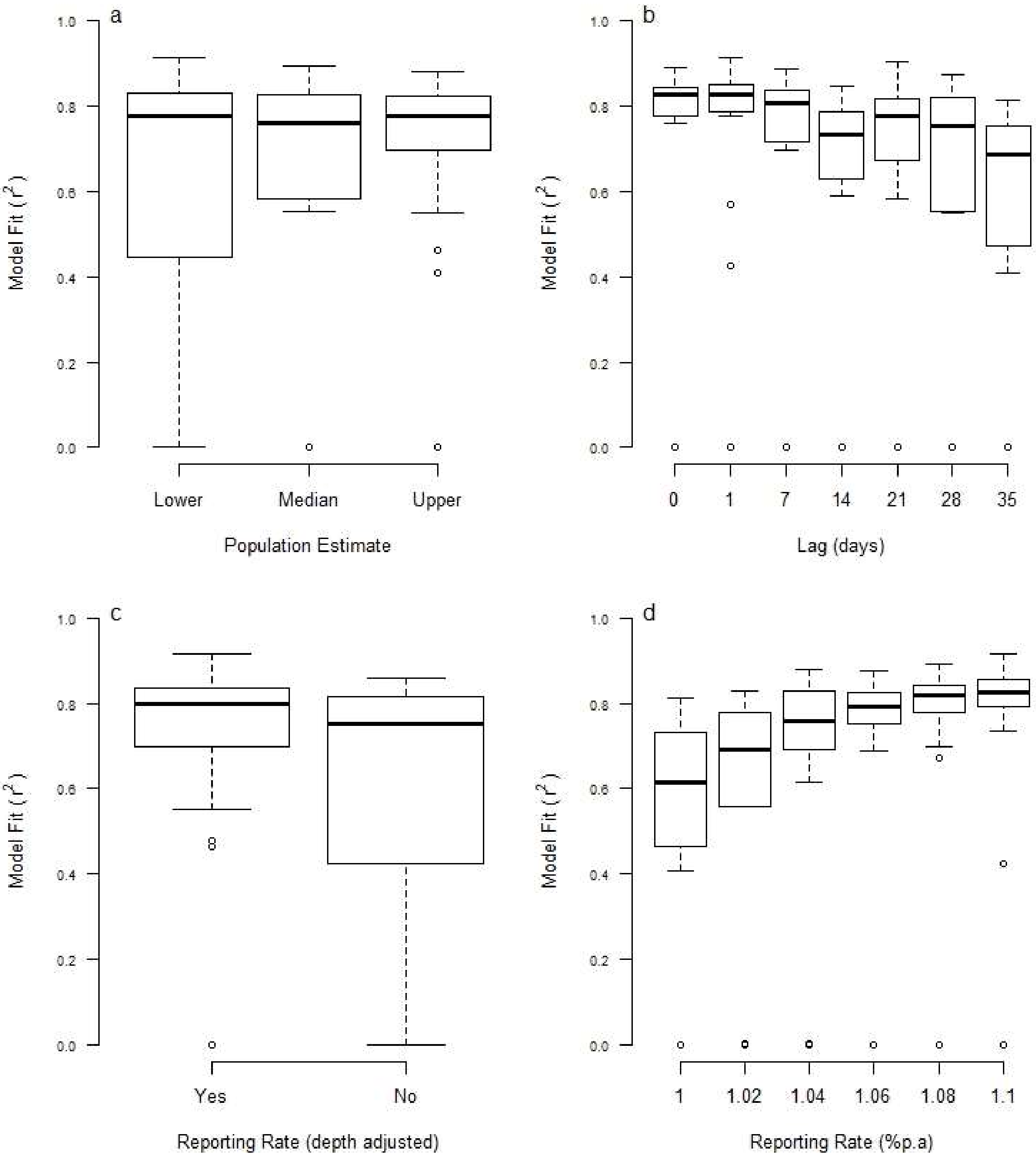

Figure 5 Box plots of model fit (r^2) for a) population estimates, b) lag time (days)between entanglement and reporting, c) depth adjusted sighting probability and d) inter-annual sighting probability increases. Boxplot with box bounds of 25th and 75th percentiles, encompassing the median (heavy line)

