TOWARD CATCH QUOTAS FOR SPINY LOBSTER (*Panulirus argus*) AT GLOVER'S REEF MARINE RESERVE

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Abstract

Beginning in 2011, fishermen catching Caribbean spiny lobster (*Panulirus argus*) at Glover's Reef Marine Reserve, Belize, have been required to keep logbooks. A depletion model with in-season recruitment was applied to the catch and catch per unit effort (CPUE) data from these logbooks. The estimated abundance of adult lobsters at Glover's Reef was about 62,000-71,000 (80% C.I. 51,000 - 21,000,000) and the fishing mortality rate was 1.46 (80% C.I.0-2.18). The catch of 42,718 lobsters was about 60% the adult population. An estimate of total abundance from a fishery-independent survey before the 2011 season opened was 13,800 (80% C.I. 447-27,200), much lower than the recorded catch in 2011. The fishing mortality rate from average lengths was 0.88. A comparison of size frequencies between a sample of the fishery and the fishery-independent survey was used to estimate four proposed selectivity models: logistic, gamma, and logistic selectivity combined with logistic migration into deeper water of either 1 in 8 or 1 in 4 lobsters (based on published data on length frequency by depth). These selectivity models were used to estimate yield per recruit, spawning biomass per recruit, and the associated fishing mortality rate (F) reference points. F_{max} ranged from 0.60 to 0.94, $F_{0.1}$ from 0.29 to 0.57, and F_{20} from 0.62 to 0.75. Catch per unit of effort from a sub-sample of the fishery from 2004 through the present indicate that the abundance of lobsters at the beginning of the fishing season varies by a factor of two or more. A total allowable catch quota for lobsters at Glover's Reef could be set by applying a target F to the estimated lobster abundance. To use these results to set a quota, it will be necessary to: (1) choose a target fishing mortality rate reference point based on the degree of precaution desired, (2) decide on a best estimate of the size selectivity of the fishery, and (3) consider the implications of year-to-year variability in abundance. It may be necessary to monitor lobster CPUE during the lobster season to determine whether lobster abundance is high or low before setting a seasonal quota. More years of data from the logbook program will allow more precise estimates of lobster abundance, and a better understanding of year-to-year and in-season variability in lobster abundance.

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1. Introduction

Caribbean spiny lobster (*Panulirus argus*) is the most economically-important species in the fishery at Glover's Reef Marine Reserve, Belize. The fishery is currently regulated by a fishing season (from June 15 to February 14 of the following year), a size limit (carapace length 3 inches, tail weight 4 ounces), a ban on the use of SCUBA, gear restrictions, and license limitation; however, there has never been a total allowable catch quota for lobsters at Glover's Reef. The objective of this paper is to evaluate the available data and consider methodologies to determine a sustainable catch level for spiny lobster at Glover's Reef Marine Reserve. To determine a total allowable catch quota, it is necessary to: (1) calculate an appropriate fishing mortality rate (F) reference point, and (2) calculate the abundance (in numbers N or biomass B) of lobsters at Glover's Reef at the beginning of the lobster season. The total allowable catch is then calculated by applying the desired fishing mortality rate to the estimated abundance.

The calculation of both F and abundance reference points may be complicated by the fact that only part of the Glover's Reef population is available to the fishery; lobsters in the Conservation Zone (the area where fishing is not permitted), and lobsters on the forereef below the maximum free-diving depth (Acosta and Robertson 2003) are not vulnerable to the fishery. Because of this, the population can probably sustain a higher fishing mortality rate than could a population in which all lobsters were equally likely to be caught. In addition, if catch and effort data from the fishery are used to estimate lobster abundance, the abundance estimate will not include the unavailable lobsters in the Conservation Zone and in deep water. The extent to which lobsters move between the Conservation Zone and the General Use Zone, and between shallow and deep water (Acosta 1999) also influences the vulnerability of lobsters to the fishery, and thus, will influence the sustainable catch level.

Commonly used fishery reference points, which have been applied to lobsters in Belize (Gongora 2010) include F_{max}, the fishing mortality rate that provides the maximum yield per recruit (YPR), and $F_{0.1}$, a more precautionary reference point calculated as the fishing mortality rate at which the slope of the curve of yield per recruit versus F is 10% of the value at the origin. Gongora (2010) calculated that for spiny lobsters in all of Belize, F_{max} is 0.85 and $F_{0.1}$ is 0.49. Reference points can also be calculated based on spawning potential ratio (SPR), which is the ratio of spawning stock biomass per recruit at a specified fishing mortality to the spawning stock biomass per recruit with no fishing. For example, F_{20}, a reference point used for spiny lobsters in the U.S.A. (SEDAR 2010), is the fishing mortality rate that would reduce the spawning stock biomass per recruit to 20% of its unfished level. The values of all of these F reference points depend on the size-selectivity of the fishery, which could vary between fishing areas in Belize. Therefore, we estimated the selectivity of the Glover's Reef fishery and calculated reference points that are specific to Glover's Reef.

Reference points can either be used as target reference points, meaning that managers set quotas with the intention of achieving a fishing mortality rate equal to the reference point, or as limit reference points, meaning that management aims to avoid exceeding the reference point (FAO 2001). In the FAO guidelines for assessment of spiny lobsters (FAO 2001), it was recommended that YPR based reference points be used as target reference points, and SPR based reference points be used as limit reference points. Thus, management could maximize yield per recruit without allowing spawning stock biomass to drop far enough to jeopardize future recruitment. The specific target and limit reference points to be used depends on the level of precaution desired.

The calculation of the current abundance of Glover's Reef was done using depletion analysis, based on catch and effort data from the 2011 season. Until this year, it was not possible to determine how many lobsters were being harvested at Glover's Reef because, although the lobster catches were recorded by the National Fishermen Producers and Northern Fishermen Cooperatives, the location of the catches was not reported accurately (Babcock et al. 2010). Beginning in June, 2012, fishermen who fish at Glover's Reef Marine Reserve have been required to fill out daily logbooks, under the Management Access Daily Logbooks program (Belize Fisheries 2011). This new data source is expected to allow the estimation of total fishable abundance of lobsters at Glover's Reef for the 2011 season. However, abundance may vary from year to year.

In addition to the new logbook data, the Wildlife Conservation Society (WCS) has been interviewing fishermen to collect data on lobster length, weight, catches and fishing effort from 2004 through the present (Grant 2004). Because the WCS samplers usually interviewed fishermen within the first week of the lobster season in each year from 2004 to 2011, this data set is useful for estimating the year-to-year variability in lobster recruitment at Glover's Reef. In addition, the length data is useful for estimating the size-selectivity of the lobster fishery at Glover's Reef.

The WCS LAMP data set, from a fishery independent underwater census focusing on conch, lobster and select finfish, is also available from 2004 through the present, and includes both length and abundance of lobsters at fixed sites in both the Conservation Zone and the General Use Zone. This data set provides data on the lengths of lobsters in the General Use Zone, which can be compared to the length distribution of the lobsters caught by fishermen to estimate selectivity. In addition, the difference in the General Use Zone versus the Conservation Zone can be used to estimate the fraction of lobsters at Glover's Reef that are in each zone. Finally, the LAMP data provide a fishery-independent estimate of the annual variability in lobster abundance.

Given these data sets, this paper will calculate a range of values for the F fishing mortality rates, the abundance of lobsters at Glover's Reef, and the resulting total allowable catch levels. We will also discuss the implications of uncertainties including: (1) what fraction of the lobsters at Glover's Reef are vulnerable to the fishery, being in the General Use Zone at depths shallow enough to be caught by free-divers; (2) how much lobster recruitment varies from one year to the next at Glover's Reef; and (3) whether lobsters self-recruit to Glover's Reef or recruit from other populations. We will also discuss what additional or alternative data and protocols could be used to determine an appropriate catch level and how many years of data will be needed before catch quotas can be implemented with confidence.

2. Methods

2.1. Fishing mortality rate reference points

The WCS fisherman interview data sets includes both carapace lengths (CL) and tail lengths (TL) for 3765 lobsters, and tail lengths for 2270 lobsters that had been cleaned before the interviewer could measure them. These tail lengths were converted to carapace lengths based on the regression of carapace length to tail length from the lobsters that were measured whole (**Table 1**).

The WCS LAMP data consist of snorkeler surveys of the lobsters at 11 patch reefs (5 in the Conservation Zone and 6 in the General Use Zone), which were sampled on 23 occasions between 2004 and the present. The LAMP data include sizes (CL) of 419 lobsters in the Conservation Zone and 285 lobsters in the General Use Zone.

To estimate the selectivity of the fishery, we compared the length frequency of lobsters caught in the fishery to the length frequency of lobsters observed by the LAMP survey in the General Use Zone. Empirical selectivity was estimated by assuming that the frequency distribution in the LAMP survey represents the true size distribution of the lobster population. Because the mode of the fishery length frequency was about 90 mm CL, we assumed that 90 mm was fully selected into the fishery. We divided the proportion in each length category in each data set by the proportion in the 90 mm category, then divided the frequencies in the fishery by the frequencies in the LAMP data to estimate empirical selectivity. The empirical selectivities were then fit to two alternative selectivity models (the logistic and Gamma selectivity models), using non-linear least squares in the R software (R Development Core Team 2012). The logistic selectivity model was fit to the empirical selectivities in the size range over which lobsters become susceptible to the fishery (between lengths 40 and 90 mm) because the logistic curve only describes the increasing part of the selectivity curve:

(1) $$s_L = \frac{1}{1+\exp(-d(L-L_{50}))}$$

where s_L is selectivity at length, and d and L_{50} are estimated parameters. The Gamma selectivity model was fit to all length seen in the fishery (between 30 and 170 mm).

(2) $$s_L = \frac{1}{\theta^k}\frac{1}{\Gamma(k)}L^{k-1}e^{-L/\theta}$$

where k and θ are estimated parameters.

The logistic selectivity curve implies that after lobsters reach the length at which they are fully selected to the fishery (about 90 mm CL) they remain equally vulnerable to the fishery. The Gamma selectivity curve implies that larger lobsters become less vulnerable to the fishery. Larger lobsters could become less vulnerable to the fishery if they migrate into deeper water as they mature, as shown by Acosta and Robertson (2003). However, the data used to estimate the true population size structure came from the LAMP survey on patch reefs, so it would not give any information on the fraction of lobsters that would have migrated to deep water.

