Strategies for improving the precision of fishing and natural mortality estimates from multiyear tagging models: a case study

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Abstract. Fisheries scientists and managers want precise estimates of fishing and natural mortality for assessments and management decisions. Because tagging can be an expensive option, maximizing potential benefits requires careful consideration of experimental design. We evaluated four options for improving the precision of estimates by conducting Monte Carlo simulations of a fishery patterned after that for the rock lobsters in north-western Tasmania, Australia. Improving tag-reporting rate and increasing the duration of the tagging study provided greater improvements in precision than increasing either the number of lobsters tagged per tagging event or the number of tagging events each year. A design based on twice-a-year tagging for three years to determine tag-reporting rate followed by an additional two or more years of once-a-year tagging provided the most precise estimates of natural mortality of all the designs considered. This design was also cost effective relative to the other options, but tag-reporting rate must be constant over the period of the study. If constancy cannot be assumed, then years of multiple tagging events may have to be interspersed among the years with single tagging events. Further improvements in mortality estimates from this multiyear tagging model could be achieved with improved tag-reporting rate.

Introduction

Managers and scientists want the most precise estimates possible of fishing mortality rates for their assessments, but financial and logistical constraints limit what can be achieved. Precise estimates permit greater resolution of changes in annual fishing mortalities so that fishing activity can be managed rationally. As fishing and natural mortality rates are an important component of many fishery assessments, the precision of these estimates strongly affects the precision of assessment outcomes.

Frusher and Hoenig (in press) obtained estimates of reporting rate and fishing and natural mortality rates from multiyear tagging models for rock lobsters in north-west Tasmania. Improving the precision of these estimates usually comes at a cost, which could involve either tagging more lobsters or improving publicity campaigns to increase tag-reporting rates. Xiao (1996) highlighted the need to evaluate the experimental design to ensure that sufficient animals are tagged to produce meaningful results. Conversely, tagging too many animals can lead to precision beyond what is required by management and thus be wasteful of both labour and funds. Changes in the study design and the rewards can also improve precision at no, or very little, additional cost (Nichols *et al*. 1991; Pollock *et al.* in press).

The present paper evaluates four scenarios that could be used to improve the relative standard errors (*Rse*'s) of fishing and natural mortality estimates obtained from multiyear tagging studies of rock lobsters.

Methods

The models used in this paper are derived from the multiyear tagging models of Brownie *et al.* (1978, 1985) as extended by Hoenig *et al.* (1998) and Hearn *et al.* (1998). The expected recoveries from a Brownie model are presented in Table 1. The survival-rate parameters (S_i) can be expressed in terms of instantaneous fishing and natural mortality rates as follows:

$$S_i = \exp\left((-F_i - M_i)\Delta t_i\right) \quad (1)$$

where F_i = instantaneous fishing mortality rate (year^{-1}) in time period i and M_i = instantaneous natural mortality rate (year^{-1}) in time period i. In these simulations M is assumed constant over time and equal for the two sexes. Consequently the subscript is suppressed. Δt_i = length of the ith time period (year).

The tag-recovery rates (f_i) are also functions of the F's and M, but the functional form depends on the relative timing of the fishing and natural mortalities. If both occur with constant intensity over the

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Table 1. Expected recoveries in a multiyear tagging study
N_i is the number of lobsters tagged in event i, f_i is the expected fraction of tags recovered in period i (between tagging events i and $i+1$), and S_i is the fraction of lobsters that survived in period i

Tagging event	No. tagged	Expected recoveries in period			
		1	2	3	4
1	N_1	$N_1 f_1$	$N_1 S_1 f_2$	$N_1 S_1 S_2 f_3$	$N_1 S_1 S_2 S_3 f_4$
2	N_2	—	$N_2 f_2$	$N_2 S_2 f_3$	$N_2 S_2 S_3 f_4$
3	N_3	—	—	$N_3 f_3$	$N_3 S_3 f_4$

course of a period (Type 2 fishery of Ricker 1975), then the tag-recovery rate can be expressed as

$$f_i = \lambda_i (1-\exp((-F_i - M)\Delta t_i))\left[\frac{F_i}{F_i+M}\right] \quad (2)$$

where λ_i is a composite parameter that represents the joint probability of three events: a tagged lobster does not die from the tagging process; a tag is not shed immediately; and a tag will be found and reported to the fisheries biologist, given that the tagged lobster has been harvested. In these simulations λ is assumed constant over time.