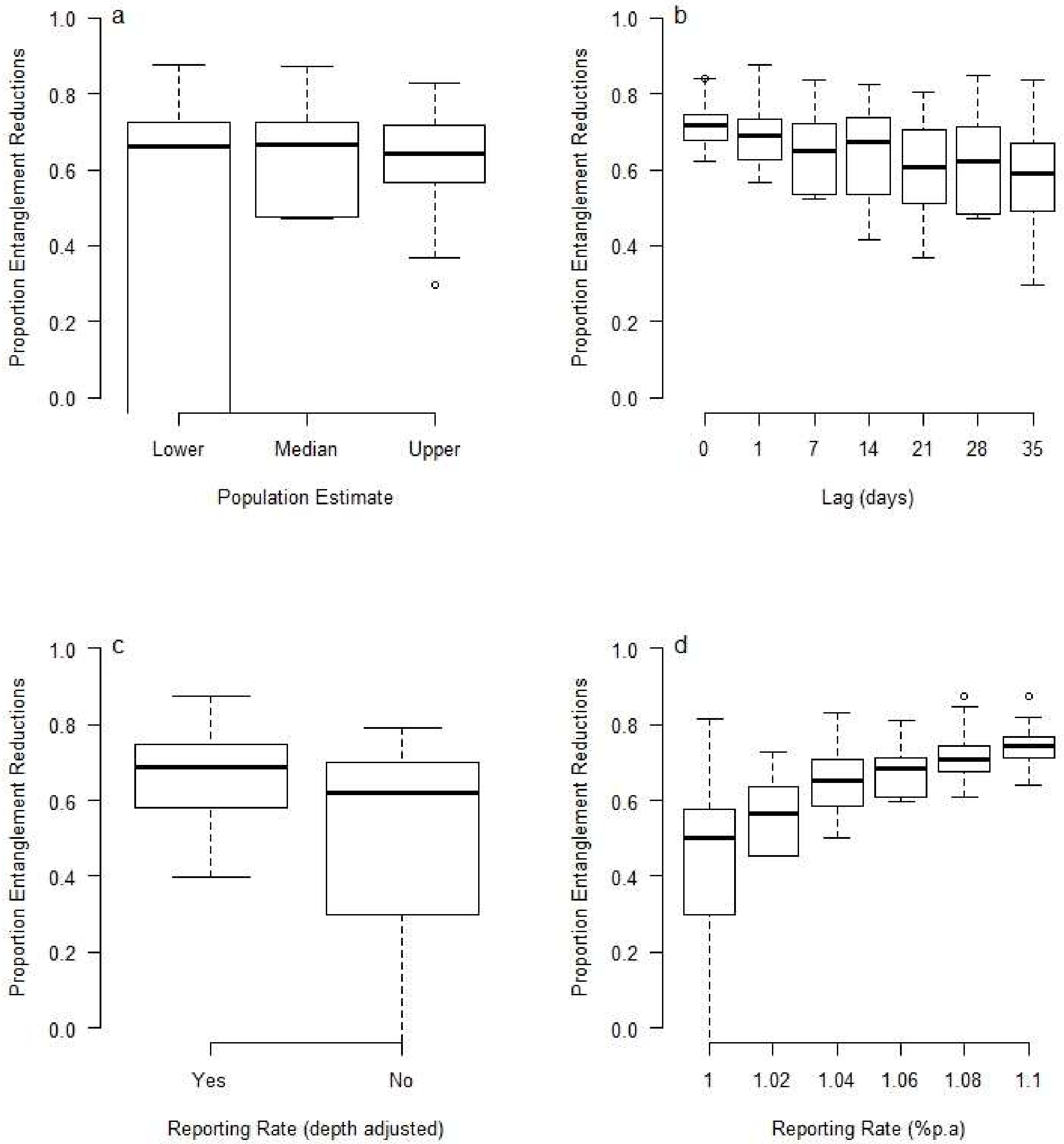

Figure 6 Box plots showing the effects of a) population estimates, b) days lagged between entanglement and its reporting c) depth adjusted sighting probability and d) inter-annual sighting probability increases on model-estimates of proportional entanglement rate reduction arising from gear modifications. Boxplot with box bounds of 25th and 75th percentiles, encompassing the median (heavy line)

Sensitivity analyses showed that the estimated impact of the gear modifications was not overly sensitive to the assumptions used in the model (e.g. whale population size, sighting probability and time-lag between entanglement and reporting) (Figure 7). The median catchability of whales was very low at 1.7 entanglements per 10^9 rope days (Figure 7a) and the gear modifications introduced during the 2014 season had an estimated median impact of reducing entanglements by 66% (Figure 7b). The model consistently found that effort in the 36.6 - 54.8 and 54.9 – 72.2m depth ranges was most associated with entanglements. Very few entanglements were attributed to the remaining depth categories (Figure 7c). The model-estimated monthly distribution of whale abundance showed a unimodal distribution ranging from low in January to April, increasing though May and June to a maximum in July declining in August with small proportions recorded from September to December (Figure 7d). This suggests that the majority of whales become entangled between May and August each year during their northerly migration.

