CCAMLR Science, Vol. 12 (2005): 143–161

AN ALTERNATIVE METHOD FOR ESTIMATING THE LEVEL OF ILLEGAL FISHING USING SIMULATED SCALING METHODS ON DETECTED EFFORT

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Abstract

A new method for estimating illegal fishing effort is put forward. The results from this new method are similar to those of the Agnew and Kirkwood (2005) method, and this suggests that the current method is adequate under circumstances of low evasion and when good knowledge exists that zero observations reflect zero illegal fishing. The new method performs better in the case of zero detections and can potentially better handle the evasion of detection by illegal activity.

Both the new and the current method suffer from the fact that the observation method used directly affects the system. This is the prevention/detection problem, in which the greater the number of detections for a given level of illegal fishing, the more often the illegal fishers will curtail their fishing trips. This leads to a negative correlation between the amount of fishing and the estimated amount of fishing for a given number of illegal cruises.

As the number of illegal cruises increases, both the estimate and the average amount of illegal fishing increase. This gives some confidence that the method can produce results that have a degree of legitimacy. However, the range of actual fishing (in the simulation datasets) for a given estimated level of fishing is very large. This range of uncertainty increases as the evasion rate increases.

This research suggests that it would be possible to calculate a precautionary assessment of illegal fishing such that the actual number of illegal fishing days is less than, or equal to, the precautionary assessment with some given level of confidence (for example 80%).

Résumé

Le présent document présente une nouvelle méthode d'estimation de l'effort de pêche illégal. Les résultats de cette méthode sont proches de ceux de la méthode d'Agnew et Kirkwood (2005), ce qui suggère que la méthode actuelle est adéquate dans des conditions de faible évasion et lorsqu'il est pratiquement certain que les observations nulles reflètent une pêche illégale nulle. La nouvelle méthode est plus performante dans le cas de détections nulles et peut mieux traiter les cas d'évasion de la détection d'activités illégales.

Tout comme celle qui est utilisée actuellement, la nouvelle méthode souffre du fait que la méthode d'observation suivie affecte directement le système. Il s'agit ici du problème de prévention/détection, à savoir que plus les détections sont nombreuses pour un niveau donné de pêche illégale, plus les pêcheurs illégaux auront tendance à écourter leurs sorties de pêche. Ceci entraîne une corrélation négative entre la quantité de pêche et la quantité de pêche qui avait été estimée pour un nombre donné de sorties de pêche illégales.

Lorsque le nombre de sorties illégales est en hausse, on assiste à une augmentation tant de l'estimation que du niveau moyen de pêche illégale. Ceci laisse entendre que la méthode peut produire des résultats qui ont un certain degré de légitimité. Pourtant, l'intervalle de pêche réelle (dans les jeux de données de la simulation) pour un niveau de pêche donné estimé est très étendu. Cet intervalle d'incertitude augmente au même rythme que le taux d'évasion.

La présente recherche laisse entendre qu'il serait possible de calculer une évaluation de précaution de la pêche illégale telle que le nombre réel de jours de pêche illégale soit inférieur ou égal à l'évaluation de précaution, pour un taux de confiance donné (disons 80%).

Резюме

Предлагается новый метод оценки усилия незаконного промысла. Результаты этого нового метода сходны с результатами, полученными по методу Агнью и Кирквуда (Agnew and Kirkwood, 2005), что свидетельствует об адекватности существующего метода в условиях низкого избежания и тогда, когда хорошо известно, что нулевые наблюдения отражают нулевой незаконный промысел. Новый метод работает лучше в случае нулевого обнаружения и потенциально может лучше учитывать избежание обнаружения при незаконной деятельности.

И новый, и существующий метод страдают от того, что используемый метод наблюдений непосредственно влияет на систему. Это – задача предотвращения/обнаружения, в которой чем больше количество обнаружений для заданного уровня незаконного промысла, тем чаще незаконные промысловики будут сокращать свои промысловые рейсы. Это приводит к отрицательной корреляции между уровнем промысла и оценочным уровнем промысла для заданного числа незаконных рейсов.

По мере роста числа незаконных рейсов и оценка, и средний уровень незаконного промысла растут. Это дает некоторую уверенность в том, что с помощью данного метода можно получить результаты, являющиеся в какой-то степени правомерными. Однако диапазон реального промысла (в наборах данных моделирования) для заданного оценочного уровня промысла является очень большим. Эта степень неопределенности растет по мере возрастания уровня избежания.

Данное исследование говорит о том, что можно рассчитать предохранительную оценку незаконного промысла, так чтобы фактическое число дней незаконного промысла было меньше или равно предохранительной оценке с некоторым заданным уровнем значимости (например, 80%).

Resumen

Se presenta un nuevo método para estimar el esfuerzo de pesca ilegal. Los resultados obtenidos con este nuevo método son similares a los obtenidos con el método de Agnew y Kirkwood (2005), lo que indica que el método actual resulta adecuado cuando existe baja evasión y se sabe con certeza que cero observaciones reflejan una pesca ilegal cero. El nuevo método funciona mejor en el caso de cero observaciones y podría tratar mejor la evasión en la detección de actividades ilegales.

El método de observación utilizado afecta directamente el sistema tanto en el nuevo método como en el método actual. Este es el problema de la prevención/detección, es decir, a medida que aumenta el número de detecciones para un nivel dado de pesca ilegal, los pescadores ilegales acortan más frecuentemente sus viajes de pesca. Esto conlleva a una correlación negativa entre la cantidad de pesca y la cantidad de pesca estimada para un número dado de viajes de pesca ilegal.

A medida que aumenta el número de viajes ilegales, tanto la estimación como el promedio de la pesca ilegal aumentan. Esto da cierta confianza en que el método puede producir resultados con cierto grado de validez. No obstante, la extensión de la pesca real (en los conjuntos de datos de simulación) para un nivel dado de pesca es muy amplio. Este margen de incertidumbre aumenta a medida que la tasa de evasión aumenta.

Este estudio sugiere que sería posible estimar con un cierto nivel de confianza (por ejemplo, 80%) un nivel precautorio de pesca ilegal tal que el número real de días de pesca ilegal sea menor que (o igual a) la estimación precautoria.

Keywords: IUU fishing, estimation of illegal/IUU fishing, encounter probability, simulation modelling, CCAMLR

Introduction

This paper considers methods which can convert a series of detections of illegal fishing effort into an estimation of the amount of illegal fishing which has occurred. The estimation can then be used to assess levels of catch, by-catch and incidental mortality which can be attributed to illegal fishing.

Illegal fishing is one component of IUU (illegal, unregulated and unreported) fishing. The assumptions within the modelling framework of this paper, particularly with regard to the behaviour of vessels when detected, mean that this method is particularly applied to illegal fishing. Thus, the term illegal fishing is used throughout this document.

In the simplest case one would like to determine how to scale the number of observations of illegal fishing to the total number of days of illegal fishing over the period of interest. A simple formula for this is:

$$F_{est} = Obs_{num} \times f_{obs} + f_{undetected} \qquad (1)$$

where F_{est} is the estimate of illegal fishing in days, Obs_{num} is the number of observations of illegal fishing, f_{obs} is the converting factor of illegal fishing days per observation and $f_{undetected}$ is the amount of illegal fishing which is not observed. For one definition of $f_{undetected}$ it could be incorporated into the multiplier f_{obs} provided that the number of observations is non-zero.