To address the possibility that larger lobsters migrate into deeper water, we developed a third selectivity model using Acosta and Robertson's (2003) data on the size frequency of lobsters on patch reefs in the Conservation Zone versus on the fore reef wall. Acosta and Robertson (2003) found that lobsters of all sizes were found on the patch reefs, but only large adult lobsters were found on the reef wall. They also found that the density of adult lobsters was 8 times higher on patch reefs in the Conservation Zone than on the forereef wall. Thus, we assumed that only 1 in 8 adult lobsters would migrate into the deep water. We rescaled Acosta and Robertsons's length frequencies so that the mean proportion in the adult size classes (76 mm and greater) was 0.125 for the fore reef and 1.0 for the patch reefs. We then divided the forereef frequencies by the patch reef frequencies, and fit the scaled logistic model to these numbers. We multiplied the logistic selectivity curve estimated from the WCS data by one minus the migration curve estimated from Acosta and Robertson's (2003) data to estimate a combined selectivity curve for Glover's Reef lobster. This curve was intended to provide a plausible migration model to allow us to explore the implications of migration into deep water for the calculation of fishing mortality reference points. Different assumptions about the fraction of lobsters that migrate to deep water, the shape of the migration function, whether migration is density dependent (we assume no density dependence) would lead to very different size selectivity in the fishery. To explore the implications of changing the fraction of lobsters that migrate to deep water, we conducted a sensitivity analysis in which we doubled this number, so that one quarter of large lobsters migrated. The fraction is not likely to be much larger than this, given that large lobsters are caught in the fishery, and observed in the LAMP survey data, both in shallow water.

To explore the implications of the minimum size limit, we also developed three selectivity curves in which the selectivity above the minimum size followed the logistic curve, and the selectivity below the minimum size was zero, for the size limits of 4.0 inches, 4.5 inches and 5.0 inches TL, which correspond to 66, 73 and 81 mm CL, respectively. Given the seven selectivity models calculated above, the fishing mortality rate reference points were estimated using yield per recruit analysis (Quinn and Deriso 1999).

Lobster numbers N_a at age a were calculated as:

(3) $$N_a = N_0 e^{-(M+s_a F)}$$

where N_0 is the numbers at the age at recruitment, when lobsters first become vulnerable to the fishery (age 2), M is the natural mortality rate, equal to 0.34 (Gongora 2010), s_a is the selectivity at age and F is the fully selected fishing mortality rate. The catches at each age in numbers are calculated as:

(4) $$C_a = \left(\frac{s_a F}{M+s_a F}\right)\left(1 - e^{-(M+s_a F)}\right) N_a$$

and the total weight of the catch is calculated by first calculating the length at age using the von Bertalanffy growth curve:

(5) $$L_a = L_\infty \left(1 - e^{-K(a-a_0)}\right)$$

with asymptotic length L_∞ =183 mm CL, K = 0.24, and a_0=0.44 (Gongora 2010). Length is converted to weight using the equation (FAO 2001):

(6) $w = 0.0046L^{2.63}$

Yield per recruit is the sum of the catch in weight across all ages. Yield per recruit was estimated for F values between zero and three for each of the three selectivity curves, and F_{max} and $F_{0.1}$ were found numerically. The spawning stock biomass at each F level was calculated as the sum of the weight of lobsters larger than 76mm, and F_{10}, F_{20} and F_{30} were calculated numerically. All calculations were done in R (R Core Development Team 2012).

2.2. Managed access logbook program

Logbook data were available from the 2011-2012 lobster season, which ran from June 15, 2011, until February 14, 2012. The crew of each fishing vessel filled out a logbook form for each day they fished, with separate rows for each individual fisherman and for each type of fish product (e.g. lobster, conch, or finfish). Each row in the dataset includes the number and weight of fish or shellfish caught, type of fish, processing type (for lobsters: tails versus head weight), and the number of hours spent fishing. Of the 42,718 lobsters reported in the Glover's Reef logbooks, only 3 were reported by skiff vessels. Therefore, only sailboats were included in this analysis.

The catches were reported as lobster tail weight and number of lobsters for each individual fishermen. In addition, lobster head meat was recorded for all the fishermen in a boat together. We did not use the head meat data. Total catches were calculated for each week by summing either the number of lobsters or the weight of lobsters. We calculated total weights from tail weight as (FAO 2001):

(7) $W_{Total} = 3.175\ W_{tail} - 0.01206$

Mean weight of lobsters was calculated as the mean of the weight per fisherman day divided by the number of lobsters per fisherman day, weighted by the number of lobsters caught.

Catch per unit of effort (CPUE) in numbers was calculated for each boat-day as the sum of the number of lobsters caught, divided by the total number of fisherman-hours. For the few cases (~2% of fisher-days) where a fisher reported lobster catches and had no total fishing hours listed for that day, the number of fishing hours was assumed to be the median number of fishing hours in a day (6 hours). Catch per unit effort in weight was calculated similarly.

2.3. Estimation of abundance in 2011 from logbook data.

The CPUE calculated from the logbooks appeared to decline during the first four months of the 2011 lobster season, then increased again toward the end of the season, presumably due to new recruitment. Therefore we used the DeLury depletion model (Robert et al. 2010, Quinn and Deriso 1999, Bataille and Quinn 2006) to estimate the number of lobsters in the General Use Zone at Glover's Reef at the beginning of the season, using only the first 16 weeks of data. We then used a variation of the DeLury model with data from the entire season to estimate both the abundance at the beginning of the season and the abundance of new recruits entering the fishery in the second half of the season (Robert et al. 2010).

During each week of the fishing season, the number of lobsters is calculated as (Robert et al. 2010):

(8) $$N_{t+1} = N_t e^{-M/52} - C_t e^{-M/104} - \lambda_t R e^{-M/104}$$

where N_t is number of legal sized lobsters in the General Use Zone at the beginning of week t in the fishing season, C_t is the catch in numbers during week t assumed to take place in the middle of the week, M is the instantaneous natural mortality rate; M is in annual terms, so it is divided by 52 for a weekly time step; R is an estimate of the recruitment of lobsters that take place during the season, and λ_t is the fraction of the in-season recruitment occurring in each week. Recruitment is assumed to occur in the middle of each week. The fishing mortality rate in each time step was approximated as $F_t=2C_t/(N_t+N_{t+1})$, and the annual fishing mortality rate was the sum of the weekly rates.

The fraction of recruitment occurring in each week (λ) could not be estimated with the data from a single year, so we fixed the values in each model run. Results are presented for a model with no recruitment in the first 20 weeks, and recruitment equally distributed in weeks 21 to 35 (λ_1-λ_{20} =0, λ_{21}-λ_{35} =1/15) . Alternative model runs in which recruitment occurred in all weeks (λ_1-λ_{35} =1/35) or only weeks 21 to 25 (λ_1-λ_{20} =0, λ_{21}-λ_{25} =1/5, λ_{26}-λ_{35} =0) did not provide adequate model fits. If the model was fit to only the first 16 weeks of data, no in-season recruitment was included (all λ_t=0). A model fit to data from the entire season with no in-season recruitment (all λ_t=0) did not converge.

N_0, the number of lobsters at the beginning of fishing season, is a parameter that must be estimated; numbers in each subsequent week can be calculated from the starting numbers, natural mortality rates, catches and (after week 20) recruitment using Equation 8.

To estimate the model parameters, the predicted abundance trend was fitted to catch per unit of effort as an index of abundance. The CPUE data was assumed to be proportional to abundance in the middle of the week, approximated by the average of abundance at the beginning and end of the week:

(9) $$I_t = q\left(\frac{N_t + N_{t+1}}{2}\right)e^{\varepsilon}$$

where I_t is the value of the CPUE index of abundance in week t of the fishing season, q is the constant of proportionality for the abundance index and ε is a normally distributed error (with variance σ^2). Both q and σ^2 are assumed to be constant across weeks within a year.

We used a Bayesian method to estimate the model parameters, implemented in the OpenBUGS software (Sturtz et al. 2010, Lunn et al. 2000), which uses a Markov Chain Monte Carlo (MCMC) algorithm to approximate the posterior distributions of the parameters.

The prior distributions of the estimated parameters were non-informative (**Table 2**), except for the prior for M, which was normally distributed with a mean of 0.34, and standard deviation of

0.04 (Gongora 2010, FAO 2001). This prior distribution constrained the value of M to be within a biologically plausible range. To ensure adequate convergence of the MCMC, we ran three chains, with 2,000,000 iterations after a burn-in of 500,000 iterations, and a thin rate of 50. With these settings, the models converged adequately according to the Gelman-Rubin diagnostic (Lunn et al. 2000).

The decline in abundance during a fishing season was also modeled using effort rather than catch:

$$N_{i,t+1} = N_{i,t} e^{-M - qU_t} \tag{10}$$

where U_t is the effort in month t. Therefore, the log of the abundance index (I) in each time period is:

$$\log(I_t) = \log(qN_0) - M(t - 0.5) - qE_t + \varepsilon_t \tag{11}$$

where E_t is cumulative effort up to the middle of month t and ε is a Normally distributed error term (Quinn and Deriso 1999, Battaile and Quinn 2006). The annual fishing mortality rate was calculated as $F=qE_t$ at the end of the season. This model was only applied to the first 16 weeks of the season, and it was not used to estimate recruitment.

2.4. Estimation of abundance of lobster from LAMP survey densities.

The LAMP survey includes counts of lobsters at five patch reefs in the Conservation Zone, and six patch reefs in the General Use Zone. Each site was visited on 23 sampling periods between 2004 and the present. We calculated the density of adult lobsters at each patch reef in each sampling period as the count of adult lobsters at each patch reef in each sampling period, divided by the area of the patch reef in hectares. The density in each sampling period and management zone was calculated as the mean of the density at the sampled patch reefs, weighted by patch reef area.

We then calculated the ratio of densities in the General Use Zone to densities in the Conservation Zone. The density ratio can be used as an indicator of how much more abundant lobsters are in the Conservation Zone than they are in the General Use Zone. Also, a very low density ratio is an indicator of stock depletion (Babcock and MacCall 2011).

Finally, the density of adult lobsters at patch reefs in the General Use Zone and Conservation Zone at Glover's Reef was multiplied by the area of reef habitat in each zone to estimate the approximate number of adult lobsters present. The area of reef habitat was estimated by adding up the area in each pixel classified as reef in the Coastal Zone Management Authority and Institute (CZMAI) habitat classification (Mumby and Harborne 1999).

These numbers should be treated as a very rough approximation, as the LAMP survey only covered a small number of patch reefs in shallow water in and near the Conservation Zone, and the numbers were expanded on the assumption that densities were the same in all reef habitat throughout the atoll, separated only by management zone.

2.5. Annual and in-season variation in abundance of lobster in the WCS catch per unit effort data set

WCS researchers collected data on the number and size of lobsters caught by a sample of fishermen on the fishing grounds at Glover's Reef between 2004 and the present. Because the WCS samplers usually interviewed fishermen within the first week of the lobster season in each year from 2004 to 2012, this data set is useful for estimating the year-to-year variability in lobster recruitment at Glover's Reef.

For each fisherman, we calculated catch per unit of effort (CPUE) in number of lobsters caught per fisherman hour. Of the 21 boats for which lobster catch and effort data were recorded, only 14 were sampled on three or more days. Because catch rates vary between boats, we only included the 14 boats that had been sampled on three or more occasions in this analysis. For these boats, there were 153 boat-days sampled, and 761 fisher-days, with a total of 5634 lobsters caught.