For example, the expected recoveries in period 2 from tagging at event 1 is $N_1 S_1 f_2$ (Table 1). Substituting equations 1 and 2 for S_1 and f_2, respectively, we can write the expected recoveries in terms of F_1, F_2, and M

$$N_1 S_1 f_2 = N_1 \exp((-F_1 - M)\Delta t_1)\, \lambda (1-\exp((-F_2 - M)\Delta t_2))\left[\frac{F_2}{F_2+M}\right] \quad (3)$$

Frusher and Hoenig (in press) analysed data from a tagging study in which lobsters were tagged three times per year, in September (before the beginning of the fishing season), February (mid-season), and May (end of female season). The male season continues past the end of the female season until August. Rather than estimating separate fishing mortality rates for each sex, they used the following approach.

(*1*) A single fishing mortality rate for males was estimated per year and was apportioned to the period of the year according to the relative amount of fishing effort occurring in the periods.

(*2*) Because the fishing season for females was contained within the season for males, the fishing mortality for females in a year was assigned to be a fraction of the male mortality; the fraction was equal to the amount of fishing effort in the female season divided by the total effort in the year.

(*3*) Natural mortality, M, was assumed equal for the sexes and held constant over years. It was apportioned to periods of the year according to the lengths of the periods.

A more detailed description of the tagging models can be found in Frusher and Hoenig (in press). Because conducting three tagging events per year may be logistically or otherwise impossible, Frusher and Hoenig also considered what results would be achieved if only two tagging events per year occurred, in September and May. Two or more tagging events per year are required to separate the total mortality rate into its natural and fishing mortality components by the method of Hearn *et al.* (1998).

Here, we use the twice-a-year tagging model as a base case and investigate four options for improving precision of natural and fishing mortality and tag-reporting rate estimates: increasing the number of animals tagged per tagging event, increasing the number of tagging events per year, increasing the tag-reporting rate, and increasing the duration of the study.

Precision and bias of estimated parameters were investigated with Monte Carlo simulation techniques. As all of the tagging models are product multinomial, the simulations are conveniently performed by the program SURVIV, described by White (1983). The standard error and mean estimates were obtained with the PROC SIMULATE command.

Relative standard error (Rse), was obtained as

$$Rse = \frac{\overline{SE}}{\overline{X}}$$

where $\overline{X}$ is the mean of the simulated estimates of a parameter and $\overline{SE}$ is the mean standard error of the estimate (taken over all simulated data sets).

Unless otherwise specified, all simulations were conducted with simulated values for tag-reporting rate (λ) of 0.22, natural mortality (M) of 0.1 year^{-1}, and fishing mortality (F) of 1.0 year^{-1}. These values were chosen to be realistic for the rock-lobster stock off north-western Tasmania. Frusher and Hoenig (in press) obtained estimates of fishing mortality in excess of 1.0 year^{-1} and reporting rate around 0.2. Their estimate of natural mortality was zero. For these simulations, tag-induced mortality and tag shedding were set to zero. Four years of tagging and six years of recaptures were simulated to parallel the tagging study conducted off north-western Tasmania. As with the model developed by Frusher and Hoenig (in press), tagging began in May of year 1 (*i.e.*, during the fishing season) and ended in May of year 4. Fishing and natural mortality were simulated on the basis of the amount of fishing effort and portion of year, respectively, that occurred between tagging events in the fishery from 1991 to 1997. Consequently, year 1 simulations were based only on the fishing effort undertaken between the May tagging and the close of the fishing season (17% of the total effort in the 1991–92 fishing year). Simulations were based on 500 lobsters tagged per sex per tagging event, as this number was achievable in the above-mentioned study. To determine the effect of additional years of tagging (*i.e.*, increasing duration of the study), we conducted additional simulations with six and eight years of tagging and six and eight years of recaptures, respectively. For each model, 1500 simulations were undertaken.