In this paper, the only type of observation considered here is that reported by a fishery patrol, although other observation platforms could be considered within this framework. The date of each observation of illegal fishing effort coupled with the pattern of fishery patrols is the main input data.

Estimating the amount of undetected illegal fishing is difficult, and the two methods described in this paper take two different approaches in dealing with this. The first method described in this paper is the Agnew and Kirkwood (2005) method, which uses a simulation model to incorporate undetected fishing into the primary multiplier (the equivalent of f_{obs} in equation 1). It also uses a method of weighting each observation depending on where it occurs in the time series and the pattern of fishery patrols.

Because it does not explicitly give a value to undetected fishing, but instead incorporates this into the scaling factor for the weighted observations, this method cannot be used in the case of zero detections. However, when there are more than zero detections it does account for the undetected as well as the detected activity.

This paper presents a new method which does allow an estimation of illegal fishing in the zero detection case. This method can be used directly to determine a simulation-based estimate of illegal fishing given a certain number of observations, or, alternatively, to determine an observation-dependent multiplier which is then used in the same way as the multiplier used in the Agnew and Kirkwood method.

This paper describes and compares the two methods. Both suffer from a problem related to observer interference in the system, called the 'prevention/detection' problem. This problem is also described and examined. The discussion section of the paper suggests methods for incorporating uncertainty into a precautionary estimate of illegal fishing.

The Agnew and Kirkwood method

Agnew and Kirkwood (2005) described how an estimated amount of illegal fishing, F_{est}, which occurs for a given set of observations for an area can be given by:

$$F_{est} = P \sum_i D_i \qquad (2)$$

where D_i is an estimation of the maximum fishing length in number of days associated with observation i. P is a simulation-based multiplier that converts the sum of maximum fishing estimates to an expected number of illegal fishing days.

D_i is derived from the data and is given by:

$$D_i = L_i - E_i \qquad (3)$$

Here, L_i is the time at which the next fishery patrol cruise covered the area of observation i and is theoretically the latest date at which the detected vessel could have been engaged in illegal fishing in the area. E_i is the date at which the previous fishery patrol cruise covered the area of observation i and is theoretically the earliest date on which the detected vessel could have been engaged in illegal fishing in the area. If there has been no previous cruise, or if there has been no subsequent cruise, then either L_i and/or E_i could be based on the latest or earliest dates on which it was possible to fish the area, or D_i could be set to some presumed maximum length of time that a vessel could have fished.

An important assumption in the calculation of D_i is that the previous and subsequent patrol vessels would have detected the illegal fisher with a probability of 1. It would be possible to correctly incorporate the probability that the illegal fisher could evade detection in the calculation of D_i although neither of the methods described in this paper implements such an incorporation.

A way of incorporating the probability of evasion or failure of detection by previous and/or subsequent patrol vessels would be to integrate over the year all vessels in the area which could have detected the illegal activity. This can be illustrated by firstly considering whether or not the illegal vessel had a chance of evading the previous patrol vessel. In this case the value of D_i is calculated:

$$D_i = O_1(L_i - E_1) + (1 - O_1)(L_i - E_2) \quad (4)$$

where O_1 is the probability that the previous vessel would have detected the illegal activity at time E_1, and E_2 is the previous possible detection time. This can be extended by an integration over the entire season using standard probability theory.

The calculation of D_i allows different observations to be given different weightings depending on the date of detection as well as the local temporal pattern of fishery patrols. In order to turn these weightings back into an estimate of the illegal fishing level they are multiplied by the simulation-derived P as in equation 2.

Simulation assessment model

The simulation assessment model presented here is based upon the Agnew and Kirkwood (2005) method. In the simulation model a large number of illegal fishing operations are individually simulated. The number of detections, the number of days illegally fished and values for D_i, the estimated maximum days fished for each detection, are recorded.

The main inputs to the simulation model are:

(i) the schedule of fishery patrol vessels (when they arrive and depart);

(ii) the characteristics of the illegal fishing cruises including:

- earliest and latest start dates for a fishing cruise;
- distribution of planned cruise duration;
- response function in the case of detection. This is the method used to determine how and if the planned illegal cruise is curtailed if its activities are detected.

In each simulation the model creates an illegal fishing trip. The trip will have a random starting time which is chosen from a uniform random distribution with a given earliest and latest starting date. That is:

$$IUU_{start,j} = Uniform(IUU_{earliest}, IUU_{latest}) \quad (5)$$

where $IUU_{start,j}$ is the starting time of a simulated illegal cruise j. $IUU_{earliest}$ and IUU_{latest} are controlling parameters.

The planned duration of a simulated trip j will be:

$$IUU_{duration,j} = Uniform(IUU_{shortest}, IUU_{longest}) \quad (6)$$

where $IUU_{shortest}$ and $IUU_{longest}$ are controlling parameters. This is the planned duration, but if the cruise is detected then a new departure time will be generated, as described below, which may curtail the duration of the cruise. In the system, a detection is usually the detection of fishing activity which is occurring, rather than a direct interception or sighting of the illegal vessel.

Once the starting and planned stopping time of the simulated cruise is generated, it is then compared with the schedule of fishery patrols. Starting with the earliest patrol, every time a patrol overlaps the illegal cruise there is a chance of detection. The assumption is that each patrol will cover the region once, so that there is only one date where the patrol has a chance of detecting the illegal cruise.

The detection chance then becomes:

$$DetectionChance = \frac{Overlap_{duration,k,j}}{Patrol_{duration,k}} \quad (7)$$

where $Overlap_{duration,k,j}$ is the length of overlap between patrol cruise k and simulated illegal cruise j, $Patrol_{duration,k}$ is the total duration of patrol cruise k.

In the Agnew and Kirkwood method it was assumed that there was a probability of 1 that a patrol vessel would detect illegal fishing effort if it travelled to the right location during the period of the illegal fishing cruise. A probability that the illegal vessel can evade detection can be incorporated in equation 7. If the probability of evasion is $P_{evasion}$ then the equation becomes:

$$DetectionChance = \frac{Overlap_{duration,k,j}}{Patrol_{duration,k}}(1 - P_{evasion}) \quad (8)$$

It should be noted that without loss of generality it would be possible to include a search area in this equation. For example, if the patrol only covers half the fishable region and there is only a 50% chance that it will cover the area that the simulated illegal fisher is operating in, assuming that the illegal fisher has no knowledge of which area will be covered. Multiplying the above detection chance by 0.5 is the same as multiplying the base detection probability ($1 - P_{evasion}$) by 0.5. Limited patrols can be simulated by changing the base detection chance. If both evasion and area cover by patrol were to be tested it would be useful to separate the factors in equation 8.

Once the detection chance is determined, a random number (between 0 and 1) is generated to determine if the vessel is detected. In the simulations in this paper the patrol cruises never overlap: if they did, then it would be important to determine which cruise had the first point of possible detection, because if the illegal vessel is detected there is a chance that it will change its behaviour.