CPUE can be biased as an index of abundance if factors such as environmental conditions and variation between fishermen affect the catch rates. Thus, we used a generalized linear model to standardize the CPUE index of abundance by removing the effects of these extraneous factors (Maunder and Punt 2004).

The Generalized Linear Model (GLM) model was:

(12) $$\log(CPUE_{i,j,k,l}) = T_i + M_j + V_k + 2way + \varepsilon_{i,j,k,l}$$

where T_i is the effect of fishing year and month (i) for the 48 months between June 2005 and January 2012 for which data were collected, M_j is the effect of moon phase (j=full, mid or new), and V_k is the effect of individual boat (k = boat 1 through 14), and $\varepsilon_{i,j,k,l}$ is a normally distributed error term. All of the second order interactions between the terms are included.

To determine which of these factors and their interaction significantly improve the model, we used Akaike's Information Criterion (AIC), and we only included models that explained more than 5% of the model deviance. In the case where vessel or any of the two-way interactions were included in the AIC best model, we treated these parameters as random effects, using the function *glmer* in R (Bates 2010, Ortiz and Arocha 2004, R Development Core Team 2012). The AIC and the BIC (Bayesian Information Criterion; Bates 2012) were used to choose the best model with random effects.

The time period (year and month) effect calculated by the mixed model was used to predict the log-CPUE for month and year and the predicted values and their standard errors were transformed from normal to lognormal to extract the temporal trend in abundance. See Babcock et al. (2010) for details of the methodology.

2.6. Fishing mortality rate estimates from size data

Average length data can also be used to estimate fishing mortality rates, using the method of Beverton and Holt (1957) as modified by and Ehrhardt and Ault (1992). The total mortality rate ($Z=F+M$) is estimated iteratively from:

$$(13) \quad \left(\frac{L_\infty - L_\lambda}{L_\infty - L_c}\right)^{\frac{Z}{K}} = \frac{Z(L_c - \overline{L}) + K(L_\infty - \overline{L})}{Z(L_\lambda - \overline{L}) + K(L_\infty - \overline{L})}$$

where L_∞ and K are the parameters of the von Bertalanfy growth curve, L_c is the minimum and L_λ is the maximum size caught by the fishery, and $\bar{L}$ is the mean size of lobsters caught within this size range. The fishing mortality rate F is calculated as Z-M. We estimated total mortality from the WCS CPUE data set, as well as the LAMP visual survey data both in the General Use Zone and in the Conservation Zone.

3. Results

3.1. Fishery mortality rate reference points

The length frequencies of lobsters at Glover's Reef (**Figure 1**) from the WCS sample show that the fishery is focusing on lobsters that are larger than the minimum size, which corresponds to a CL of about 76 mm. In addition, the LAMP fishery-independent survey observes lobsters, especially in the Conservation Zone, that are larger than the largest size taken in the fishery.

According to the empirical selectivities that were estimated by dividing the length frequencies in the fishery by the length fisheries observed in the LAMP surveys in the General Use Zone, lobsters are most likely to be captured between the sizes of 90 and 120 mm CL (points in **Figure 2**). Because the LAMP survey samples patch reefs that are close to the Conservation Zone boundary, it is possible that large lobsters move from the Conservation Zone to the nearby patch reefs in the General Use Zone, so that the LAMP data overestimates the number of large lobsters in the General Use Zone. In this case, the increasing selectivities of small lobsters would be accurately estimated, but the decreasing selectivities of large lobsters would not. A logistic selectivity curve, estimated by assuming that all lobsters over 90 mm (**Figure 2a**) are fully selected, is consistent with this hypothesis. The Gamma selectivity curve (**Figure 2b**), which allowed the selectivity to drop at larger sizes provided a better fit to the data. However, this curve would be biased if lobsters move in and out of the Conservation Zone.

To separate out the size selectivity of the fishery from the possibility that larger lobsters migrate into deeper water, we used the data from Acosta and Robertson (2003) to estimate the fraction of lobsters that migrate from shallow to deep water (**Figure 3a**). The fraction of lobsters in deep water seems to peak around 100 mm. A scaled logistic curve fit to the selectivities for lengths up to 110 mm seems to provide a good fit.

The fishery selectivity curve estimated by combining the logistic selectivity in **Figure 2b** with the scaled logistic function estimated from the fraction in shallow water (**Figure 3a)**, yields a fishery selectivity (**Figure 3b**) that looks similar to the simple logistic selectivity, except that the selectivity of large lobsters is always less than 1.0. This implies that, because some of the population is too deep to be captured by free-diving fishermen, they are not vulnerable to the fishery.

The yield per recruit curves estimated using the logistic selectivity model or the models with migration were quite similar to each other (**Figure 4a**). The Gamma model, which implied that many large lobsters are invulnerable to fishing gave a very flat yield per recruit curve, in which increasing fishing mortality did not substantially reduce the yield per recruit, as expected. For all three yield per recruit curves, the yield per recruit at a very high fishing mortality rate (F=3) was more than 80% of the maximum yield per recruit; this is a consequence of the fact that there is a minimum size limit in the fishery, so that, even if all the lobsters are caught as soon as they recruit into the fishery, the yield per recruit is fairly high. Nevertheless, at high fishing mortality rates, the spawning stock biomass declines to a few percent of unfished levels, because the lobsters recruit into the fishery around the size at maturity (**Figure 4b**). This implies a risk that recruitment may be drastically reduced at high fishing mortality rates.

The fishing mortality rate reference points calculated from yield per recruit and spawning stock biomass per recruit range from 0.39 to 1.34 (**Table 3a**), depending on the degree of precaution that is desired in managing the fishery, and the assumed selectivity curve. The Gamma selectivity model estimated F_{max} = 0.99 and $F_{0.1}$ = 0.60, which was similar to the results of Gongora (2010, F_{max} = 0.85 and $F_{0.1}$ = 0.49). This is reasonable, as Gongora (2010) estimated the reference points from a catch at age model that estimated separate fishing mortality rates for each age. The two alternative migration models give results intermediate between the logistic model (in which all adult lobsters may be caught) and the Gamma model (in which selectivity decreases to zero at the larger sizes). Of the F reference points, F_{20} and F_{30} are the least dependent on the assumptions made about selectivity. Increasing the size limit would increase the target fishing mortality rates (**Table 3b**).

3.2. Managed access logbook program

The managed access logbook database provides data from 455 vessel-days for sailboats and 66 vessel days for skiffs during the 2011-2012 lobster season (**Table 4**). Fishers on sailboats caught lobsters in 79% of the recorded vessel-trips during the lobster season, while fishers in skiffs caught lobsters on only one vessel-trip. The total recorded catch for the season was 42,718 lobsters, or 21,600 pounds tail weight.

Both catch and effort declined during the first five months of the season, as did catch per unit effort in numbers (**Figure 5**). Beginning in November (week 20), there was an increase in catch, effort, and CPUE, consistent with some recruitment of lobsters into the legal size range in the latter half of the season.

The mean weight was fairly constant across the season, with perhaps a slight increase in the first 10 weeks of the season (**Figure 5d**). Interestingly, there does not seem to be a decrease in size in the second half of the season, when the abundance increases. We would expect the average size to decrease if there was a large in-season recruitment of young lobsters growing large enough to enter the fishery. The fact that this does not occur may imply that the in-season recruitment consists in part of older lobsters migrating into the fished area.

Histograms of the number of lobsters caught per fishermen and the pounds tail weight per fisher day (**Figure 6**) indicate that the numbers reported by each fisherman are often rounded to the nearest five. The correlation between the number and weight of lobsters caught is 0.94, and nearly all records show a linear relationship between numbers and weight (**Figure 6d**) as expected.

3.3. Depletion estimates of abundance and fishing mortality

The CPUE of lobsters declined during the first sixteen weeks of the season, during which time 80% of annual catch of lobsters occurred (34,000 lobsters). The depletion models fit to catch (**Table 5**, **Figure 7**) or effort (**Table 6**, **Figure 8**) during the first 16 weeks both estimated that the population of lobsters at the beginning of the season was around 65,000 lobsters (80% C.I. 51,600 to 111,000). Abundance declined in 16 weeks to just under half the starting numbers, and about half of the legal-sized lobsters available to the fishery were caught. The abundance at the beginning of the season was fairly precisely estimated using the data from the first 16 weeks, because the rapid depletion of the population during this time period provided an informative CPUE data series. The fishing mortality rates estimated for this period (around 0.70) are an underestimate of the total annual fishing mortality rate, because there are additional catches later in the year.

When the model was fit to data from the entire season (**Table 7, Figure 9**), estimating additional recruitment in the latter half of the season, the starting biomass was estimated to be lower (median 54800), but the model estimated significant recruitment later in the season (median 15800). Thus, the total number of lobsters available to the fishery was 71,300 (80% C.I. 60,400 to 21.4 million), of which about 60% were caught. For this model, the estimates of the starting abundance, in-season recruitment, and fishing mortality rate were highly uncertain. Although the model estimated that the abundance of legal sized lobsters was probably between 60,000 and 80,000 lobsters, there was a non-zero probability that the abundance was several orders of magnitude higher (**Table 7, Figure 9**). Because of the long right tail in the posterior probability density of the starting abundance, the posterior mean of the starting biomass was very high, and the coefficient of variation (CV) was high. The larger uncertainty in the parameter estimates is caused by the small sample size using only one year of data, and the fact that the CPUE data are quite variable from one week to the next. When more years of data are available, the estimated biomass and fishing mortality rates will be much more precisely estimated. Another source of uncertainty is the assumed pattern of recruitment during the season, which could be estimated if more years of data were available.

The fishing mortality rate was estimated to be 1.46 (80% C.I. 0 to 2.18). Using the F reference levels from any of the selectivity models, the median estimated F was more than twice F_{max}, the level that would produce the maximum yield per recruit. It was also more than twice F_{20}, a reasonable precautionary level to prevent lobster spawning stock biomass from declining. The estimated fishing mortality rates are higher than the national average (Gongora 2010) and too high to be sustainable. The credibility intervals included F values below $F_{0.1}$, and above F_{10}.

3.4. Estimation of abundance of lobster from LAMP survey densities.

In all but four of the sampling periods in the LAMP data set, the density of adult lobsters was higher in the Conservation Zone than in the General Use Zone (**Figure 10a**), as expected. The density ratio (**Figure 10a**) ranged from zero to 4.1, with a mean of 0.65 and median of 0.33. The mean density ratio from the beginning of the 2009 lobster season to the present is 0.28.