We also looked at the costs associated with various study designs. Costs of tagging were derived from costs incurred during tagging studies conducted from 1992 to 1995. These costs included vessel charter (A$1800 per day), travel (A$450 per trip) and accommodation of a field officer (A$100 per day), and costs of tags (A$0.50 per tag). No rewards were offered for tags. Costs did not include the salary of the field officer, as it was assumed that the officer would be a regular employee of the research section. The opportunity costs incurred because the field officer might have undertaken other scientific activities have not been considered. Both the travel cost and the cost of tags are set for each trip irrespective of the number of days required to tag 500 lobsters of each sex. The shorter the trip the greater would be this contribution on a per-day basis, but both these costs are minor compared to the cost of vessel charter. The difference in fixed costs between a 5- and a 20-day trip is approximately 5% on a daily basis.

Results and Discussion

Baseline simulations

In the baseline simulations the most precise estimates of fishing mortality were obtained for years 2 to 5 (Table 2). The higher *Rse* of the first year's fishing-mortality estimate was expected given that the simulations mimicked the real tagging study and only 17% of the fishing effort in the first year was expended between tagging and the end of the fishing year. The higher *Rse* of the estimate for the last year is assumed to be due to the low number of tag returns. No new tags were available for capture after the May tagging event in year 4, and the high exploitation rate would leave few tags available for recapture from all previous tagging events. Under high exploitation, therefore, tagging might need to be maintained to yield low relative standard errors of fishing-mortality rate estimates. Although tag-reporting rate was simulated as low (0.22), the *Rse* of approximately 0.15 suggests that this parameter is estimated relatively precisely. In contrast, the *Rse* of the natural mortality estimate was high, indicating the poor precision in estimating this parameter from the twice-a-year tagging model.

Hearn *et al.* (1998) found that they were able to estimate tag reporting rate and natural and fishing mortality rates reasonably well in simulated situations where F was only twice M and tag reporting rate was only as low as 50%. In contrast, the annual fishing-mortality estimates for the Tasmanian rock-lobster fishery (Frusher and Hoenig in press) are 10 times the estimate of M, and tag-reporting rate is less than half.

Increasing the number of lobsters tagged per tagging event

The most marked improvement in the relative standard errors of fishing and natural mortality estimates was obtained when the number of tagged lobsters was increased from 250 to 500 per sex per tagging event (Figs 1*a* and 1*b*). At 500 tags per tagging event per sex, the relative standard error (*Rse*) of the natural mortality estimate was 1.03 (Table 2, base case).

The *Rse* of the natural mortality estimate improved by only 13% if fishing mortality was held constant over all years (Fig. 1*a*), but the actual gain in precision depended on the degree to which the assumption of constant fishing mortality is met. Furthermore, Frusher and Hoenig (in press) outlined the advantages of estimating fishing mortality for each year. Even if 2000 tagged lobsters of each sex were released twice each year, the *Rse* of estimates of M only declined to 0.59, when F was estimated annually. The improvement was marginal, to 0.50, when F was held constant over all years, but the logistics of tagging so many lobsters each year are unrealistic in the Tasmanian fishery. Increasing the number of tags and using a model with fewer parameters may therefore not suffice for obtaining precise estimates of natural mortality rate.

The selection of 500 lobsters of each sex to be tagged at each survey appeared appropriate, as the greatest improvement in *Rse* of estimates of F and M was achieved when the numbers tagged increased from 250 to 500 per sex (Fig. 1). Increasing the number of tagged lobsters each tagging event improved the *Rse* of annual fishing mortality rate estimates by approximately 18% when the number of

Table 2. Improvements in the relative standard error (*Rse*) of annual fishing mortality (F_i), natural mortality (M), and tag-reporting rate (λ) estimates resulting from an increase in (*A*) number tagged per tagging event per sex from 500 to 750, (*B*) frequency of tagging from twice per year to three times per year, (*C*) tag-reporting rate from 0.22 to 0.5, (*D*) tag-reporting rate from 0.22 to 0.7, (*E*) the duration of tagging by 3 additional years of once-a-year tagging, and (*F*) the duration of tagging by 5 additional years of once-a-year tagging