If the illegal vessel is detected, then the detection is added to the total number of detections in the simulation and the date of detection is determined, which is at a random date during the period of overlap. This is used to generate the simulated D_j which is the simulated estimated maximum fishing time associated with that vessel, assuming that the previous and subsequent patrols would have detected the vessel when they were in the same area.

$$D_j = L_j - E_j \quad (9)$$

This follows the same form as the calculated D_j except that here, L_j is the randomly determined time within the previous patrol cruise where the patrol was in the same area, and likewise E_j is the randomly determined time within the subsequent patrol cruise when the patrol was in the same area.

If the cruise on which the detection occurred was either the first or the last of the patrol schedule, then D_j is set to a default maximum of 60 days.

If the illegal fishing cruise was detected, then there is a chance that its stopping time will be changed. It might decide to leave earlier than was originally planned. Following Agnew and Kirkwood, a new potential departure date, which is a random date between the next fishery patrol cruise and the detection time, is generated. If this new departure date is sooner than the original plan then it will be taken, but if it is later, then the original plan is followed. This simulates a system in which illegal fishers will tend to curtail their fishing, but if they are near the end of their trip they may continue, particularly if the detection does not involve a sighting of the actual illegal fishing vessel, but instead the detection of evidence of illegal fishing, such as the presence of fishing lines. This method has the computational advantage that each illegal cruise can be detected only once.

Having determined a value for D_j for each detection, and the amount of fishing associated with each simulated cruise F_i whether it was detected or not, it is then possible to calculate the desired multiplier P:

$$P = \frac{\sum_i F_i}{\sum_i D_i} \quad (10)$$

Note that $\sum_i F_i$ includes both detected and undetected illegal fishing effort so that the multiplier P then incorporates a level of undetected illegal fishing effort. Because this is used in equation 2 to multiply the sum of the actual maximum fishing efforts (D_j), it will always produce a result of zero when there are no detections.

One of the features of the new method presented here is that it can give an estimate of the level of fishing associated with zero detections.

The new method

The new method reverses the problem by asking what the expected level of illegal fishing associated with a given number of detections might be. It can also be used to determine a value for P which is used in the same manner as the Agnew and Kirkwood method (in equation 2).

This method uses a number of sets of simulations. Each set of simulations has a different number of illegal fishing cruises, each acting independently, starting from the bare minimum number of cruises which could rise to the actual number of detections, and rising up to an arbitrarily large number of cruises. The sets of simulations should cover all possible numbers of illegal cruises for which there is some minimal probability of obtaining the actual number of detections. For example, if there are three detections within a time period then the starting set of simulations would have three illegal cruises, the next would have four and so on until there are so many cruises that the chance of producing only three detections is 0.001% or less.

From this we can then determine the expected amount of fishing or an appropriate multiplier P given the number of detections.

For a given number of detections Obs_{num} the appropriate value to use for P is:

$$P = \sum_{j=Obs_{num}}^{\infty} pr(v = j \mid Obs_{num}) D_j \qquad (11)$$

where $pr(v = j \mid Obs_{num})$ is the probability that the number of illegal cruises $v = j$, given that the number of detections was Obs_{num}. This is calculated by:

$$pr(v = j \mid Obs_{num}) = \frac{f_{Obs,j}}{\sum_i f_{Obs,j}} \qquad (12)$$

Here $f_{Obs,j}$ is the number of simulations in set j (i.e. the set with j cruises) which had Obs_{num} detections. For example, with j of 5 and Obs_{num} of 2 this would be the number of simulations with five illegal cruises in which there were exactly two detections.

Hence $pr(v = j \mid Obs_{num})$ is the number of simulations in set j which had Obs_{num} detections divided by the total number of simulations in all sets which had Obs_{num} detections.

An alternative is to bypass the use of the multiplier P and use this method directly to get an estimate of the number of days fished. This gives

$$F_{est} = \sum_{j=Obs}^{\infty} pr(v = j \mid Obs_{num}) F_j \qquad (13)$$

where F_{est} is the number of days fishing to be attributed to the given level of detections.

This is the equation which needs to be used when the number of observations is zero. When the number of observations is greater than zero, P is calculated using equation 11 and this is applied as per equation 2.

In this study, equation 11 is used in order to compare the P produced in this method to the one produced using the Agnew and Kirkwood method. Some preliminary tests suggested that the use of equation 13 for observations greater than zero does not qualitatively affect the results of the method, but further work is warranted.

Experiments

The simulation model described above was used as the basis for creating a simulated dataset against which these methods could be tested. The use of this simulated dataset allowed a comparison to be made between a dataset with known dynamics and values, and estimations of that dataset.

One patrol boat schedule was used in most of the simulations. This patrol boat schedule has six patrols starting every 30 days and lasting for 16 days. All dates are given in number of days from some arbitrary starting day.

Alternative schedules were explored to look at the effects of different levels of fishery patrol coverage on the predictive ability of the models. In these schedules the regularity of the patrols was maintained but the number and duration was reduced. There were four alternatives tested:

- 10% coverage – one patrol of 10 days in each 100 day period;
- 25% coverage – 15-day patrols covering a quarter of the period;
- 35% coverage – 15-day patrols covering 35% of the period;
- 50% coverage – this is the basic patrol schedule shown in Table 1.

The illegal vessels arrived no earlier than day 1 and no later than day 200. The planned illegal cruise duration was between 40 and 60 days.

The illegal cruises were entirely independent from each other. This assumption allows the use of the same method as the simulation method to generate a given number of independent illegal fishing cruises.

An individual simulation consists of placing a number of illegal cruises into the model. These

Table 1: Basic fishery patrol vessel schedule. Starting and ending dates are the first and last days on which the vessel is patrolling the region.

Vessel	Starting date	Ending date
One	30	44
Two	60	74
Three	90	104
Four	120	134
Five	150	164
Six	180	195

Table 2: A comparison of the calculated value *P* between the different methods. The original Agnew and Kirkwood method assumed an evasion probability of 0, the modified method relaxes this assumption by applying equation 8. In the new method the multiplier depends on both the evasion parameter and the number of detections. The ranges in the 'New method' column covers the cases of 1 to 20 detections. When there are zero detections, then the new method uses equation 13 to determine expected illegal fishing and *P* is not used. The ranges presented in column 3 represent the entire range of estimates for that level of evasion to two decimal places.

Evasion	Multiplier *P*		
	Agnew and Kirkwood method	Modified Agnew and Kirkwood method	New method
0	0.19	0.19	0.22–0.23
0.2	N/A	0.25	0.27–0.28
0.5	N/A	0.37	0.43
0.8	N/A	0.99	1.06

cruises operate, are possibly detected and possibly curtail their fishing cruise in response to detection, completely independently of all other illegal cruises. The cruises are modelled using the same operating assumptions as assumed by the Agnew and Kirkwood method described above. The actual number of fishing days is recorded, along with the number of detection events which occurred and the estimation of *D*, the total maximum fishing length associated with each detection event. This allowed the calculation of the estimated number of fishing days for that simulation. To estimate the number of fishing days associated with the set of detections, *P* is calculated using the simulation described above. The calculation of *P* uses the same parameters controlling the behaviour of the illegal cruises as was used in each actual simulation.