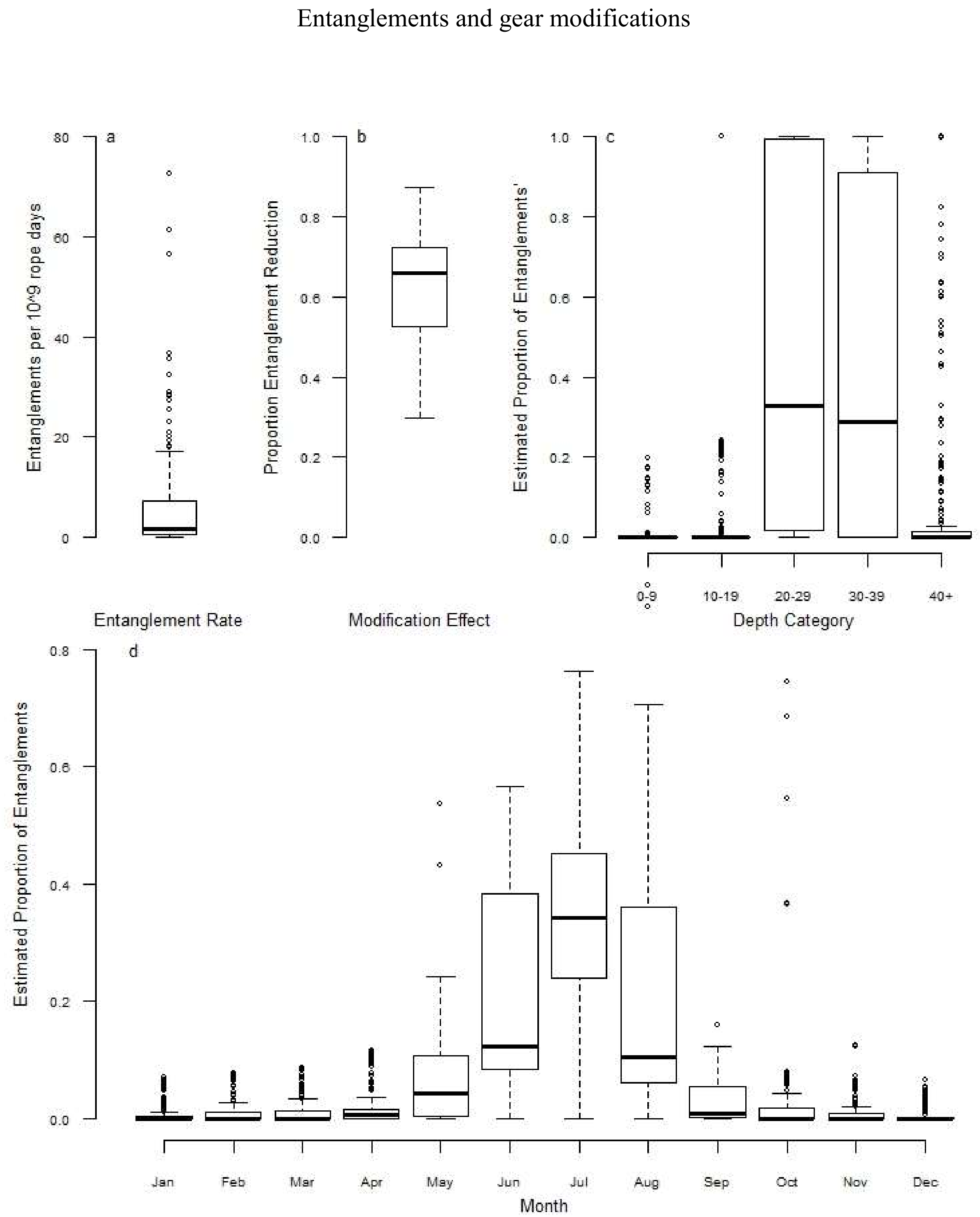

Figure 7 Box plots from sensitivity analysis for a) entanglement rate, b) effect of gear modifications, c) depth category of migration (fathoms) and d) months of migration. Boxplot with box bounds of 25th and 75th percentiles, encompassing the median (heavy line)

Estimated peak whale abundance in Augusta, where commercial whale watching vessels interact with the northerly migration only, generally occurred at a similar time each year (early July), with 12 of the 17 years occurring within a “normal band” of a one week period from 8-15 July (Figure 8a). Those years when peak abundances were outside this seven day band were in 2001, 2006, 2012, 2013, and 2014. In 2001 and 2012, peak abundance was later than normal, respectively occurring five and three days later than the upper end of the “normal band” (15 July) (Figure 8a). In years when peak whale abundance occurred earlier in Augusta, whales arrived 11, 13 and three days earlier (in 2006, 2013 and 2014, respectively), than the lower end of the “normal band” (8 July) (Figure 8a). There was a clear separation between the regions, with Albany and Augusta, where commercial whale watching vessels only interact with northbound whales, recording peak abundances on 15 and 11 July, respectively, while Cape Naturaliste and Perth, where commercial whale watching vessels only interact with southbound whales, recorded peaks in abundance on 14 and 19 October, respectively. This represents a difference of around three months between peak abundances at each location (Figure 8b) and is reflective of the time taken for whales to migrate from the south of the State to breeding grounds in the north, before returning to waters off the State’s southern region.

