

Can vessel monitoring system data also be used to study trawling intensity and population depletion? The example of Australia's northern prawn fishery

Roy Deng, Cathy Dichmont, David Milton, Mick Haywood, David Vance, Natasha Hall, and David Die

Abstract: We explore the potential of using data from Australia's northern prawn fishery (NPF) vessel monitoring system(s) (VMS) to examine trawl track, trawling intensity, and stock depletion due to trawling. We simulate VMS data by subsampling global positioning system (GPS) fixes from the NPF fishing vessels at different polling intervals to examine their accuracy in describing trawl tracks. The results of the simulations suggest that VMS data with polling intervals longer than 30 min cannot accurately estimate trawl tracks. The analysis of high-polling-frequency VMS data collected in four (later reduced to three) 6 nautical mile \times 6 nautical mile grids that historically received high levels of fishing effort showed that trawling was not random and some areas were trawled up to 28 times in the tiger prawn fishing season and the impact varied among years. The results of a catch-depletion analysis suggest that fishery catch-per-unit-effort and cumulative catch may not be proportional to overall target-species biomass in areas with highly aggregated trawl effort. The VMS data also showed a large number of trawls can occur in productive areas and that trawling impacts on benthos may be quite marked.

Résumé : Nous examinons la possibilité d'utiliser les données de du système de surveillance des navires (VMS) de la pêche crevette du nord de l'Australie (NPF) pour étudier les pistes de chalutage, l'intensité du chalutage et l'épuisement des stocks dû au chalutage. Nous simulons les données VMS en sous-échantillonnant les coordonnées des navires de pêche NPF obtenues par le système de positionnement global (GPS) à différents intervalles d'échantillonnage afin de déterminer leur précision pour décrire les pistes de chalutage. Les résultats de nos simulations indiquent que des données VMS basées sur des intervalles d'échantillonnage supérieurs à 30 min ne permettent pas d'estimer correctement les pistes de chalutage. L'analyse de données VMS échantillonnées à fréquence plus élevée (HPF) obtenues sur quatre grilles (réduites subséquemment à trois) de 6 \times 6 milles marins, qui ont, dans le passé, traditionnellement été soumises à des pressions de pêche élevées, montre que le chalutage ne se fait pas au hasard et que certaines régions sont soumises à jusqu'à 28 fois au chalutage durant la saison de pêche de la crevette tigrée et que l'impact varie d'une année à l'autre. Les résultats d'une analyse d'épuisement des captures indiquent que les captures par unité d'effort de cette pêche et les captures cumulées peuvent ne pas être proportionnelles à la biomasse globale de l'espèce visée dans les régions où l'importance du chalutage est fortement concentrée. Les données VMS montrent aussi qu'il peut se produire un important chalutage dans les zones productives et que les impacts du chalutage sur le benthos peuvent être très considérables.

[Traduit par la Rédaction]

Introduction

Current prawn (shrimp) stock assessment models do not explicitly take into account small-scale spatial variation in prawn distribution (Fu and Quinn 2000; Dichmont et al. 2003). Most stock assessments assume that fishing effort is randomly distributed within the known fishing grounds

(Hilborn and Walters 1992). However, with the advent and wide use of vessel monitoring system(s) (VMS) in many fisheries, there is great potential to utilize the VMS data to improve spatially explicit fishery models (Die and Ellis 1999). If prawn trawling is nonrandom and aggregated in areas of high abundance of the target species, it is possible that catch-per-unit-effort (CPUE) is not proportional to over-

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all biomass. This may affect the management advice that is given on the basis of the target-species assessments. As well, studies through the world are showing that the seabed can be repeatedly trawled each year (Rijnsdorp et al. 1998; Schratzberger and Jennings 2002). The impacts of repeated trawling are cumulative and vary among taxa (Poiner et al. 1998; Tanner 2003). Some benthic fauna, such as sponges, might be severely impacted by a single trawl, whilst others (algae, bryozoans, Pennatulacea) might be able to withstand several repeated trawls, but their vulnerability increases with successive trawls (Poiner et al. 1998).