Results

Most of the datasets were created using the Agnew and Kirkwood method modified to incorporate evasion probability, except for the comparison of calculations for *P* displayed in Table 2. The results suggested that the two methods produced largely qualitatively similar outputs (see above).

Discussion

The new method produced results which were fairly similar to the Agnew and Kirkwood method (Figure 1). Although the new method depends on the number of detections as well as the level of evasion, the range which is produced by different numbers of detections is very narrow (see Table 2). This means that the results differ primarily by the multiplier that is used and so the results are qualitatively similar, but the estimates of illegal activity are higher (and hence more conservative) using the new method.

One of the advantages of the new method is that it allows an estimation of illegal fishing to be made in years in which there are no detections. It can often be the case that an absence of detections is due to qualitatively different behaviour in the illegal fishers, namely that they have stopped fishing there. An absence of detections could possibly be due to a decrease in the amount of effort put into detections. If there is no external evidence to suggest a sudden change in behaviour, then it is natural to assume that they are behaving the same way in those years but that luck has been on their side. The new method allows an estimation to be made of the expected level of illegal fishing under these circumstances, which become more likely with sparser patrols and higher levels of evasion (Figure 5).

One of the key results to be derived from Table 2 is the importance of accurately determining the level of evasion. It is very difficult to determine accurately the actual evasion probability. However, an incorrect assessment of the level of evasion would give a significantly large error in the calculation of P even when there is a high level of patrol coverage.

Both the Agnew and Kirkwood and the new method suffer from the prevention/detection problem. This problem is exhibited in Figures 2 to 5. The problem arises because the observations of the system affect the system directly. Because illegal cruises will tend to curtail activities once they are detected, the more detections there are (for a given number of illegal fishing cruises), the more the cruises will tend to be curtailed. Also the more detections there are, the greater will be the estimated level of illegal fishing. This means that for a given number of illegal cruises there is a negative correlation between the estimate of illegal fishing and the actual amount of illegal fishing under all the tested circumstances. In all cases in Figures 2 to 5 there is a negative correlation between the calculated and the actual amount of illegal fishing.

Figure 6 demonstrates what occurs in the absence of the prevention/detection problem. In the simulations which make up the graphs in this figure, the illegal cruises do not respond to being detected at all, but act as if they were not detected. The variation in the amount of fishing which actually occurs is due to the probability distribution function which controls the planned length of the illegal fishing cruises. There is still considerable variation in the estimate of the amount of fishing which occurs, even when there is zero evasion. Here, for example, when the simulated days fished lies between 220 and 270, the estimates range primarily between 100 and 400 with virtually no correlation.

Figure 7, however, suggests that there is still some merit in using these methods. As the number of cruises increases, both the actual amount and the estimate of fishing increase. It implies that it might be possible to use a likelihood method to determine a precautionary assessment of the level of illegal fishing.

A suitable precautionary assessment of illegal fishing would be the value such that the actual number of illegal fishing days is less than, or equal to, the precautionary value with some given level of confidence (for example 80%). Figure 7 suggests the basis on which such an assessment could be calculated.

Figure 8 demonstrates the effect of different levels of coverage in the case in which there are 10 illegal cruises acting in the fishery and an evasion level of 0. As the level of coverage increases, the amount of illegal fishing decreases. Above some threshold level of coverage, the estimated amount of illegal activity does not increase appreciably. In the simulations in this paper this was a 25% level of coverage, when evasion was 0. The lowest level of detection corresponds to 10% coverage by only two fishery patrols. Figure 5 indicates that when the level of coverage is low, the issue of evasion increases in importance. With evasion levels of 0.2 and 0.5 in simulations with only five illegal cruises, the estimate of illegal activity bears little resemblance to the level of actual illegal activity in the simulations.

Further work

In all the simulations examined here, the parameters used in the simulation are the same as those used to generate the data against which the method is tested. A key question as to the robustness of the method is how poorly it would do if the assumptions about how the illegal fishers were behaving were incorrect in various ways. Obvious elements to test would be the average planned illegal fishing cruise length (as done in Agnew and Kirkwood, 2005) and the estimation of the probability of evasion.

Some of the extensions discussed in the model description should be implemented for further work. These include the routine use of equation 13 to bypass the calculation of the multiplier P, which was not used in this paper, so as to facilitate comparison between the different methods. Also the more complete calculation of illegal fishing trip length to replace equation 4 could be implemented.

It is not expected that either of these additions would make a qualitative difference to the output of the model.

The method presented in this paper could be extended to include other types of observational regimes. This could include sightings from other commercial vessels operating in the fishery or opportunistic sightings from other vessels passing through the area. Extending the methods in this manner would increase the level of coverage that could be assumed, although it would raise further issues in establishing effective coverage and vessel-based evasion probabilities.

Conclusions

A new method for estimating illegal fishing effort is put forward. The results from this new method are similar to those of the Agnew and Kirkwood (2005) method, and this suggests that the current method is adequate under circumstances of low evasion and when good knowledge exists that zero observations reflect zero illegal fishing. The new method performs better in the case of zero detections and can potentially better handle the evasion of detection by illegal activity.

However, both the new method and the Agnew and Kirkwood method suffer from the type of observation method used, which directly affects the system. This leads to a negative correlation between the amount of fishing and the estimated amount of fishing for a given number of illegal cruises. Fundamental to the use of these methods is an understanding of the degree to which this problem can be mitigated through a better understanding of the behaviour of illegal fishing vessels.

As the number of illegal cruises increases, both the estimate and the average amount of illegal fishing increase. This gives some confidence that the method can produce results that have a degree of legitimacy. However, the range of actual fishing (in the simulation datasets) for a given estimated level of fishing is very large. This range of uncertainty increases as the evasion rate increases.

This research suggests that it would be possible to calculate a precautionary assessment of illegal fishing such that the actual number of illegal fishing days is less than, or equal to, the precautionary estimate with some given level of confidence (for example 80%).

This research indicates that there is a minimum level of patrol coverage below which the results are particularly poor. In the ideal case, the results improved much more gradually when there were patrol vessels present more than 25% of the time. However, when the evasion ability was greater than 0, even having vessels present 50% of the time, or more frequently, might not be sufficient. The testing of patrol coverage levels under adverse assumptions remains to be explored.

All this research is predicated on a simulation model which accurately reflects the behaviour of the illegal fishers. Understanding and modelling the actual and potential evasive behaviour of illegal vessels and illegal fleets is an obvious priority. It remains to be seen how robust these methods are when inaccurate estimations are made of the behaviour of the illegal fishers.

Acknowledgements

The author is grateful for the detailed comments and suggestions on this research project given to him by Andrew Constable, Steve Candy and Campbell Davis. In particular he wishes to acknowledge the help that Steve Candy provided in formulating the new method presented in this paper. He would also like to thank his anonymous reviewers for their extensive and useful comments.

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Agnew, D.J. and G.P. Kirkwood. 2005. A statistical method for estimating the level of IUU fishing: application to CCAMLR Subarea 48.3. *CCAMLR Science*, 12: 119–141 (this volume).