Simulations are based on $M = 0.1$, $F = 1.0$, and $\lambda=0.22$, two tagging events per year, 500 lobsters tagged per sex per tagging event, 4 years of tagging, and 6 years of recaptures, except for E and F where there are 3 years of two tagging events per year followed by 3 (E) or 5(F) years of one tagging event per year

Parameter	Base case *Rse*	% improvement in *Rse* from base case					
		A	B	C	D	E	F
M	1.03	10.8	14.6	34.9	58.4	63.7	72.0
λ	0.15	19.4	24.6	—	—	53.8	67.8
F_1	0.27	18.1	4.5	34.9	46.3	63.6	64.3
F_2	0.15	18.8	20.5	40.9	55.2	44.1	46.1
F_3	0.14	18.9	21.0	41.2	55.7	40.5	43.7
F_4	0.13	18.9	21.7	40.8	55.1	39.8	45.7
F_5	0.14	18.4	21.3	39.5	53.5	29.1	42.9
F_6	0.25	16.9	21.4	38.3	52.5	44.1	62.5

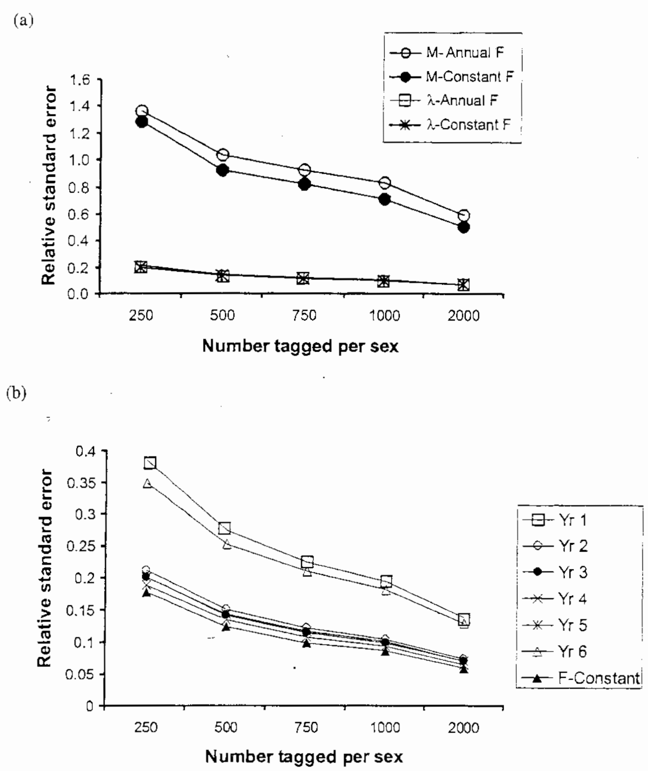

Fig. 1. Improvement in relative standard error of (*a*) natural mortality (*M*) and tag-reporting rate (λ) estimates and (*b*) fishing mortality (*F*) estimates resulting from increased number of lobsters tagged. Values are presented for cases in which fishing mortality was estimated annually or set to be constant over all years.

lobsters tagged increased from 500 to 750 per sex (Table 2). Although these improvements may appear worthwhile, the *Rse* of fishing-mortality rate estimates were already relatively low, varying from 0.13 to 0.15 for years 2 to 5 (Table 2). Managers therefore need to consider the precision required for appropriate management decisions.

Tag-reporting rate showed marginally better improvements in *Rse* than did *F*'s as the number of lobsters tagged was increased (Fig. 1*a*). Whether *F*'s were calculated for all years combined or annually made no difference in the improvement of the *Rse* of tag-reporting rate. Like F's, tag-reporting rate was relatively precise (*Rse* = 0.15) at 500 tags per sex per tagging event.