VMS data may also be useful in assessing the effects of trawling on the benthic communities throughout a fishery. To date, these effects have been examined mainly at a small scale with experimental manipulations. This is due to the fact that most experiments are only cost effective at a scale of a few square kilometres. For example, Poiner et al. (1998) repeatedly trawled six 2.7 km long and 30 m wide tracks in the Great Barrier Reef region to simulate commercial fishing of the same ground. In this case we may be able to use VMS data to link these small-scale experiments at a single time with fishery-wide trawl effects over several years.

The northern prawn fishery (NPF) is the most valuable nationally managed trawl fishery in Australia and covers about 800 000 km² of northern Australian waters. At the end of 2002, about 100 trawlers were operating in the NPF and caught about 4600 t of banana prawns (*Penaeus merguensis* and *Penaeus indicus*) and 2000 t of tiger prawns (*Penaeus esculentus* and *Penaeus semisulcatus*). Trawl fisheries such as the NPF are coming under increasing pressure to demonstrate that their impacts on target and bycatch species and on the benthic communities are sustainable. This requires an understanding of the distribution and scale of trawl effort (Poiner et al. 1998; Tuck et al. 1998).

The fishing methods used to capture banana and tiger prawns are quite different. In the NPF, banana prawns form dense aggregations visible as muddy stains from the air where their position is recorded by fishing company spotter planes or on the fishing vessel's echo sounders. These aggregations are fished intensively during daylight for the first couple of weeks of the fishing season each year (April). When catch rates decline to a level where it is no longer economically viable to continue fishing for banana prawns, the fishers switch to targeting tiger prawns. Tiger prawns do not aggregate to the same degree as banana prawns and are generally only catchable by demersal trawl gear at night, when they are active. During daylight, tiger prawns tend to bury themselves in the substrate.

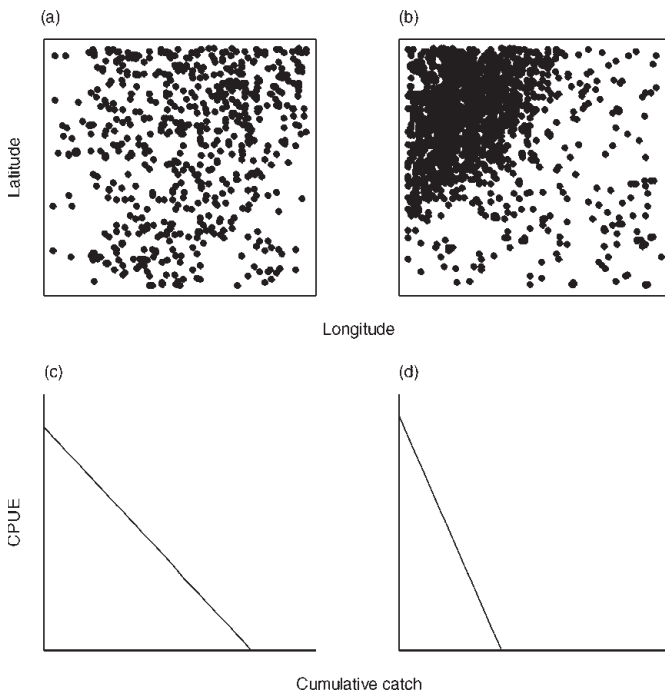
Although tiger prawns do not form dense schools like banana prawns, their distribution across the seabed is not uniform and the fishers employ a searching strategy to enable them to identify and target areas of high tiger prawn abundance. NPF fishing vessels are equipped with twin otter trawls and when fishing for tiger prawns, a single trawling operation lasts between 3 and 4 h. A small (4 m head rope length) beam or otter trawl known as try gear is generally operated between the two main fishing nets. The try gear is retrieved every 30–40 min, allowing the fishers to monitor their catch rates without retrieving the main gear. When they are satisfied with the catch rate from the try gear they will

turn the vessel around and retrace the vessel's track, hoping to reproduce or better the catch rate. This practice is facilitated by the use of a global positioning system (GPS) and plotters that record the vessel's position every minute and allow the fishers to annotate their electronic charts, recording prawn catches, areas of untrawlable ground, or places that have produced high catches. The GPS and plotter technology, which was introduced into this fishery in 1998, has increased fishing power in this fishery significantly (Robins et al. 1998).