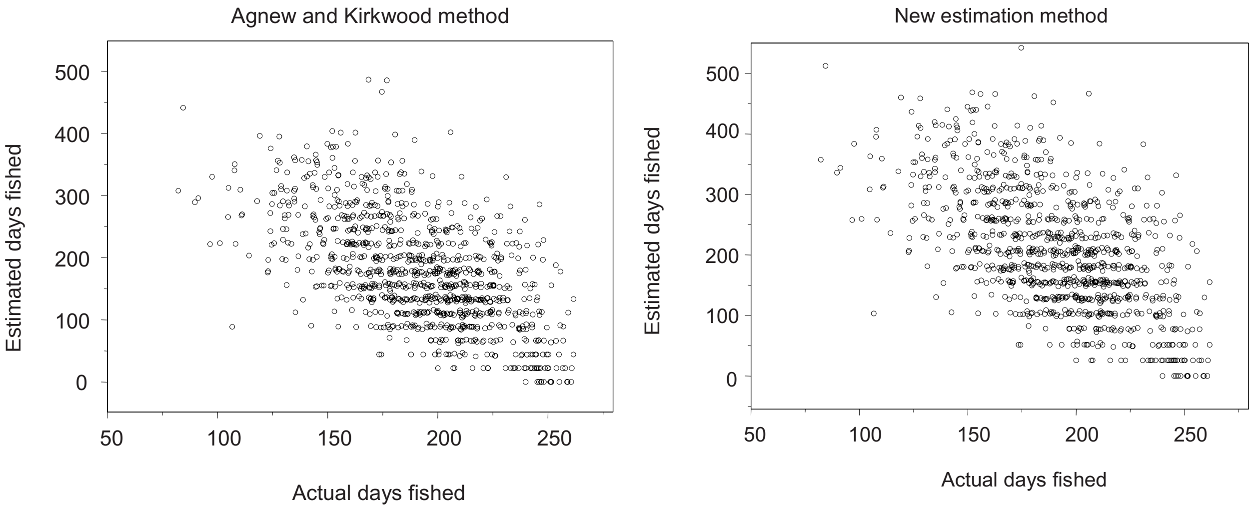


Figure 1: Comparison of the Agnew and Kirkwood (2005) method with the new method. This graph displays the results of 1 000 simulations showing the correlation between the estimation of the days of illegal fishing in each simulation against the actual days of illegal fishing in the simulation. In each simulation there were five cruises and an evasion level of 0.5. Note that they are identical except for a slight scaling factor.

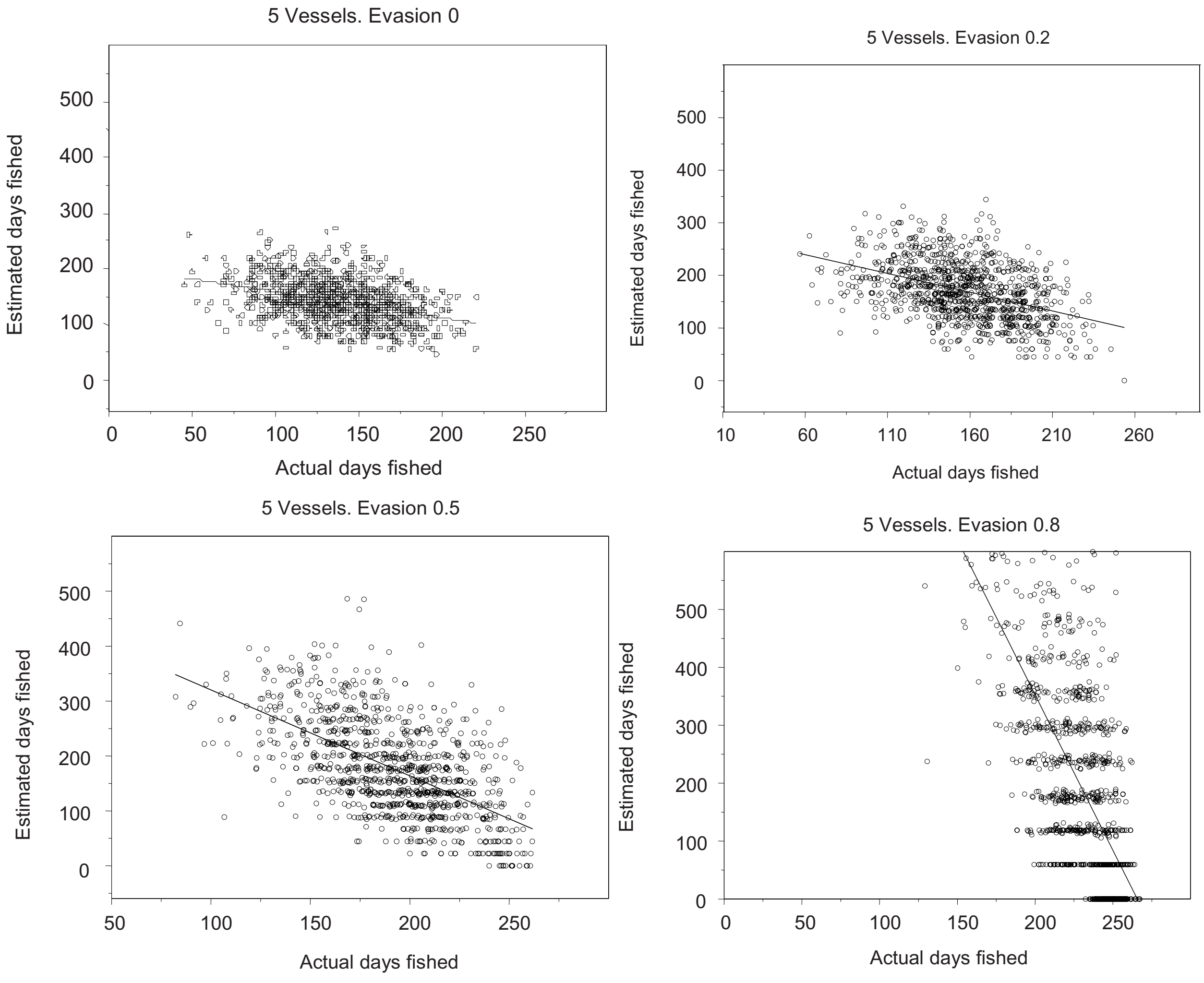


Figure 2: Five cruise simulations. Each of the graphs represents the response to a different level of evasion for the five cruise simulations. The line is a linear least-squares fit to the data. The estimation method is that of Agnew and Kirkwood (2005).