Increasing the number of tagging events per year

Natural mortality estimates showed a 15% improvement when frequency of tagging was increased from twice per year to three times per year (Table 2).

Increasing the frequency of tagging improved the precision of all but one of the fishing-mortality estimates by approximately 20% (Table 2). For the reasons mentioned above, the low, 5% improvement in *Rse* of the first year's *F* estimate is not surprising.

Tag-reporting rate showed the greatest improvement in *Rse* with increasing frequency of tagging, although as already mentioned, the *Rse* of tag-reporting rate is low.

Increasing either the number of lobsters tagged per event or the number of events per year involved tagging 1500 lobsters per sex per year. The additional tagging period per year produced only minor gains in precision compared to tagging more lobsters each tagging event.

Increasing the tag-reporting rate

Frusher and Hoenig (in press) attributed the poor precision in natural-mortality estimates to the high exploitation rates and low tag-reporting rate. As tag reporting rate is low, increasing it could improve estimates. Ways to do so include releasing tags with substantial rewards (Nichols *et al.* 1991; Pollock *et al.* 1995; Pollock *et al.* in press) and increasing fishers' awareness of the importance of returning tags. The latter could be achieved by means of regular visits to the fishing ports to speak with both vessel skippers and crews. Increasing tag-reporting rate from 0.22 to 0.5 improved the *Rse* of estimates of *M* by 35% (Table 2). A further increase in tag-reporting rate to 0.7 improved the *Rse* by an additional 24%. Significant improvements in tag-reporting rate are therefore required to improve the precision of estimates of *M*, although a 281% improvement in tag-reporting rate still resulted in relatively high *Rse* values of 0.5 for estimates of *M*.

Increasing tag-reporting rates from 0.22 to 0.5 and 0.7 decreased the *Rse* of *F*'s by approximately 40% and 55%, respectively (Table 2).

Increasing the duration of the study

To separate the total mortality rate into its natural and fishing mortality components, one must obtain an estimate of the tag-reporting rate. There are several means of doing so, including tagging more often (Hearn *et al.* 1998; Frusher and Hoenig in press) or using high-reward tags, planted tags, or a program of catch sampling (Pollock *et al.* 1995) all have associated costs. Once reporting rate has been estimated, it can be inserted as a fixed parameter into annual tagging models if the data analyst is confident that reporting rate is not likely to have changed appreciably over time. If ongoing estimates of fishing mortality are required, then annual tagging models could be applied for several years and interspersed with models with two tagging events per year to ensure that an appropriate tag-reporting rate is being used.

To indicate the precision of *F* and *M* estimates under the above scenario, we simulated a model in which 3 years of twice-yearly tagging were followed by 3 years of once-yearly tagging. Tagging events were based on the Tasmanian lobster fishery; tagging occurred before the fishing season for 6 years and after the female fishing season for the first 3 years only. The model was based on

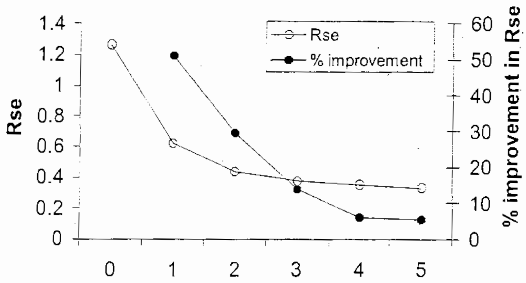

Fig. 2. Comparison of *Rse* of natural-mortality estimates as the number of years of once-a-year tagging increase after an initial 3 years of twice-a-year tagging.