According to the CZMAI habitat map (Mumby and Harborne 1999), there are 879 hectares of reef habitat in the Conservation Zone and 3627 hectares in the General Use Zone. This map includes the entire central lagoon of Glover's Reef, and the surrounding fringing reef to the edge of the wall, but does not include the deeper areas that are also used by lobsters. Expanding the densities from the LAMP survey, the estimated total numbers of adult lobsters at Glover's Reef had a mean of 12,000 and ranged from 1,200 to 36,000 (**Figure 11**). The standard errors of these estimates are large, because the standard error of the densities was large due to the relatively small sample size in the survey. The actual variability in the abundance estimates may be much higher, due to the unknown implications of expanding density estimates from a small number of locations to the whole of Glover's Reef.

From the LAMP sample in April 2011, there were 13,800 lobsters around the beginning of the 2011 lobster season, of which 7600 were in the General Use Zone. This is probably an underestimate because the population would have been higher in June, right before the lobster opening, than it was two months earlier. This number is about 40% of the total catch reported in the logbooks, or 20% of the numbers estimated from the logbook data using depletion models.

3.5. Annual and in-season variation in abundance of lobster in the WCS catch per unit effort data set

The Generalized Linear Mixed model (GLMM) standardized CPUEs from the WCS fishery sample appear to show the same pattern in CPUE that was observed in the 2011-2012 logbook data; a decline at the beginning of the season followed by an increase (**Table 8**, **Figure 12, Figure 13**). The best model included only the time period (month) and the random effect of vessel. Focusing on only the first month of each fishing season (**Figure 13b**), the abundance of lobsters at Glover's Reef appears to vary from one year to the next by as much as a factor of two. This has important implications for the calculation of a catch quota for the fishery in any particular year. Although we may know the desired fishing mortality rate, the catch quota cannot be set accurately without an understanding of the variability in annual recruitment.

3.6. Fishing mortality rate estimates from size data

The fishing mortality rate estimated from the fishery based on total length (**Table 9**) was 0.88. The mortality rate was much lower in the LAMP data for the General Use Zone, perhaps implying that lobsters migrate out of the Conservation Zone.

4. Discussion

4.1. Data availability and future research

The current status of the lobster population at Glover's Reef, as estimated by the various data sources, is shown in **Table 10**. The estimated fishing mortality rates range from 0.88 to 1.46, with credibility intervals ranging from 0 to 2.18. The estimates of abundance at the beginning of the 2011 lobster season from the depletion models are around 55,000-68,000 adult lobsters, while the LAMP density estimates indicate that there were only 13,800 adult lobsters at Glover's Reef.

The data that have been collected so far at Glover's Reef are very useful for determining the status of lobsters and setting management targets. However, the estimates of abundance will be greatly improved as more years of data become available. For example, Acosta and Robertson (2003) reported that lobsters recruit at Glover's Reef throughout the year. However, it is not known whether there are seasonal patterns of growth or movement. Thus, the seasonal pattern of lobster recruitment into the population that is vulnerable to the fishery is not known. Given multiple years of data, it may be possible to estimate this pattern within the model. Additional research could also reduce the uncertainties in the estimates of abundance and fishing mortality rates. The fraction of adult lobsters that migrate from shallow to deep water was estimated based on Acosta and Robertson's (2003) data from the late 1990s. The fraction of adult lobsters that migrate could be higher or lower depending on environmental factors or the density of lobsters, so further study of this issue is warranted. The question of how many lobsters move across the boundary of the Conservation Zone should also be addressed, as migration could influence the sustainable harvest level. Finally, the analyses in this paper assume that the logbooks are a complete record of the catches in the lobster season at Glover's Reef. If they are not, then the estimated total abundance would be biased, probably underestimated.

4.2. Calculation of a catch quota

The selection of a target and limit fishing mortality reference points is a management decision, not a scientific one. The fisheries managers, fishermen and other stakeholders must determine how to weigh the tradeoff between maximizing yield and minimizing the probability of collapsing the spawning stock biomass due to overfishing. The highest risk and the highest yield are associated with the F_{max} reference point. This reference point is used as a limit reference point, but is not often used as a target reference point because it is thought to allow too much risk of overfishing. The more precautionary $F_{0.1}$ reference point is commonly used, but may lead to foregone yield. The SSB-based F reference points more directly address risk of depleting the spawning stock biomass. For slow-growing species that become vulnerable to fisheries before they mature, reference points of F_{40} or F_{50} are commonly used; F_{30} is a more common reference point for many types of species. For spiny lobsters, because they are a productive fast-growing species, and tend to be managed with size limits to protect immature individuals, SPR reference points of F_{20} or even lower are commonly used. We consider F_{20} a reasonable reference point for Glover's Reef lobsters.

Unfortunately, settling the question of which F reference point to use does not solve the problem of setting a total allowable catch quota for Glover's Reef. The choice of selectivity model, uncertainty in the estimates of abundance and year to year variability in abundance have a larger impact on the appropriate total allowable catch quota than does the choice of *F* reference level. The catch equation (Equation 4) can be used to calculate the expected annual catch for any given *F* reference level and starting biomass level (**Table 11a**). **Table 11a** is a decision table, in which the rows represent the management decision to be taken, in this case the target *F* reference level, and the columns represent the scientific uncertainty. The scientific uncertainty has two components, the size selectivity of the fishery, and the current abundance. Of the four selectivity curves, the curve with migration of one in eight adult lobsters is probably the most realistic, although it is also possible that something closer to the gamma selectivity would be more realistic if a large fraction of lobsters move into deep water. The uncertainty in the abundance at the beginning of the year is more problematic. The CPUE data indicate that the abundance at the beginning of the year can vary by a factor of two from one year to the next. **Table 11a** shows values of starting biomass of 30,000, 60,000 and 120,000 to capture this variability. The variability in abundance between years means that a quota set using data about abundance in previous years may be incorrect. For example, assume that the "migration of 1in 8" selectivity curve is correct, and the target *F* reference point is $F_{0.1}$. The quota is set equal to 14,200 assuming that the abundance next year will be approximately the same as that in 2011. If it turns out that the abundance is actually 30,000, the realized *F* will be twice the target level and will be more than F_{20}. Conversely, if it turns out that abundance is actually 120,000, the realized *F* will be half the target level, and the fishermen will lose out on half the catch they could have taken. At the current biomass level, the appropriate quota for most of the *F* reference points and selectivity models would be lower than the 2011-2012 catch (**Table 11b**).

One possible solution to the problem of year-to-year variability in lobster recruitment at Glover's Reef would be to adjust the quota based on data collected from fisher logbooks during the lobster season. One possible algorithm would be:

1) Choose target *F* (e.g. F_{20})
2) Use depletion analysis to calculate abundance in previous years, and catchability (q)
3) Assume next year's abundance will be the same, calculate the TAC and predicted CPUE:
   Expected CPUE = q x expected N
4) Calculate CPUE from logbooks in first two weeks of season
5) If CPUE is more than x% different from expected, adjust quota by y%
6) Repeat later in season

The values of CPUE that would trigger action would have to be pre-determined, so that the in-season analysis would be quick and easy. At the end of the season, a depletion analysis could be conducted to determine what the actual fishing mortality rate was across the fishing season. Such a mechanism would facilitate achieving the correct fishing mortality rate, despite annual fluctuation in lobster recruitment.

The variability in lobster abundance from one year to the next raises several interesting questions. A fundamental question is whether the lobster population at Glover's Reef is self-recruiting or whether the population is maintained by recruits that come from other lobster populations in Belize or elsewhere in the Western Caribbean. Fishery management reference points calculated per recruit are often used for spiny lobsters, because they do not require understanding the recruitment dynamics of lobsters. Lobsters have a long (6 month) larval duration so that they are capable of long migrations; however, the larvae may use behaviors such as vertical movement to increase retention near their spawning area (Butler et al. 2011). A genetic study found that it is possible to distinguish lobsters from Glover's Reef from lobsters from Hol Chan, implying that lobster populations in Belize are able to self-recruit (Truelove 2010). If the population at Glover's Reef is largely self-recruiting, then it might be possible to increase recruitment by increasing spawning stock biomass. In that case, it would be desirable to calculate the relationship between spawning stock biomass and recruitment, and calculate fishery management reference points related to stock recruit relationship such as Fmsy, the fishing mortality rate that maximizes total yield and SSBmsy, the spawning stock biomass that supports Fmsy. The fact that the current density ratio of adult lobsters in the General Use Zone versus in the Conservation Zone is 0.28 implies that the spawning stock biomass of lobsters at Glover's Reef may be depleted below one third of its unfished level. The spawning stock biomass that sustains MSY might be around this level, or it could be lower or higher. These reference points could not be calculated without long-term data about lobster recruitment at Glover's Reef.

Conversely, if recruitment at Glover's Reef is not related to biomass at Glover's Reef, but is instead related to environmental conditions or spawning stock biomass in the surrounding region, then using per-recruit F reference points and in-season adjustment of the fishing quota would be the most appropriate management system. Because lobsters tend to have variable recruitment every year, they are sometimes managed with ad-hoc management systems in which catch limits are adjusted based on a set of indicators of population status and trends (e.g. Prince 2008, Kay et al. 2012).

5. Conclusions and Recommendations

The new managed access logbook data provides useful data for estimating the abundance and fishing mortality rates of lobsters at Glover's Reef. Based on these data, during the 2011-2012 season the catch of lobsters was probably higher than would be recommended under an F_{20} fishing mortality rate. Estimates of abundance, along with information on sustainable fishing mortality rates and variability in abundance over time, are needed to set a total allowable catch quota. Because the abundance of spiny lobster at Glover's Reef varies considerably from one year to the next, we do not recommend setting a quota based on our estimates of abundance from a single lobster season. Rather, it would be advisable to use the logbook data from at least two or three more years to estimate lobster abundance before setting quotas. With more years of data it will also be possible to see whether the pattern of in-season recruitment in the second half of the season is something that happens every year. Further research on the size selectivity of the fishery, including the fraction of lobsters at each size that migrate into deeper water where they are not vulnerable to the fishery, would reduce the uncertainty in our estimates of the sustainable catch quotas. Once some of these uncertainties have been resolved, it will be possible to use a decision table (**Table 11a**) to set a catch quota. In-season monitoring of catch rates would be useful to determine whether the quota needs to be adjusted because lobster recruitment is exceptionally good or exceptionally bad in a particular season.

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8. Tables and Figures

Table 1. Estimated parameter values for CL=a+b*TL, calculated from 3765 lobsters caught at Glover's Reef between 2004 and 2012.

	a	b	R^2
Combined	6.72	0.58	0.52
Female	12.84	0.52	0.51
Male	-1.97	0.66	0.60

Table 2. Parameters and their prior distributions for the Bayesian depletion models.