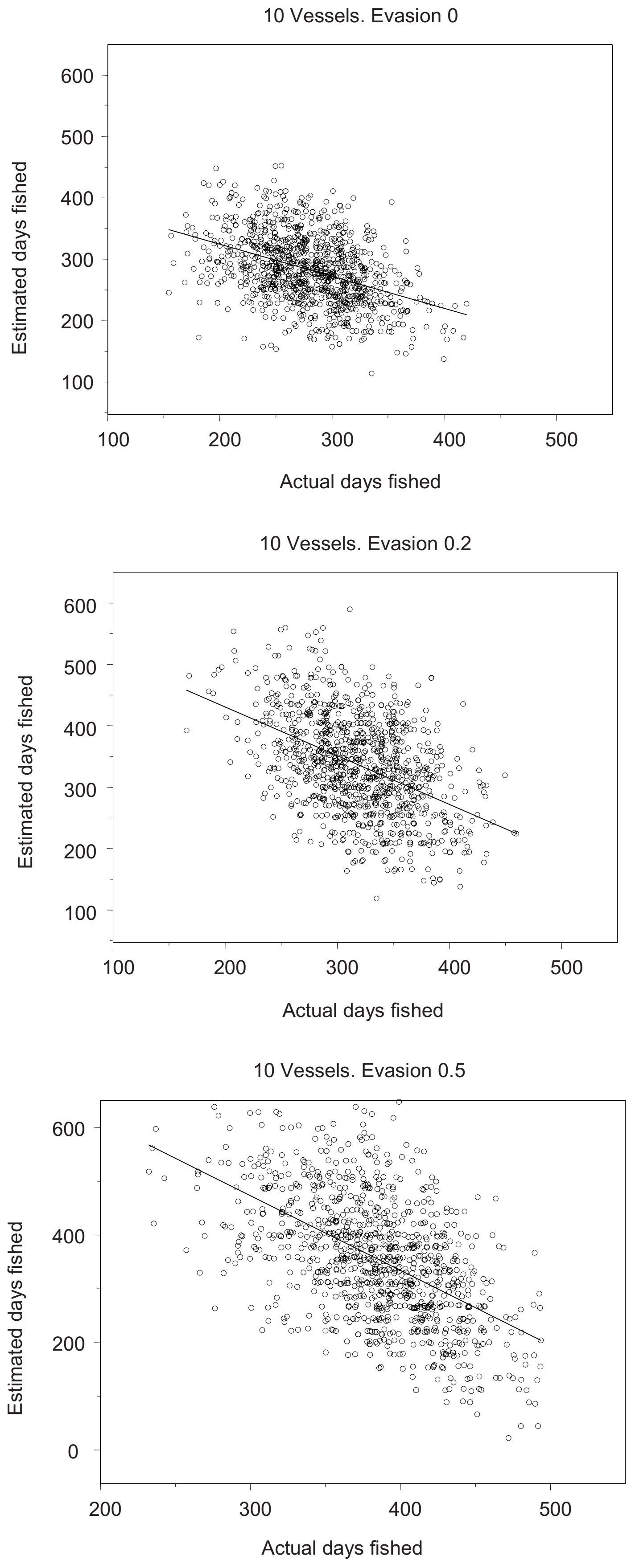


Figure 3: Ten illegal fishing cruises with different levels of evasion (0, 0.2 and 0.5) with linear least-squares fit. The estimation method is that of Agnew and Kirkwood (2005).

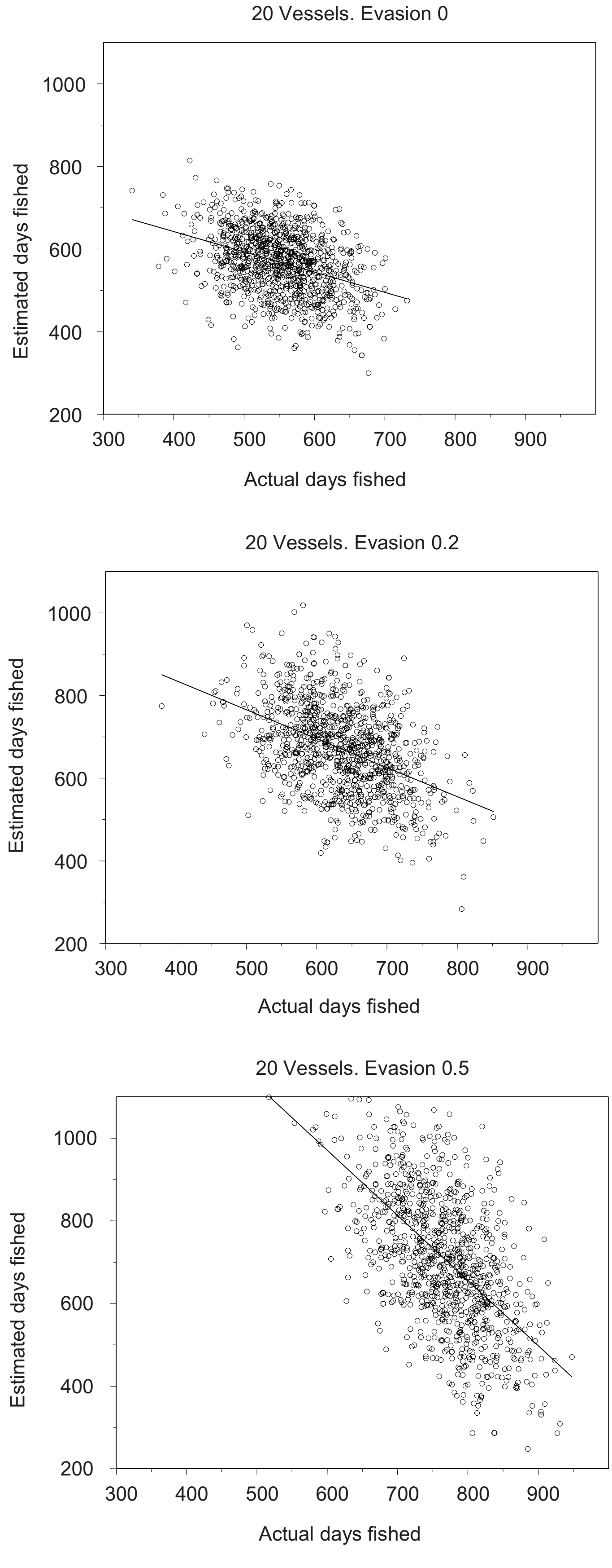
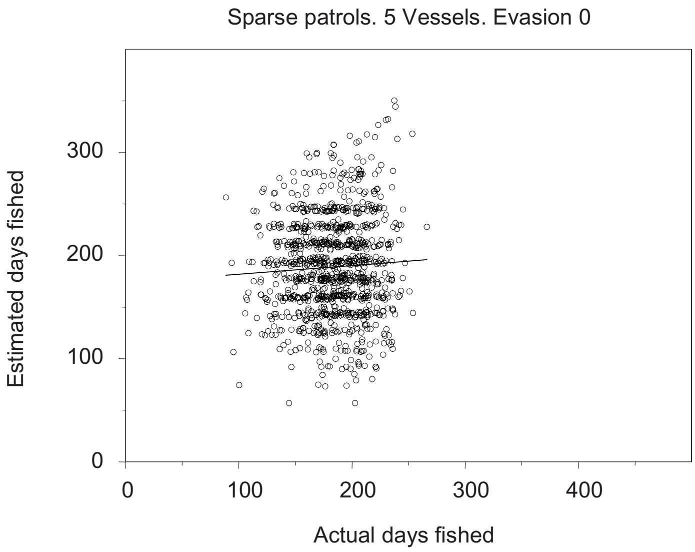
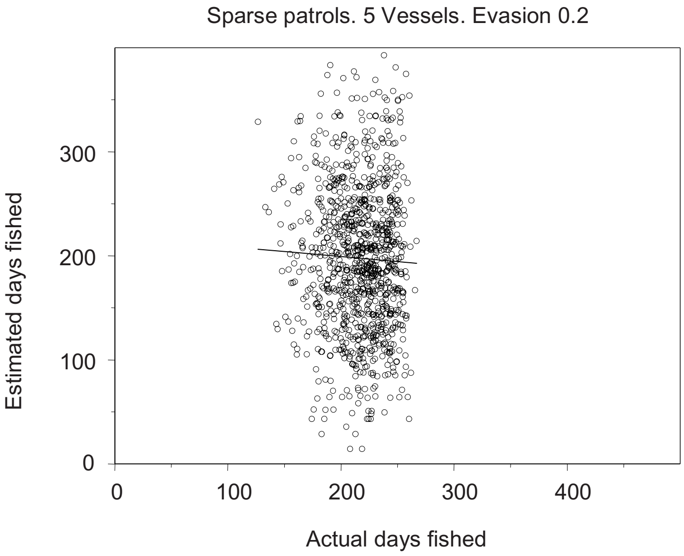