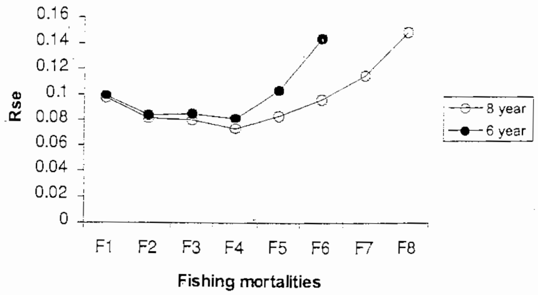

Fig. 3. Comparison of the relative standard error (*Rse*) of fishing-mortality estimates from models with 3 years of twice-a-year tagging followed by either 3 years (6-year) or 5 years (8-year) of once-a-year tagging.

tagging of 500 lobsters of each sex per tagging event; reporting rate was simulated as 0.22, natural mortality as 0.1, and fishing mortality as 1.0. This model gave a 63.7% improvement in the *Rse* of estimates of *M* over those for the base case with 4 years of tagging twice a year and 6 years of recaptures (Table 2). The improvement in *Rse* of the estimate of *M* over that for the previous options is considered to be due to the three extra years in which tagging was undertaken.

Knowledge of the extent of improvement in precision of *M* estimates with increased duration of tagging is required for planning of tagging studies. To evaluate the potential gains in precision of estimates of *M* associated with increasing the duration of tagging, we undertook simulations with 1 to 5 additional years of tagging after an initial 3 years of twice-a-year tagging (Fig. 2). Although the *Rse* value started to plateau after 2 years of once-a-year tagging, addition of a third year did improve the *Rse* of the *M* estimate by 13.7%. Improvements in *Rse* of less than 10% were achieved after the third year of once-a-year tagging. Achievement of an *M* estimate with a *Rse* of less than 0.3 would be unlikely if tag-reporting rate remained

Table 3. Relative standard errors (*Rse*) of fishing (*F*) and natural (*M*) mortality rates estimated from a model with 3 years of two tagging events per year followed by 3 years of a single tagging event per year

The percentage improvement in the *Rse* when reporting rate is increased from 0.22 to 0.5 is shown

Parameter	*Rse* at 0.22	*Rse* at 0.5	% improvement in *Rse*
M	0.38	0.21	43
*F*1	0.10	0.06	35
*F*2	0.08	0.05	37
*F*3	0.08	0.05	39
*F*4	0.08	0.05	38
*F*5	0.10	0.06	41
*F*6	0.14	0.08	39

low and fishing mortality continued to be high, irrespective of the duration of the study.

All *Rse* values of *F*'s except for the last year were 0.1 or less (Table 3). Although still low, the higher *Rse* value of the last year was considered to result because it was the last year of tagging. We confirmed this conclusion by running the model with an additional two years of once-a-year tagging (*i.e.* 3 years of tagging twice per year followed by 5 years of tagging once per year). In the 8-year model, the *Rse* of the final-year fishing mortality estimate was 0.15, but the *Rse* of fishing mortality for year 6 was 33% lower than that for the 6-year model (Fig. 3).

As increasing the tag-reporting rate provided the greatest improvement in the *Rse* estimates of the previous three options, we investigated the effect of improving tag-reporting rate on the 6-year model (3 years of tagging twice per year followed by three years of tagging once per year). Improving the tag-reporting rate from 0.22 to 0.5 improved the *Rse* of annual *F*'s by 35 to 40% and *M* by 42% (Table 3). Thus a combination of prolonged tagging and improved participation by fishers appears the most promising way of improving the precision of estimates of *F*'s and *M* from a heavily exploited population.

An important assumption in using the combined model, in which twice-a-year tagging is followed by once-a-year tagging, is that reporting rate is constant. Tag-reporting rate might vary for a number of reasons, however, including a possible increase in fishers' willingness to cooperate when management plans for the fishery are favourable or a decrease when they are unfavourable. Fishers can also become 'bored' with continuing to return tags once the novelty of the system wears off. Because tag-reporting rate can change, we recommend that twice-a-year tagging be interspersed with once-a-year tagging if long periods of tagging are being considered.

The improvements in precision that resulted from increases in the tag-reporting rate demonstrate that model estimates are sensitive to such changes. Thus confidence that tag-reporting rate is not changing is important.