Satellite-based VMS technology has been operating in fisheries around the world for several years (Drouin 2001). It was mainly introduced as a surveillance system to ensure that fishers comply with seasonal and spatial closures (Australian Fisheries Management Authorities (AFMA) website: <http://www.afma.gov.au/>). However, it has potential uses in assessing stock and evaluating the ecosystem impacts of trawling. The approach developed for the NPF would be applicable to most trawl fisheries in other countries. VMS provides trawl location data at greater spatial resolution than those that could normally be collected from logbooks. Potentially, these data could be applied to problems at both fine and coarse scales, thus bridging the gap between small-scale environmental-impact studies and fishery-wide stock assessment. Similarly, GPS is now widely used throughout many fisheries. Robins et al. (1998) found that the use of GPS and plotter systems has increased the catch of prawn trawl fisheries by enabling the fishers to target schools more accurately. Because coarser VMS data can be treated as a subset of the finer GPS data set, GPS data are a critical data source for examining the accuracy of trawl tracks through simulation of VMS data.

VMS data can be used to assess a potential environmental or fishery impact and determine its spatial extent. One of our objectives is to evaluate the capacity of VMS data to be incorporated into spatial aspects of applied fisheries research in the NPF tiger prawn fishery. As VMS data are mainly designed for surveillance purposes, the polling frequency varies widely among fisheries. We need to examine VMS to find the lowest polling frequency that can be used to describe the trawl track without significant bias. Another objective is to apply VMS data to stock assessment and evaluation of trawling impacts. A potential use of VMS data is in population-depletion analysis to estimate population size or better define fishery assessment model parameters by linking trawl position with logbook catch data. Many current stock-assessment models assume that target-species CPUE is linearly proportional to biomass (Hilborn and Walters 1992). This may not be the case in these highly aggregated and intensively fished areas. The catch or CPUE of trawl fisheries can be affected by gear saturation, where fishers negatively impact each other's CPUE by fishing intensively in a small area. On the other hand, in highly aggregatory species this linearity between CPUE and biomass can also be affected because fishers can maintain a high CPUE by continuing to move and to target aggregations, although the overall abundance of the stock may be decreasing. Therefore, we wanted to test the hypothesis that the decline rate of the depletion curve in highly aggregated fishing areas is artificially higher or lower than that in randomly fished areas (Fig. 1).

Fig. 1. Expected types of fishing patterns in trawl fisheries. (a) Random: this plot shows all the vessel monitoring system(s) (VMS) records for one 6 nmi \times 6 nmi grid for August–September 1998. (b) Aggregated: this plot shows all the VMS records for another 6 nmi \times 6 nmi grid for August–September 1998. (c and d) The corresponding hypothesized rates of depletion of random and aggregated patterns, respectively, when it is assumed that catch-per-unit-effort (CPUE) is linearly related to biomass.



Materials and methods

To assess the feasibility of undertaking studies of trawling intensity with VMS data, there are several steps in the analysis. The different data sets and their resolution/coverage are described in Table 1. Initially, an acceptable approximation of each trawl track has to be identified by comparing tracks obtained from GPS data with simulated VMS fixes taken at a range of polling frequencies. Then high-polling-frequency VMS (HPFVMS) data were collected and used to calculate trawling intensity. Once this has been calculated, the vessel logbook catch records have to be matched with the trawl tracks in order to undertake a population-depletion analysis. In this case, the coverage of the HPFVMS data was too small, so the standard-frequency VMS data needed to be joined to the data set.

We define one trawl track as one vessel trawling during a single night, as the NPF in the relevant period is a nighttime trawl fishery. An onboard GPS can provide positional data at high frequency (e.g., 1–5 s) and a set of fine-scale GPS records from a trawler can be treated as a continuous trawl track. Since GPS data from past trawls are a valuable record, they are usually retained by the skipper and are not freely available. A few skippers have made their GPS data available to us. These positional data are recorded at intervals of approximately 100 m (equivalent to approximately 1 min at

a trawling speed of 3 kn (1 kn = 1.85 km/h)) and the track calculated from this can be treated as “true” vessel track.