Parameter	Description	Prior	Range
M	Natural mortality rate	M=Normal(μ=0.34, σ=0.04)	-∞ - ∞
N_0	Exploitable abundance of lobsters at the beginning of the lobster season	log(N_0)=Uniform	0 to 1.0E8
R	Number of lobsters that recruit into the fishery during the season	log(R)=Uniform	0 to 1.0E8
q	Catchability for CPUE abundance index x 1000	log(q_j)=Normal(μ=0, σ=0.001)	1.0E-9 to 10
σ^2	Observation error variance for CPUE abundance index	1/ σ_j^2=Gamma(0.01,0.01)	0.001-100

Table 3. Fishing mortality rate reference points estimated for Glover's Reef lobsters.
(a) Alternative models of current selectivity

Selectivity	F_{max}	$F_{0.1}$	F_{10}	F_{20}	F_{30}
Logistic	0.60	0.29	1.19	0.62	0.39
Migration fraction 0.125	0.68	0.32	1.34	0.70	0.45
Migration fraction 0.25	0.78	0.38	1.53	0.80	0.51
Gamma	0.99	0.60	1.32	0.79	0.56

(b) With an increasing size limit

Size limit	F_{max}	$F_{0.1}$	F_{10}	F_{20}	F_{30}
4.0 inches TL	0.60	0.29	1.21	0.62	0.40
4.5 inches TL	0.62	0.29	1.28	0.64	0.41
5.0 inches TL	0.68	0.30	1.57	0.72	0.44

Table 4. Summary of the managed access logbooks during the 2011-2012 lobster season.

	Sailboat	Skiff
Vessels	11	7
Vessel-days	455	66
Vessel-days with lobster	359	1
Fisher-days with lobster	2973	3
Lobster number	42715	3
Lobster tail weight (lbs)	21572	1.5

Table 5. Summary of depletion model results, fit to catch for the first 16 weeks of the season.

Parameter	Mean	CV	Q10	Median	Q90
N_0	8.24E+07	12.2	55400	67500	111000
F	0.71	0.37	0.38	0.73	1.00
Fraction caught	0.47	0.30	0.31	0.50	0.61
N_{final}/N_0	0.46	0.29	0.33	0.43	0.61
q	0.05	0.40	0.03	0.05	0.07
C-sd	0.24	0.22	0.18	0.23	0.31
Bayesian p value	0.45	NA	NA	NA	NA

Table 6. Summary of depletion model results, fitted to effort.

Parameter	Mean	CV	Q10	Median	Q90
N_0	1.09E+06	13.2	51600	61700	96100
F	0.66	0.37	0.35	0.68	0.95
Fraction caught	0.53	0.27	0.36	0.56	0.67
N_{final}/N_0	0.48	0.26	0.35	0.45	0.63
q	0.00	0.37	0.00	0.00	0.00
C-sd	0.24	0.22	0.18	0.23	0.31
Bayesian p value	0.45	NA	NA	NA	NA

Table 7. Depletion model fitted to catch for the entire season with additional recruitment in week 21 to 35.

Parameter	Mean	CV	Q10	Median	Q90
N_0	3.98E+08	5.48	45600	54800	2.09E+07
F	1.33	0.56	0.00	1.46	2.18
Fraction caught	0.51	0.45	0.00	0.60	0.71
N_{final}/N_0	0.47	0.38	0.29	0.42	0.79
q	0.06	0.59	0.00	0.06	0.10
C-sd	0.44	0.16	0.35	0.43	0.53
R	8.76E+06	17.1	5200	15800	31700
$R+N_0$	4.07E+08	5.48	60400	71300	2.14E+07
Bayesian p value	0.55	NA	NA	NA	NA

Table 8. Analysis of deviance for the Generalized linear model of CPUE from the WCS fishery data.

(a) AIC best model. Moon phase explained less than 5% of the deviance, so it was removed.

	Df	Deviance	Resid. Df	Resid Dev	F	Pr(>F)	% Deviance
NULL	760	544.2					
T	47	131.4	713	412.8	5.6	0	0.24
V	13	48	700	364.7	7.41	0	0.09
M	1	0	699	364.7	0.08	0.7831	0.00
T × M	4	17.8	695	346.9	8.92	0	0.03

(b) Mixed model results. Vessel (V) is a random effect, as are all interactions

Model	AIC	BIC
T+V	1811.89	2043.62
T+T × V	1816.18	2047.92
T+M+V	1813.58	2054.58
T+M+V+T × V	1807.95	2053.59
T+M+V+T × M	1811.50	2057.13
T+M+V+V × M	1815.25	2060.88
T+M+V+T × V+T × M	1807.40	2057.67
T+M+V+T × v +V × M	1809.95	2060.22
T+M+V+T × M+V × M	1812.79	2063.06
T+M+V+T × v+T × M+V × M	1809.40	2064.30

Table 9. Calculation of fishing mortality from average length from the WCS fishery data.

Data source	n	Lc	n in range	$\bar{L}$	SE	Z	M	F
Catch	3804	90	2107	105.3	0.31	1.22	0.34	0.88
LAMP GUZ	284	90	111	114.5	2.2	0.67	0.34	0.33
LAMP CZ	410	90	257	118.7	1.52	0.54	0.34	0.2

Table 10. Current (2011) status of the lobster fishery at Glover's Reef, showing median values.

	N_0	F	N_0+R	F/F_{20}	$N_{fished}/N_{unfished}$
Length-based		0.88		1.2-1.4	
Depletion model (whole season)	54800	1.46	71300	1.8-2.1	
Depletion model (16 weeks)	67500				
Depletion model with effort (16 weeks)	61700				
Density estimate			13800		0.28

Table 11. Decision table showing the catch quotas corresponding to a range of values of *F* or *N* (in thousands) for four selectivity models.

(a) Catch quota in thousands

Selectivity	Logistic			Migration 1/8			Migration 1/4			Gamma		
N (1000s)	30	60	120	30	60	120	30	60	120	30	60	120
F_{max}	11.6	23.3	46.6	12.8	25.5	51.1	14.0	28.1	56.2	16.4	32.8	65.7
$F_{0.1}$	6.4	12.8	25.6	7.2	14.3	28.6	8.0	16.1	32.1	11.7	23.4	46.8
F_{10}	18.3	36.6	73.2	19.5	39.0	78.1	20.8	41.6	83.1	19.3	38.7	77.4
F_{20}	11.9	23.8	47.6	13.1	26.1	52.2	14.3	28.6	57.3	14.2	28.4	56.8
F_{30}	8.4	16.7	33.5	9.3	18.6	37.2	10.4	20.7	41.5	11.0	22.0	44.0

(b) Catch quota as a percent of the 2011-2012 catch

Selectivity	Logistic			Migration 1/8			Migration 1/4			Gamma		
N (1000s)	30	60	120	30	60	120	30	60	120	30	60	120
F_{max}	27	55	109	30	60	120	33	66	132	38	77	154
$F_{0.1}$	15	30	60	17	33	67	19	38	75	27	55	110
F_{10}	43	86	171	46	91	183	49	97	195	45	91	181
F_{20}	28	56	111	31	61	122	33	67	134	33	66	133
F_{30}	20	39	78	22	44	87	24	48	97	26	52	103

Figure 1. Length frequencies of lobsters from the LAMP survey in the Conservation Zone, LAMP survey in the General Use Zone, and from the WCS samples of the fishery.

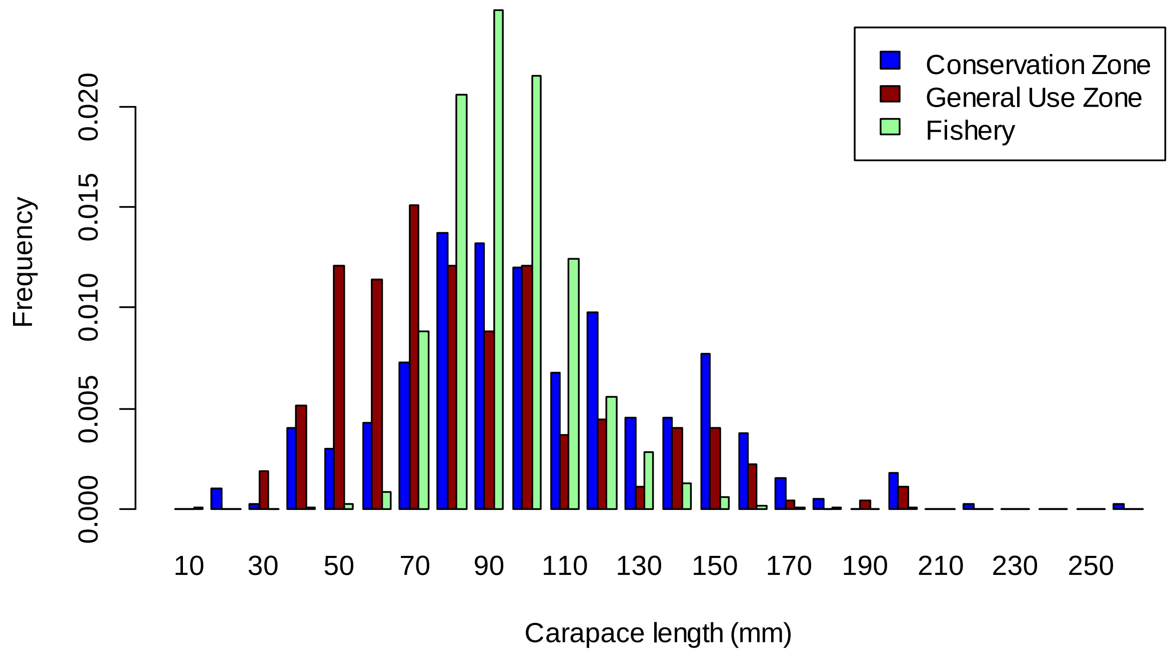


Figure 2. Empirical selectivities (points) and fitted logistic (a) and Gamma (b) selectivity curves estimated by comparing the length frequencies in the catch to the length frequencies in the LAMP fishery independent survey in the General Use Zone.