Table 4. Catch rate, estimated number of days, and associated costs required to tag 500 and 750 legal-size male (M) and female (F) lobsters for the three survey periods

Number of pots fished per day = 80. Daily costs based on the maximum days required to tag the specified number of lobsters for either sex (e.g. May = 33 days for 500 tagged lobsters and 49 days for 750 tagged lobsters)

Survey period	Catch rate (#/pot lift)		Estimated number of days to tag				Estimated daily cost ($A)	
			500 lobsters		750 lobsters		500	750
	M	F	M	F	M	F	M	F
Feb.	0.44	0.40	15	16	22	24	1944	1934
May	0.30	0.19	21	33	31	49	1921	1917
September	0.53	0.61	12	11	18	16	1958	1946

Table 5. Comparison of costs associated with improving the precision of fishing, natural mortality, and tag-reporting rate estimates

Option	Cost A$
Increasing number of tagged lobsters from 500 to 750 per sex for two tagging events in a year.	$42050
Increasing frequency of tagging from two to three tagging events per year, each with 500 lobsters tagged per sex. The additional tagging event occurs in February.	$31100
Cost of each additional year of once-a-year tagging of 500 lobsters per sex. Tagging undertaken in September.	$23500

Fortunately, the low Rse values of tag-reporting rate show that it can be estimated with good precision.

Cost analysis

We have demonstrated which options provide the best improvements in estimates of fishing and natural mortality, but the cost effectiveness of the various options must be considered because tagging can be expensive. Mean catch rates of male and female lobsters for each survey period were obtained from surveys undertaken from May 1992 to May 1995. The catch rates are averaged for each survey period over all years (Table 4). May has the lowest catch rates, particularly of females, and therefore requires the greatest number of days for tagging of any given number of female lobsters.

Increasing the number of tags involves tagging an extra 250 lobsters per sex during September and May and was the most expensive option (Table 5). Increasing the frequency of tagging involved tagging 500 additional lobsters per sex during February. For these two options, the total numbers of tagged animals released per year are the same. The lower cost associated with undertaking an extra survey reflects the higher catch rates in February than in May. Vessel-charter costs account for approximately 93% of the total costs, so the number of days required to tag lobsters determines the cost efficiencies. Including a February tagging survey involves an extra 16 days, whereas increasing the number of tags from 500 to 750 in May and September requires 21 extra days. The cheapest option was to add an additional tagging year to the study. It improved the *Rse* of the estimate of M and the penultimate year's F in addition to estimating F for an additional year.

The costs associated with the option of increasing tag-reporting rate are unknown, and the improved results cannot be guaranteed. An increased publicity campaign and the offer of rewards for return of tags might lead to substantially higher tag returns for a modest price. Nichols *et al.* (1991) found substantial improvements in tag-reporting rate with the use of reward tags. Such tags should be considered in the design of tagging projects, given the improvements in the precision in parameter estimation when tag-reporting rate increased.

Although the costs of tagging appear high, approximately 93% of the cost is associated with vessel charter. Using research vessels or forming alliances with fishers under which charter costs are reduced can minimize this cost.

Conclusions

Our study has shown that M is a difficult parameter to estimate precisely from a fished stock where exploitation rate is high and M and tag-reporting rates are low, even if 'state of the art' tagging models are employed. Increasing either the number of lobsters tagged or the number of tagging surveys per year had limited impact on improving the relative standard error of F_i or M estimates. Improving tag-reporting rate improved the precision of F_i and M estimates substantially. An increase in the tag-reporting rate from 0.22 to 0.5 doubled the improvement in the precision of F_i and M estimates that result from an increase in either the number of lobsters tagged or the frequency of tagging. Unfortunately, improvements in tag reporting rate cannot be guaranteed, although reward tags should be considered. The best improvement in the precision of F_i and M estimates resulted when the duration of the study was increased. Twice-a-year tagging is required to estimate tag-reporting rate if no other options for estimating tag-reporting rate are available. Costs can be minimized if tagging is undertaken only once per year after an initial period of twice-per-year tagging. Under the assumption of constant reporting rate over time, a model based on once-a-year tagging after an initial period of twice-a-year tagging provided the lowest relative standard errors of F_i and M, and these can be further improved if tag-reporting rate can be increased. Increasing the duration of the study was also the cheapest option and had the additional benefit of providing estimates of F for additional years.

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