Figure 4: Twenty illegal fishing cruises with different evasion probabilities (0, 0.2 and 0.5) with linear least-squares fit. The estimation method is that of Agnew and Kirkwood (2005).





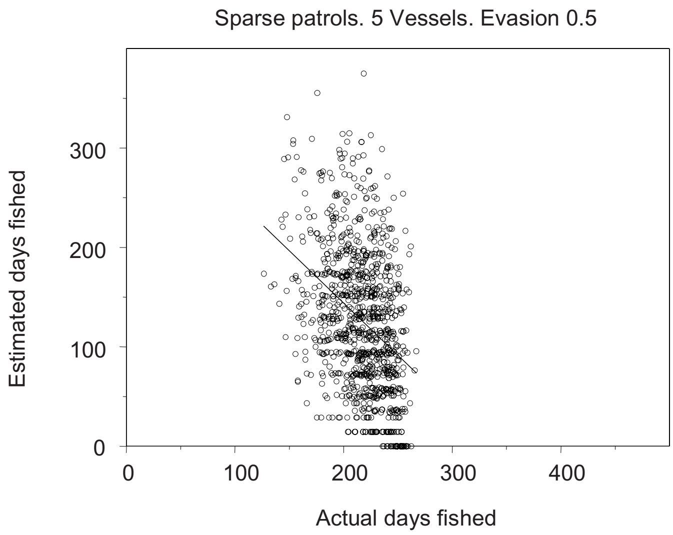
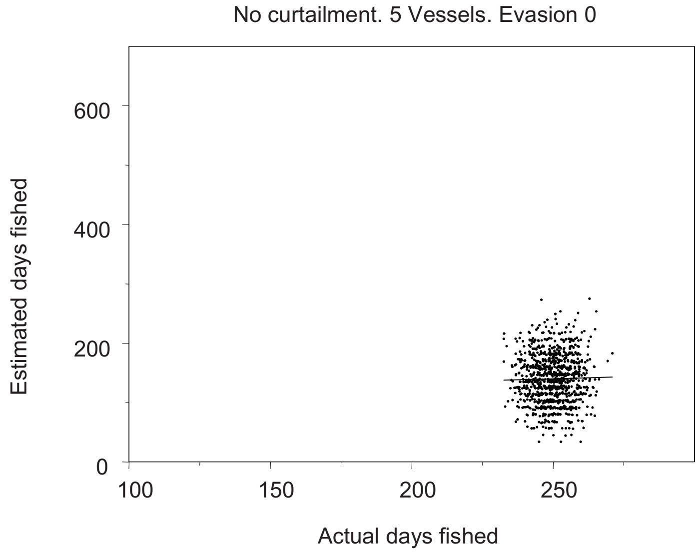
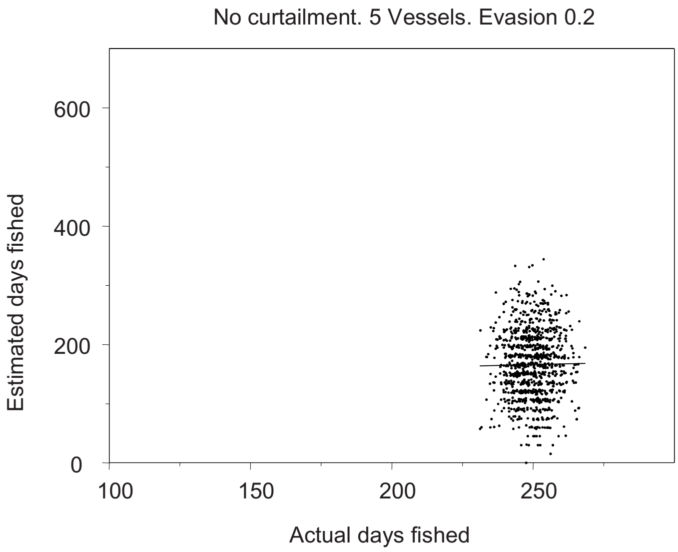
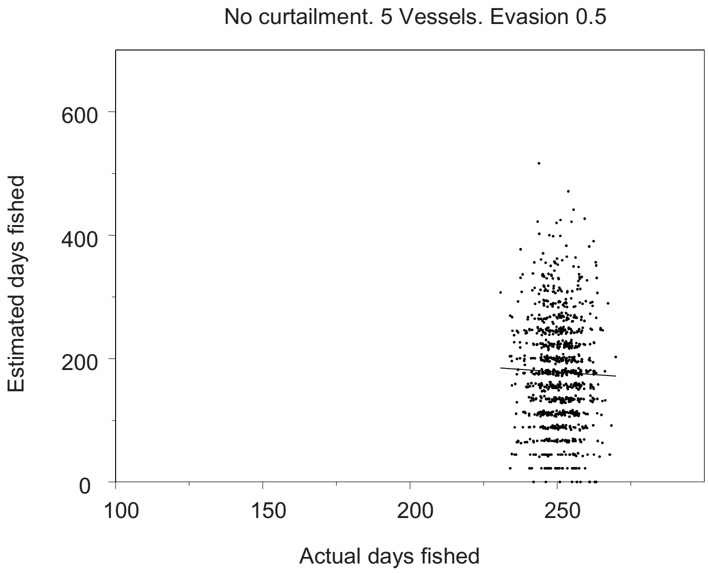


Figure 5: The sparse patrol schedule. Each graph shows the results from 1 000 simulations of five cruises with varying levels of evasion (0, 0.2 and 0.5) with linear least-squares fit. The estimation method is that of Agnew and Kirkwood (2005).