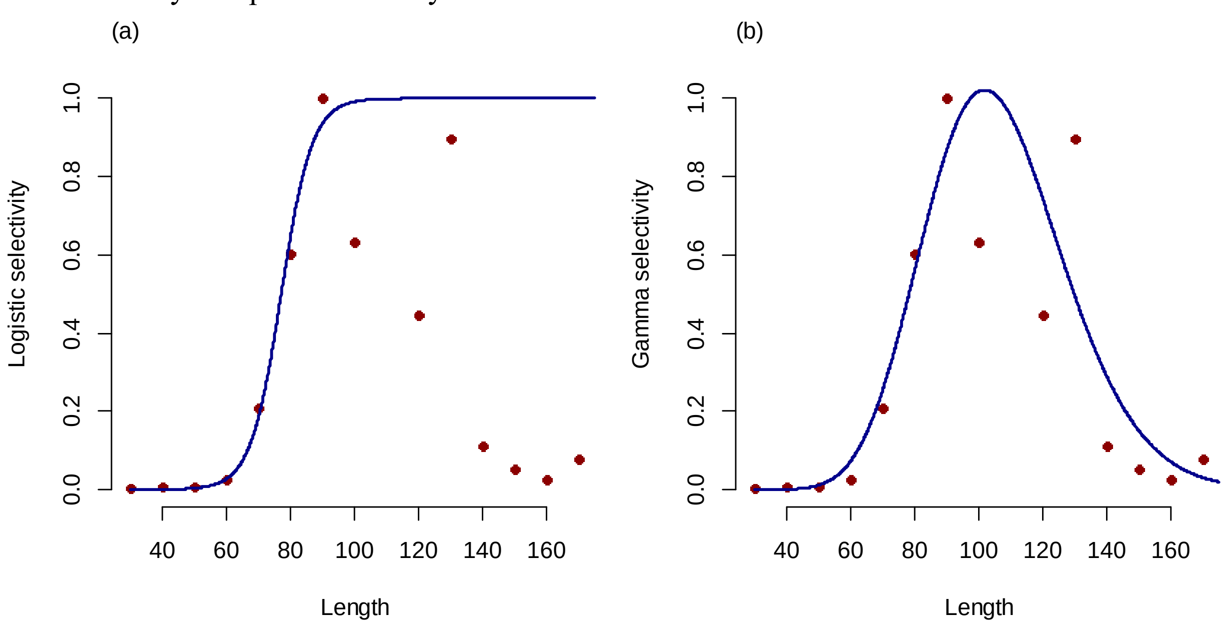


Figure 3. Fraction of lobsters that have migrated from shallow to deep water based on data from Acosta and Robertson (2003) (a) assuming that one in eight lobsters migrate, and the combined selectivity curve (b) estimated by multiplying the logistic selectivity curve estimated for Glover's Reef lobster by the fraction of lobsters remaining in shallow water.

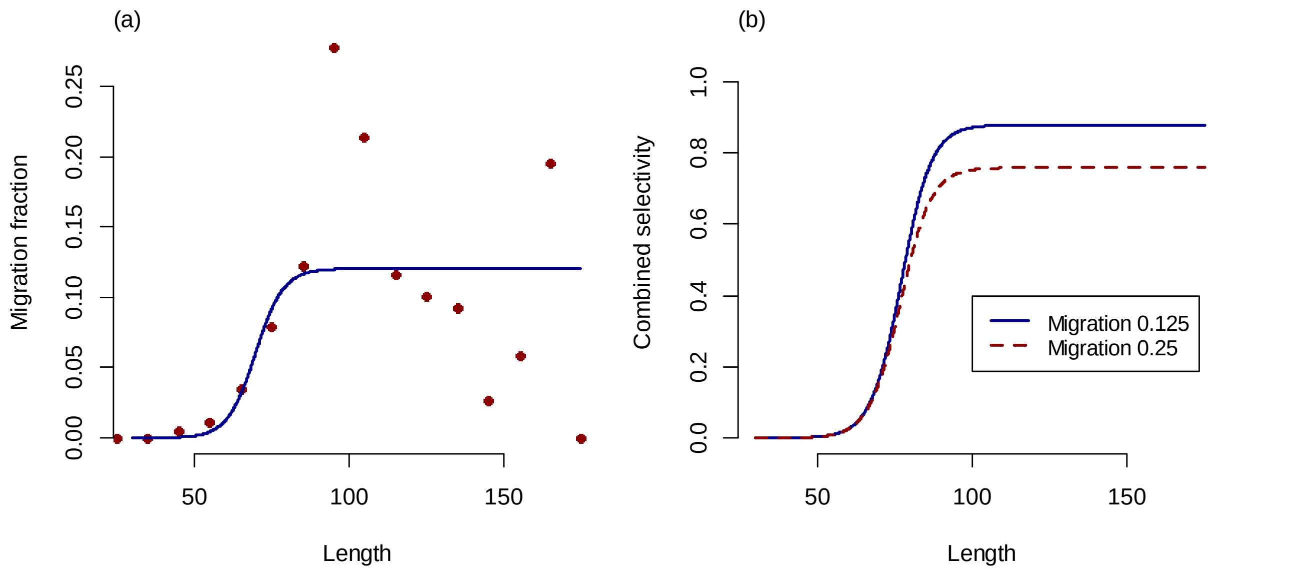


Figure 4. Yield per recruit curves (a), and spawning stock biomass per recruit relative to the unfished level (b), calculated for four alternative selectivity models.

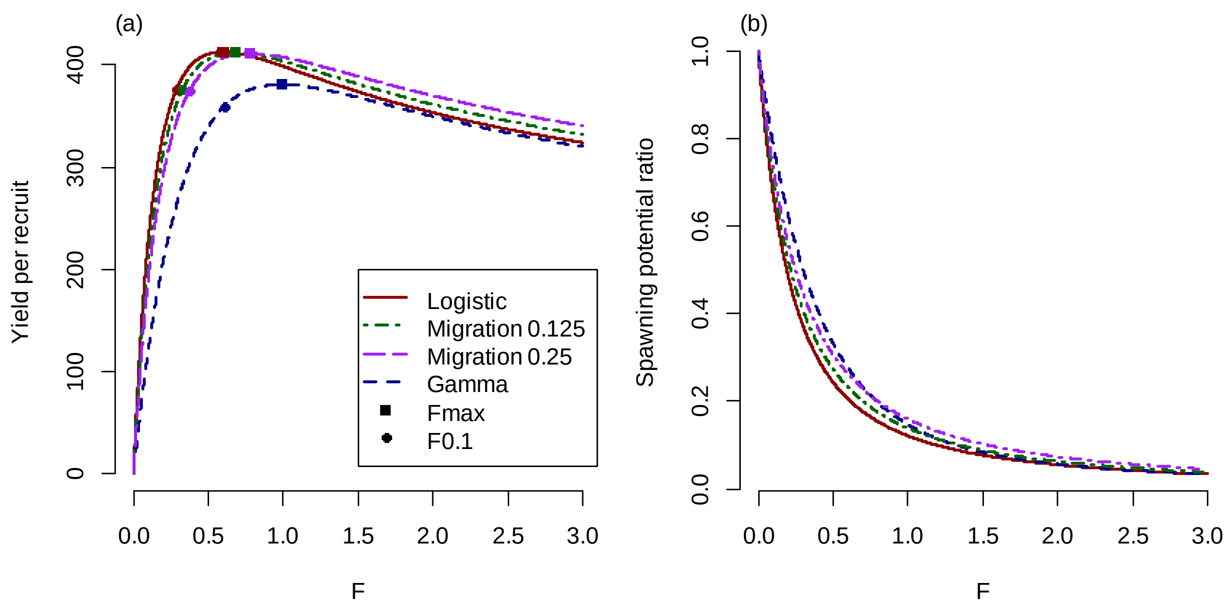


Figure 5. Summary of the managed access logbook data for the 2011 lobster season (June 15, 2011 – February 14, 2012): (a) catch, (b) effort, (c) mean catch per unit effort, and (d) mean whole weight.

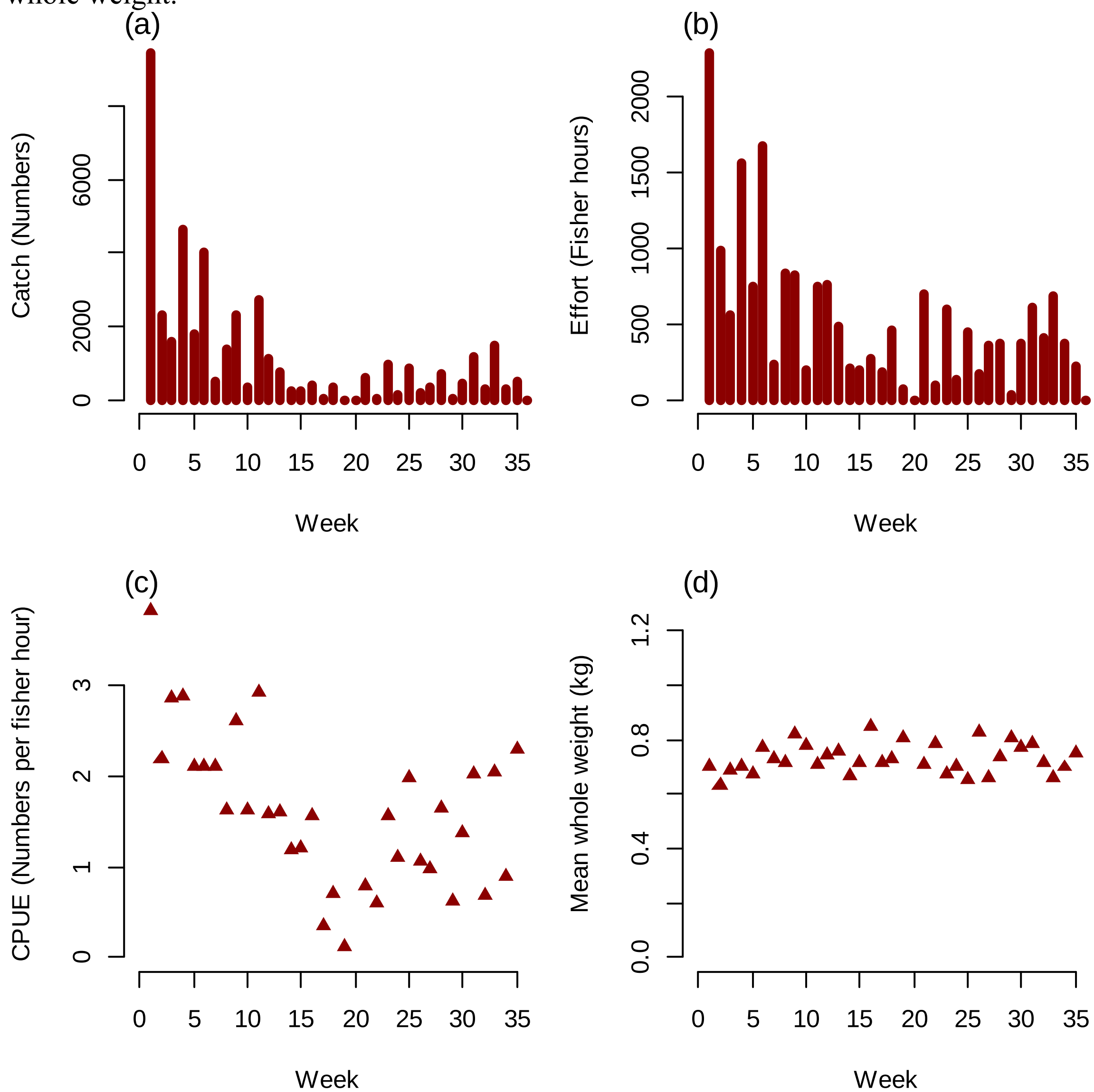


Figure 6. Lobsters caught per fisherman day: (a) number per fisher-day the WCS fisher interview samples, (b) number per fisher-day in the logbooks, (c) pounds tail weight per fisher-day in the logbooks, and (d) logbook pounds tail weight versus number of lobsters by fisher-day.