A VMS consists of three main components: the tracking unit on board the vessel, the transmission medium, and the base station. The tracking unit has its own integrated GPS and is programmed to send positional data to the base station via the transmission medium (communication satellites) at regular intervals. Reports from the boat can also be automatically collected at a predetermined location or time (AFMA website: <http://www.afma.gov.au/>). In the Australian NPF, VMS is a requirement for all catcher, carrier, and processor vessels (AFMA website: <http://www.afma.gov.au/>). It would be ideal to acquire the VMS data at the same fine scale as GPS data for research purposes. However, transmission of these data from the vessel to the base station via satellite is quite expensive, consequently VMS data are generally transmitted much less frequently. This allows government agencies to collect information on trawl location at a reasonable cost. Therefore, the routine VMS data in the NPF vary widely in resolution and in most cases are quite coarse. Under the auspices of this research, we collected HPFVMS data from the deliberately selected areas, each a 6 nautical mile (nmi) \times 6 nmi grid square, at a polling frequency of 20 min for 2 years (1998 and 1999). Four areas were originally selected but one area was subsequently closed to fishing. These areas were chosen from the AFMA daily logbook records because historically they were all subject to a high level of effort. We also used the same years’ routine VMS data as the auxiliary data set for this research.

Logbooks in the NPF are filled in daily and the fishers are obliged to give the position where their largest catch was made each night. The data are reported at a coarse scale of a single catch and location value per 24 h of fishing. However, fishers usually trawl 3–4 shots per night when targeting tiger prawns. Each logbook record contains the vessel’s name, the vessel identity number, the date, the catch of each target species group, and the location at which the largest catch in the night was obtained. Logbook data from two fishing seasons from August to October in 1998 and 1999 were used.

As VMS data are much more detailed than we need, some data preprocessing had to be conducted to eliminate non-fishing records. From fishers’ GPS records we also determined that one of the three areas (grid A) contained significant amounts of untrawlable ground, whereas the other two were relatively free of untrawlable ground.

Accuracy of trawl tracks at various polling frequencies

To compare characteristics of tracks recorded at a variety of different polling intervals, we characterized each track in terms of (i) track area (TA): the area that would be covered if trawling occurred in a straight line between successive points (no overlap); (ii) area passed once (AP1): the area of track referenced once only; (iii) percent area passed once (PAP1): the ratio of the area passed once to the corresponding track area. As well, we assume that the vessel maintains approximately the same speed when fishing. The relationships among these characteristics are as follows:

$$(1) \quad PAP1 = AP1 \times 100/TA$$

Table 1. Summary of data sets used in this study.

| Data set | Abbreviation | Spatial resolution | Temporal resolution | Spatial coverage | Temporal coverage | Objective(s) |
|--|--------------|--------------------------------|-----------------------|----------------------------------|---------------------------------|---|
| Satellite-based vessel monitoring system data | VMS | Depends on temporal resolution | From minutes to hours | Northern prawn fishery (NPF) | 1998 and 1999 | Population-depletion analysis |
| High-polling-frequency vessel monitoring system data | HPFVMS | 2000 m | ≤20 min | Three 6 nmi × 6 nmi grids | August–October of 1998 and 1999 | Trawling-intensity calculation; population-depletion analysis |
| Global positioning system data | GPS | 100 m | 1 min | 100 night tracks from 4 skippers | 1998 | Input for simulation VMS data at various polling frequencies |
| Vessel daily catch record data | Logbook | Various | 1 day | NPF | 1998 and 1999 | Population-depletion analysis |