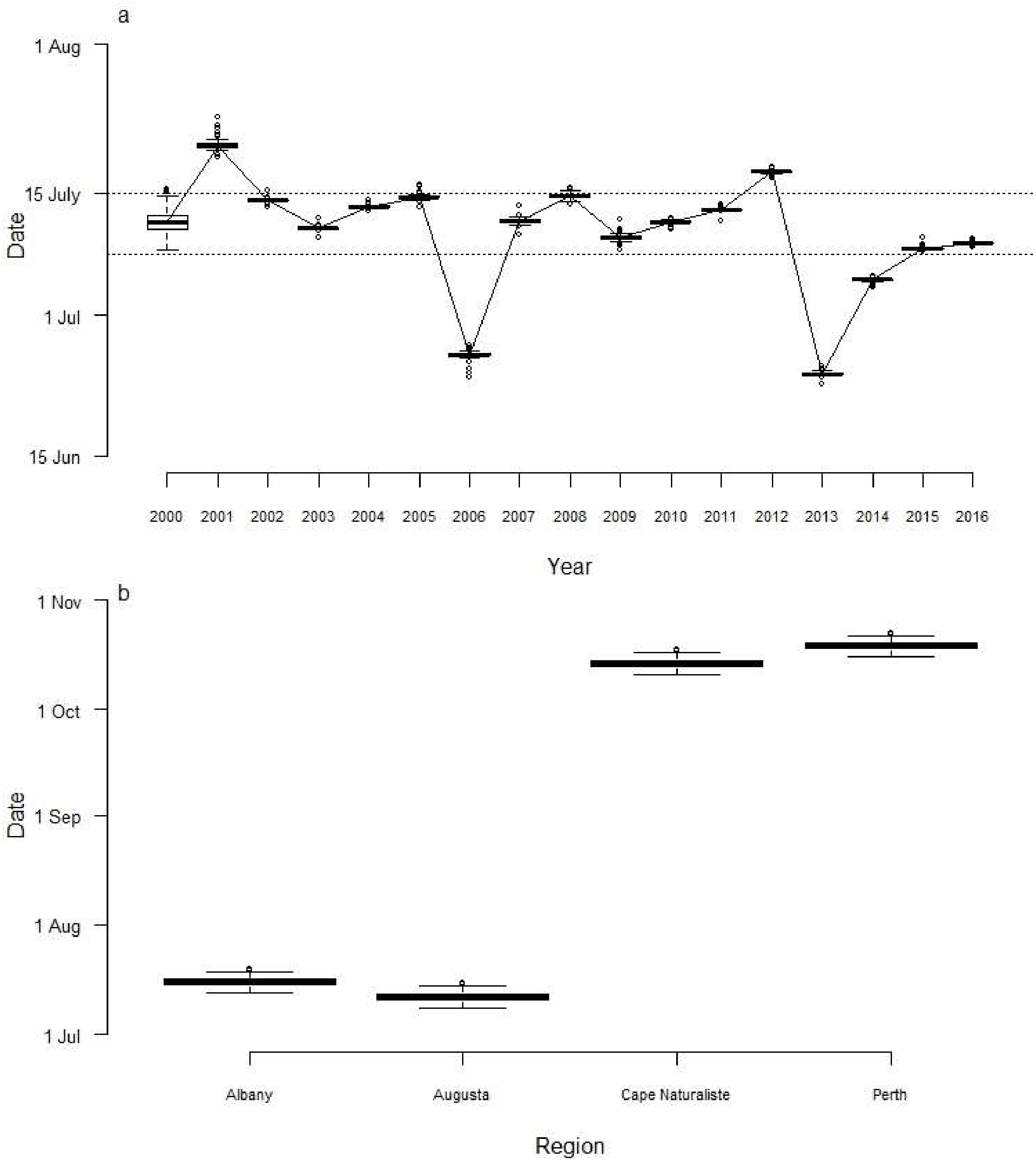

Figure 8 Box plots from sensitivity analysis showing dates of peak migration a) annually at Augusta (dotted line represents band of 'normal' migration timing), b) by region, standardised to year 2000. Boxplot with box bounds of 25th and 75th percentiles encompassing the median (heavy line)

DISCUSSION

There was a noticeable decline in entanglements in WCRLF gear from a peak of 17 in 2013 to two in 2015 and four in 2016, with modelling suggesting this reduction was linked to the introduction of gear modifications. By incorporating changes in fishing effort distribution, an increasing whale population, inter-annual changes in migration timing, various sighting probabilities and the introduction of gear modifications, our model was able to accurately represent the time series of whale entanglements in the WCRLF. Furthermore, sensitivity analyses for several parameters (sighting probability and time between entanglement and reporting humpback population estimates) indicated the estimated impact of the gear modifications was robust to our assumptions. The model estimated that the gear modifications introduced in 2014 reduced the rate of entanglement by two thirds.