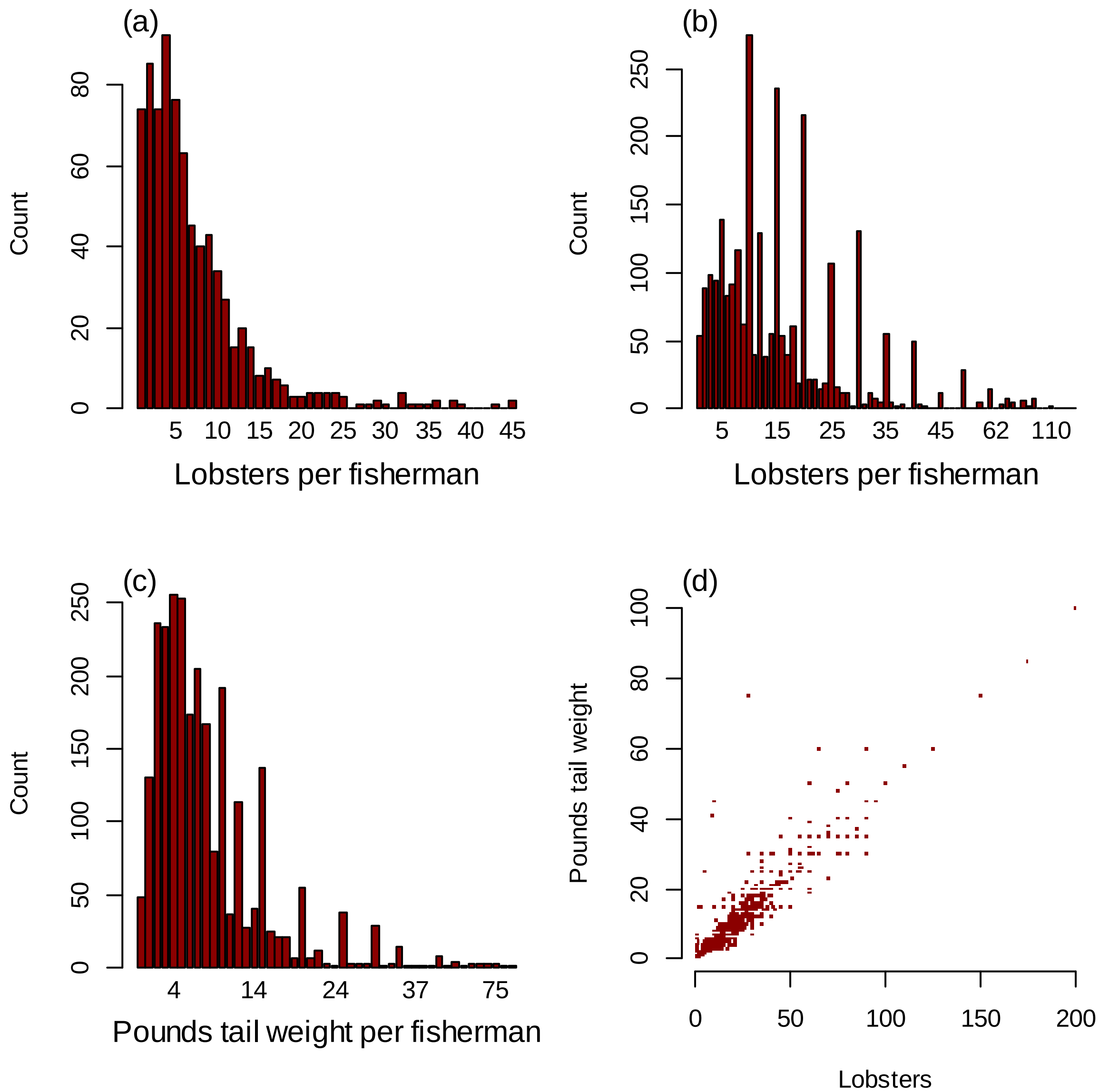


Figure 7. Bayesian depletion model results fitted to catch, showing (a) the prior and posterior probability density function for the abundance at the start of the season, and (b) the median and 80% credibility intervals of the number of lobsters for the first 16 weeks of the season.

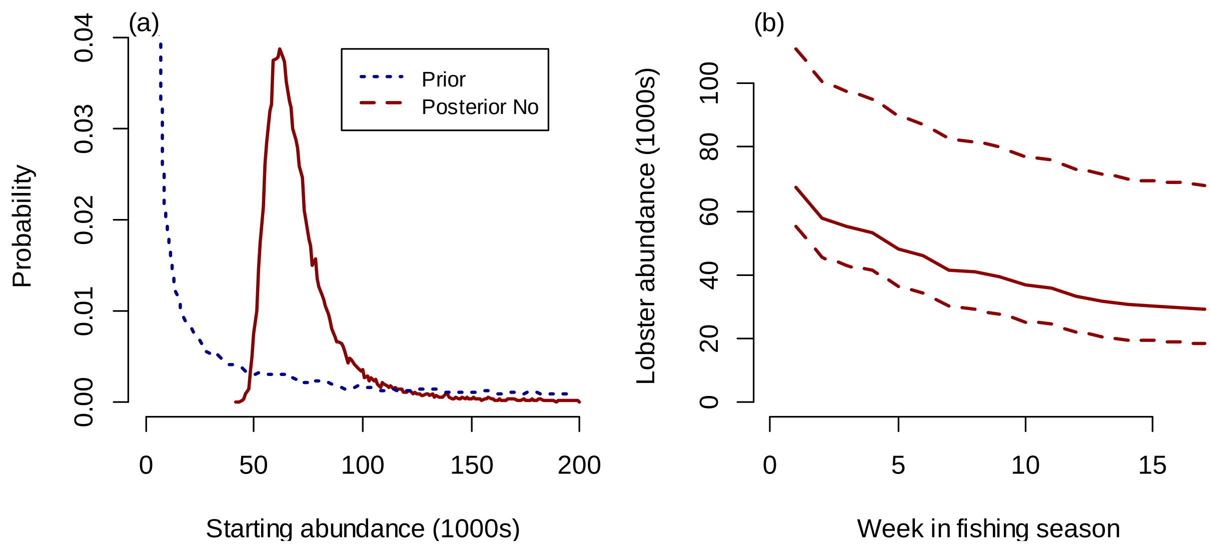


Figure 8. Bayesian depletion model results fitted to effort for the first 16 weeks of the season, showing (a) the prior and posterior probability density function for the abundance at the start of the season for values below 200,000, and (b) the median and 80% credibility intervals of the number of lobsters.

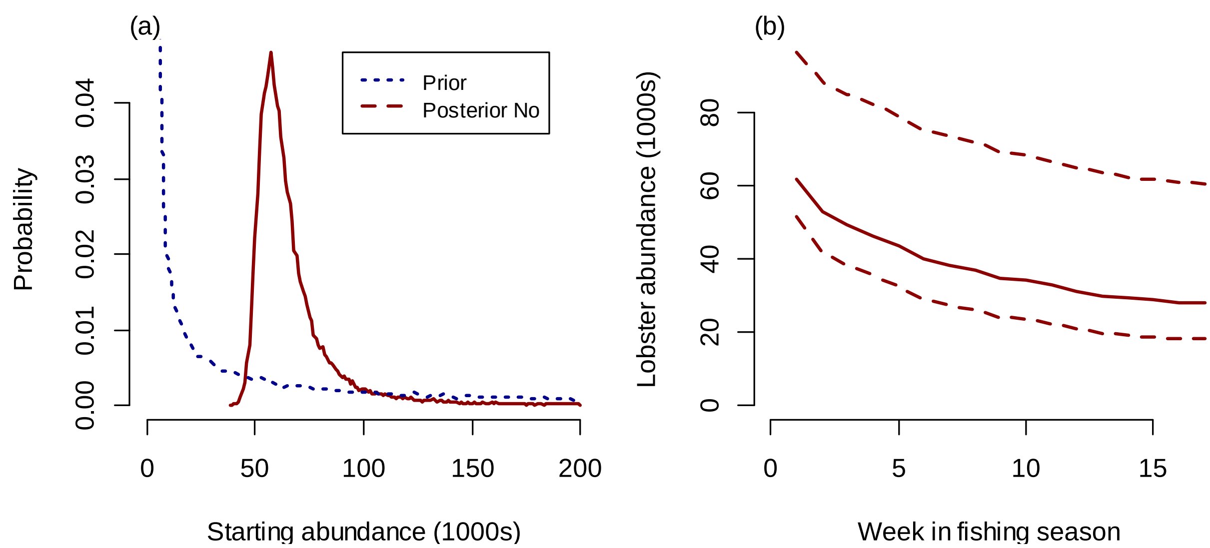


Figure 9. Bayesian depletion model results fitted to catch for whole 2011-2012 season, with estimated additional recruitment in the latter half of the season, showing (a) the prior and posterior probability density function for the abundance at the start of the season and recruitment during the season for values below 200,000, and (b) the median and 10% and 85% quantiles of the number of lobsters.

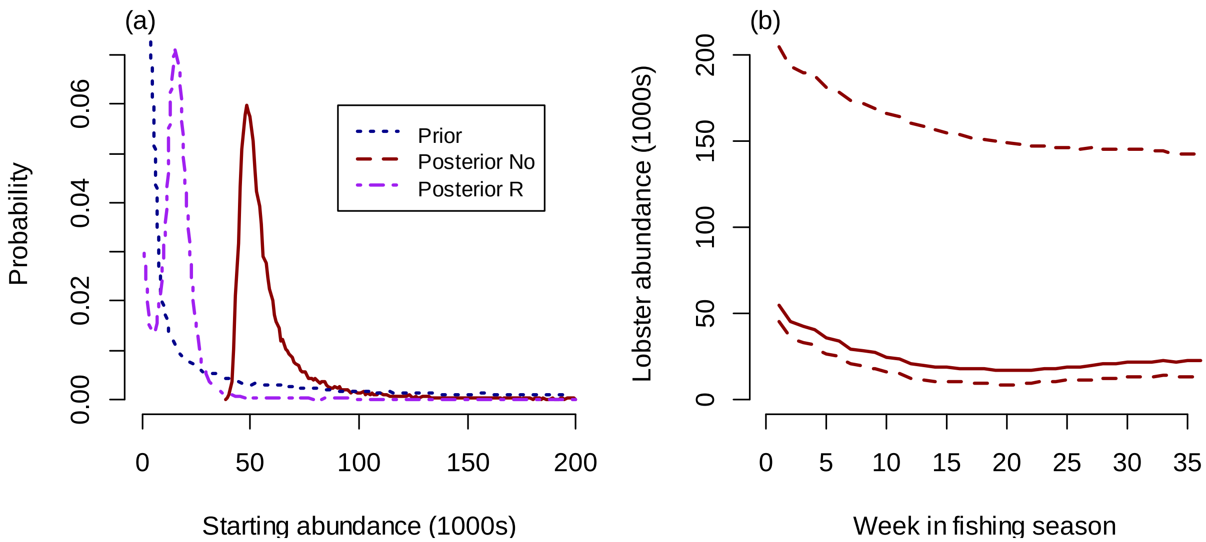


Figure 10. From the LAMP visual survey, (a) the average density of adult lobsters on patch reefs during each sampling period, in each management zone plus and minus one standard erro, and (b) the ratio of adult lobster densities in the General Use Zone to density in the Conservation Zone.