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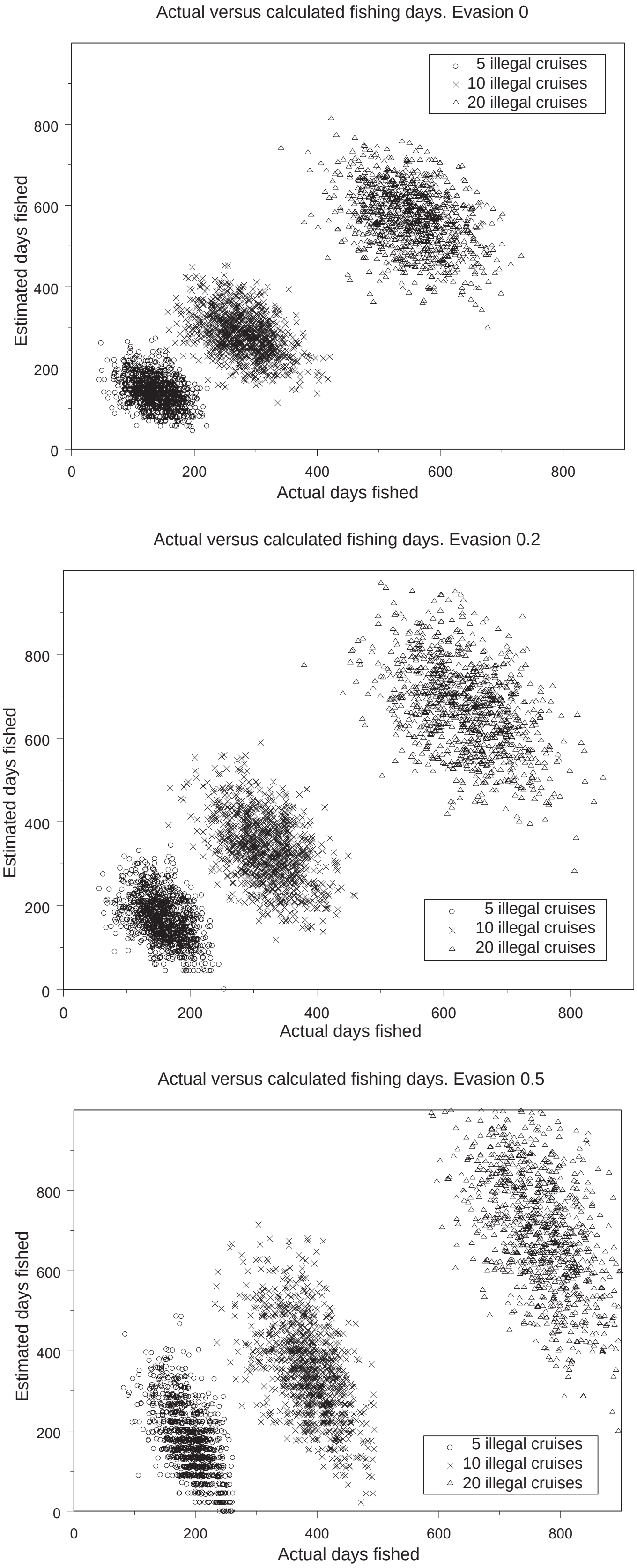
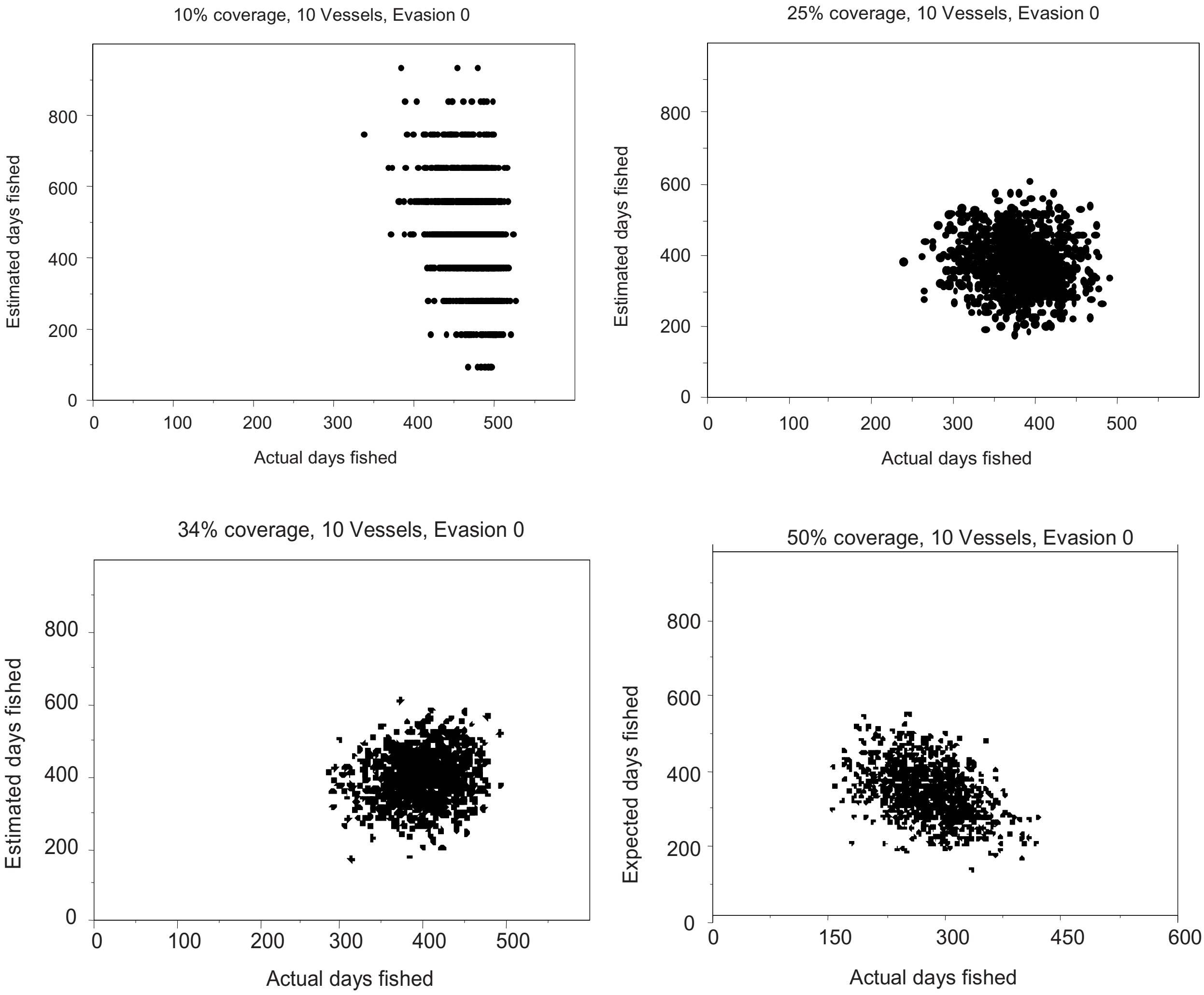


Figure 7: Combined graphs, different cruises but the same evasion probability. The graphs in this figure combine the appropriate graphs from Figures 1, 2 and 3. The plots in this graph are presented as different shapes to indicate that they are qualitatively different. The estimation method is that of Agnew and Kirkwood (2005).



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