The rationale behind the legislated gear modifications focused on reducing the amount of slack rope. It was thought loops of slack rope can form around the whale before any tension is exerted on the line. Through the inclusion of a weighted component to the top third of the rope length, this segment of rope will be always under tension and therefore less likely to entangle a whale. Similarly a reduction in the total rope used (maximum rope length of double the water depth) and a limit on float numbers, may also reduce the likelihood of entanglement or reduce the entanglement complexity.

Our model estimated the density of migrating whales (and hence entanglements) was highest within the 36.6 - 54.8 m depth category. These depths were traditionally fished with two to three times the water depth of rope and three to four floats. Off Western Australia these depths are often exposed to strong ocean currents in autumn/winter (Leeuwin Current) which can cause ropes and floats to become submerged, which is why fishers historically used longer ropes and more floats to aid in their retrieval during these conditions. However, during calm periods (weak currents and light winds) the positively buoyant rope would float on the surface and potentially lead to the entanglements of migrating whales. It was the elimination of this slack surface rope that was the primary intent of the gear modifications, and appears to be the likely cause for the successful reduction in whale entanglements.

Another important component of the mitigation measures was their application to waters generally deeper than 20 m. This provided a region of the fishery where fishers could fish without gear modifications, providing an incentive, through not having to modify their gear, to fish in shallower areas thereby removing effort from the main area of whale migration and entanglements. The model demonstrated that the shallower area of the fishery is very unlikely to contribute to overall entanglements. However, it does not appear that fishers have preferentially moved into this depth region with the proportion of rope days in the <18.3 m depth range remaining relatively constant before and after the introduction of gear modifications in 2014.

The timing of peak migration for the Western Australian population was very consistent, with 12 of the 17 years examined peaking within a one week period each year. However, there were some notable outliers to this, with whale abundance peaking up to two weeks earlier than normal in 2006 and 2013, and around four days earlier in 2014. Prior to 2010 when the WCRLF was effort controlled, the pattern of fishing between years was consistent. The earlier migration which occurred in 2006 resulted in a greater overlap of whales and fishing effort, and hence the largest number of reported entanglements (six) during this effort-controlled period of the fishery.

Entanglements and gear modifications

Gear modifications were enforced in the fishery on 1 July 2014. Seven entanglements were recorded that season, though five occurred prior to the introduction of the gear modifications. It is noteworthy that, while not as early as the 2006 and 2013 migrations, the 2014 migration appeared to be earlier than normal and likely accounted for the early entanglements that season. However, the earliest migration recorded was in the 2013 season, which corresponded to the largest number of entanglements recorded for this fishery.

The estimated reduction in entanglements due to gear modifications was over 65%. However, the observed reduction in entanglements was greater, with the two and four entanglements reported in 2015 and 2016 respectively. This represented an 88% and 76% reduction in entanglements from the 17 recorded in 2013. While the model did incorporate inter-annual variation in the timing of the migration, it didn't vary the depth distribution of migrating whales between years.

Whilst migrating along the Western Australian coast during the austral winter, the humpbacks encounter the Leeuwin Current. This warm water current partially emanates from Indonesia and flows southward from the states North-West Cape (22°S), along the edge of the continental shelf on west coast and often extends onto the south coast of Australia (Pearce 1991). Whales migrate counter to the current's flow during their northerly migration along the Western Australian coast. Therefore, to maximise swimming efficiency, they are likely to avoid swimming directly into the current. This is an area of on-going research but a preliminary examination of the location of the Leeuwin Current in 2013 showed that there was a strong flow which pushed onto the continental shelf, potentially altering the location of the whale migration in that year. This dynamic could not be captured in the model.