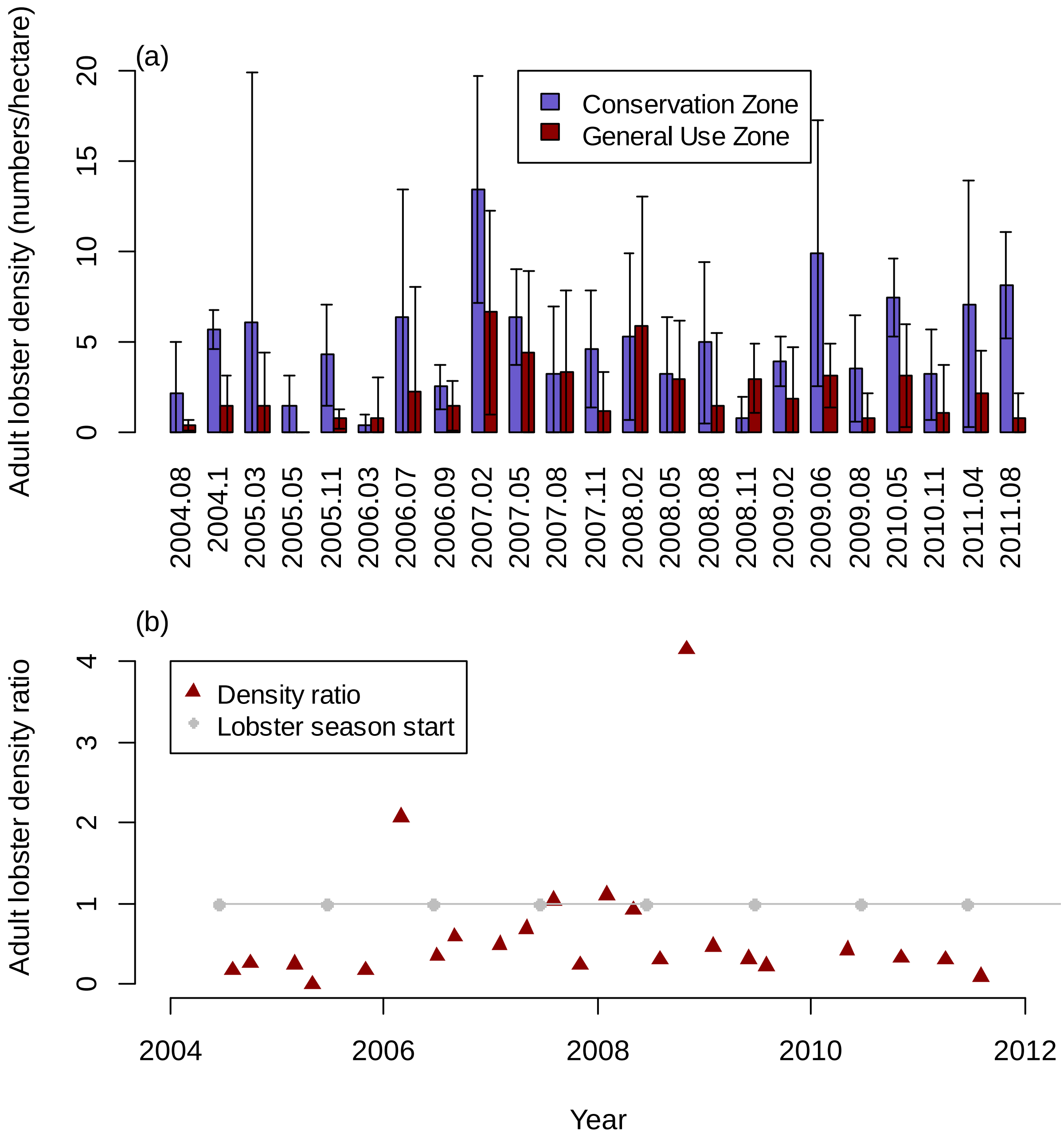


Figure 11. Total number of adult lobsters, calculated by expanding the estimated densities times the area of reef habitat in each zone.

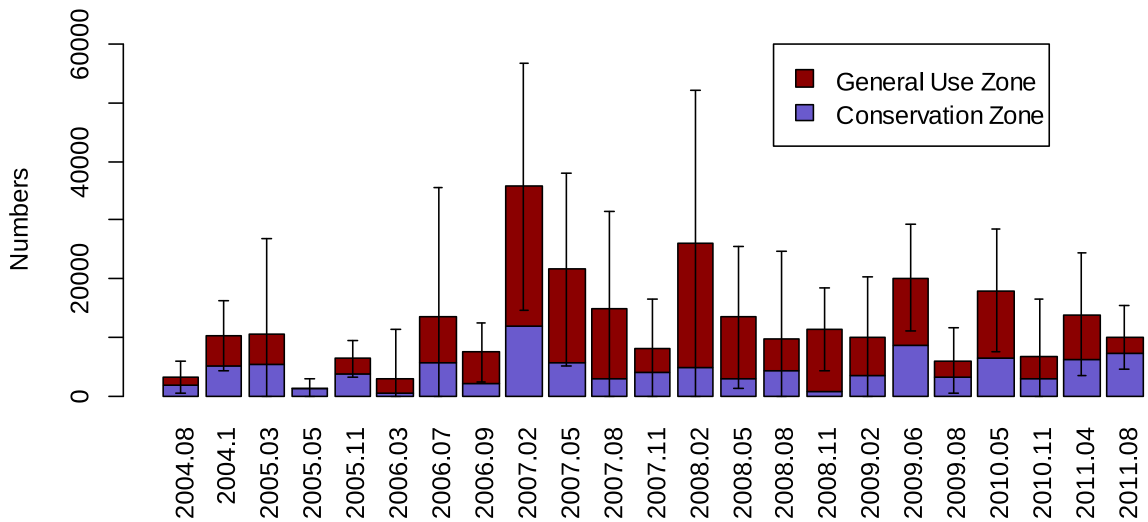


Figure 12. CPUE GLMM diagnostics.

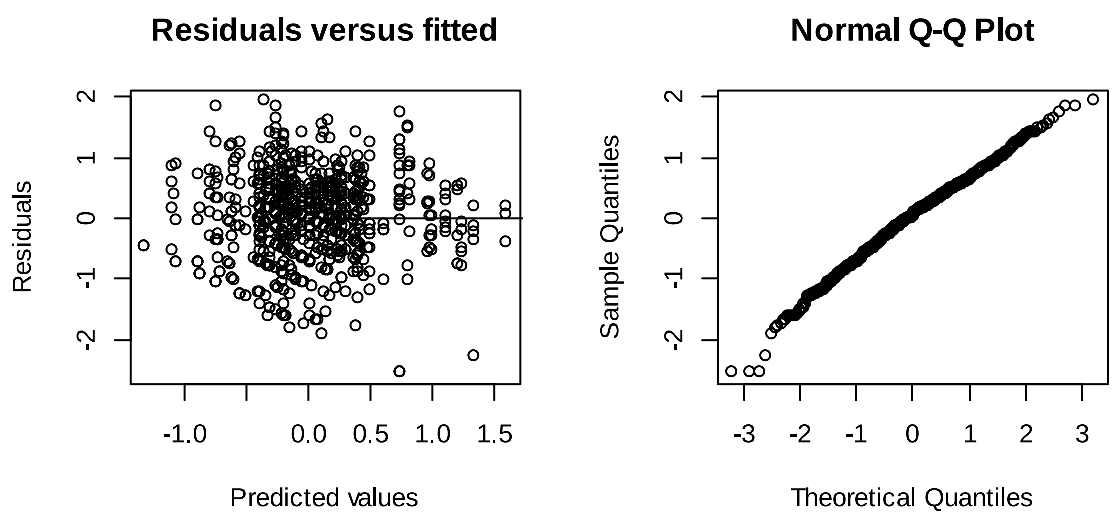
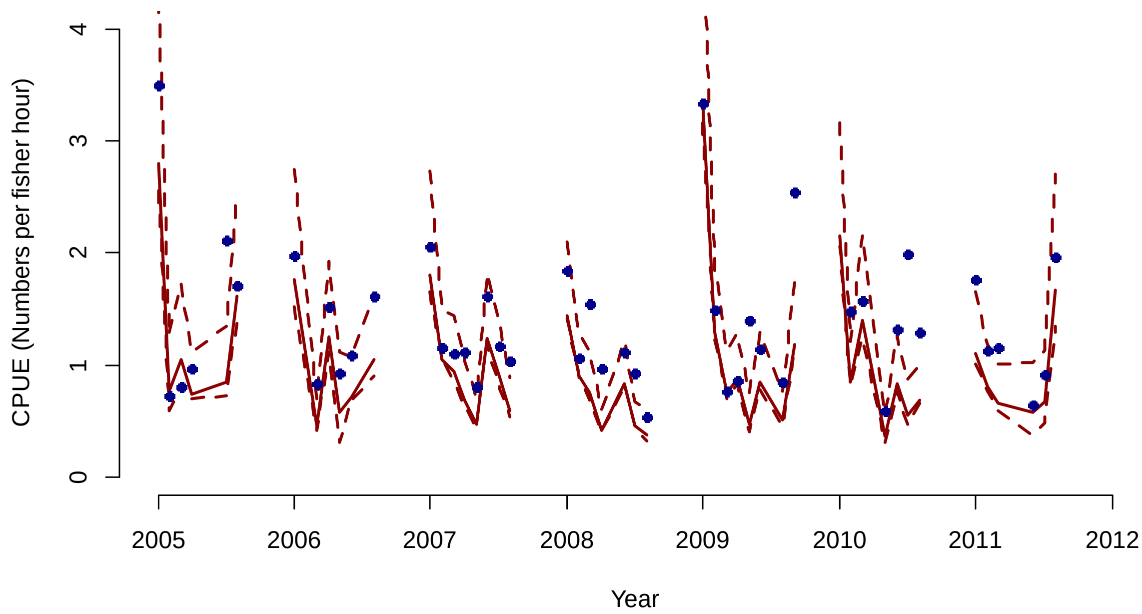


Figure 13. WCS CPUE in numbers of lobsters per fisherman hour, standardized by year and month, with boat as a random effect. Dashed lines are 95% confidence intervals, points are raw data.

(a) All sampled months



(b) First month of each season