The model estimated that the main months when whales were susceptible to entanglement within the fishery were from May to August, corresponding to the humpback whale migration northwards through the fishing grounds. While whales then return through the fishery again from September to November on route to Antarctica (Groom & Coughran, 2012; Jenner et al., 2001), the model doesn't identify this as a period of increased entanglement rates. The northern migration was traditionally the period when there was temporal overlap between lobster fishing and whale migration off the state's west coast. Since the move to year-round fishing, this pattern has persisted. The Leeuwin Current peaks in flow during the northerly migration and this may force whales inshore to improve migration efficiency. Whilst weaker during whales' southerly migration, the Leeuwin Current still flows southward along the edge of the continental shelf. Therefore, maximising migration efficiency would see whales migrating further offshore on their southerly migration taking advantage of the southern flow of the Leeuwin Current. This would result in whales being further offshore and spatially separated from fishing gear, hence reducing entanglement rates.

Catches of *P. cygnus* have been influenced by different recruitment levels resulting from, in part, variations in Leeuwin Current strength. To manage these variations in puerulus settlement levels, the fishery has undergone a number of management changes which have influenced the number of pots which are fished (de Lestang et al., 2012). When under an input control system, these management changes generally resulted in a reduction effort (the number of pots fished) and hence rope days. Had these management changes not occurred, it is likely there would still have been an increase in entanglements solely due to the increasing whale population. The model incorporating no management changes was very similar to that of the 'best' model from 2000-

2008, however the two models diverged in 2009. In 2009 a series of effort reductions was in force in the WCRLF to sustainably manage the fishery (de Lestang et al., 2012), resulting in a decline in the amount of ropes/float in the water. Further and more dramatic effort reductions were present during the 2010 migration, with some parts of the fishery closed by mid-May (de Lestang et al., 2012). While entanglements increased in 2011, they were very similar to what would be expected under this traditional fishing effort distribution. Modelling suggested that should the pattern of fishing which occurred in 2000-2004 (closed from 1 July to 14 November) have continued through until 2016, the estimated number of entanglements would have been 13. Importantly this suggests that a simple management response of reverting to previous effort regimes including season end, is unlikely to have achieved a reduction in whale entanglements to levels recorded pre-2010.

While entanglements can have serious impacts on populations size and recovery (Johnson et al., 2005; Knowlton & Kraus, 2001), the issue of humpback whale entanglements off Western Australia is not considered to impact the population's recovery (Bettridge et al., 2015). The social concern over whale entanglements in this instance is an ethical one about reducing prolonged periods of suffering (Moore et al., 2006). It appears the decline in reported whale entanglements from 2013 to 2016 is due in a large part to the implementation of gear modifications. Model estimates have shown gear modifications have halved entanglements, though they may be as effective as reducing entanglement rates by over 65%. However, with an increasing whale population size off Western Australia (Ross-Gillespie et al., 2014) as with other humpback populations world-wide (Bettridge et al., 2015), future entanglements are likely to increase. Also the total number of whales entangled each year is not known and difficult to estimate. Additional mitigation of whale entanglements requires a better understanding the mechanisms of entanglements and the migratory behaviour of whales is necessary to achieve continued improvement in mitigation efforts. This will greatly assist in the development of additional gear modification or management arrangements to continue fishing during the whale migration.

ACKNOWLEDGEMENTS

The authors would like to thank the Fisheries Research and Development Corporation for their financial support of this project (FRDC Project 2014/004), as well as the following people or organisations for their invaluable support: John McMath, Western Rock Lobster Council, John Servas Jnr., Matthew Kalajzich, Travis Normington, Terry Mouchemore, Bruce Cockman, Jeff Cockman, Darren McCagh, Craig Chitty, Sam Koncurat, James Waters, Chris Williams, Bradley Testar, Clinton Moss, Marc Jurinovich, Bart Gaurino, Curt and Micheline Jenner, John Bannister, Kristan Porter, David Cousins, Steve Train, Patrice McCarron and Michael Moore. We also wish to acknowledge Rory McAuley, Matias Braccini, Nick Caputi, Nick Blay and Graeme Baudains for their review of the manuscript

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