We defined a trawl track as the path of a vessel recorded by a GPS over a single night's fishing (approximately 14 h) and this will approximate the true track. One hundred GPS-recorded trawl tracks from four vessels at polling intervals of 1 min (about 100 m apart) were analysed. We assumed that the vessels travelled in a straight line between adjacent points. This assumption is reasonable when one considers the size of the vessels, the length of trawl wire between the nets and the vessel, and typical turning radii of vessels engaged in trawling. A typical NPF trawler is between 20 and 25 m long, the ratios of trawl wire length to water depth used in this fishery are approximately 5:1, which corresponds to between 75 and 200 m of trawl wire, and the turning radius of a vessel whilst trawling is typically between 100 and 200 m. To produce a trawl track between point locations, it was assumed that trawl width was 30 m (based on standard trawl gear used in the fleet) and that the vessels trawled in a straight line between adjacent (1 min interval) points. We interpolated longitudinal and latitudinal coordinates for the outer extents of a 30 m wide rectangle (15 m each side of the vessel) between the VMS points.

Each of the longitudinal and latitudinal coordinates was assigned to a corresponding central cell reference with dimensions of 0.001 decimal degrees (approximately 11.7 m by 11.7 m). A file containing these cell references was written with the condition that the cell reference has not previously been recorded for neighbouring interpolated points. By doing this check, it could be assumed that each cell was only recorded once per pass. We summed the passes in each cell and used the frequency of passes in subsequent spatial analyses. Each track could then be described by its characteristics.

Trawling intensity

We calculated the trawling intensity in the selected grids with real HPFVMS data collected by AFMA. Based on the results of the GPS data simulations that the shorter polling interval had less chance of underestimating track area, three 6 nmi × 6 nmi grids (A, B, and C) were selected for polling at intervals of less than 20 min. These grids in the southern Gulf of Carpentaria represented the most intensively fished areas in the NPF at that time. The plots of polls from these areas represent two types of fishing patterns: random and aggregated. For this analysis, three data sets were combined: HPFVMS data, daily logbook catch data, and routine VMS data. The HPFVMS data were used to estimate trawling intensity, which is the number of times a particular piece of seabed is passed over by a trawl.

Owing to the costs, the VMS data do not record whether the vessel is fishing or in transit. This information can only be inferred from the vessel speed, calculated from the distance travelled between adjacent polling points and the time taken. Unless the vessel is travelling in a straight line between adjacent polling points, velocity calculated in this manner will always be underestimated. The following decision rules were used to exclude the records where fishing was not taking place: (i) vessel in a nonfishing location (port, seasonal- or permanent-closure areas); (ii) vessel whose speed was >4 kn (considered to be in transit), as trawling speed is usually about 3.2–3.5 kn and transit speed over large distances is usually >7 kn; (iii) vessel at anchor, as the location does not change for several hours; and (iv) daytime

records (0800–1800), as daytime fishing is banned in the NPF during the period tested. Given that vessels transit at higher speeds than those used for trawling and that anchoring or transiting is most likely to happen during the daytime, when fishing is banned, there is only a small chance that nontrawl data were retained after these restrictions were applied.

The following assumptions were also made: (i) the vessels travel in a straight line between polls; (ii) trawling width is 15 m on both sides of the vessel; (iii) one trawl track (30 m wide) is the trace of one vessel for one fishing night.

This third assumption allows VMS data and logbook data to be linked through a unique combination of vessel name and date identifier common to the logbook and VMS data. In this way, the catches in logbooks can be attached to a track and thus enable us to undertake depletion analyses.

The simulations of trawl tracks with HPFVMS data were undertaken in a geographical information systems (GIS) package (ArcInfo®; Environmental Systems Research Institute, Inc. 1982–2002). The VMS information was in the form of a series of positional fixes (points). These points were loaded into the GIS and converted into separate lines, each representing a vessel's track for a night of fishing. To characterize the area of the seabed trawled, the lines were buffered 15 m either side to model the width of a typical pair of NPF trawl nets. In this manner, the area trawled each night by a vessel was represented by a 30 m wide "strip". These strips were overlaid in the GIS and the trawling intensity at each point of the seabed was estimated by counting the strips overlying it.

Population-depletion analysis

The depletion analysis required routine VMS data, HPFVMS data, and logbook data. To undertake depletion analyses, we needed to link the logbook catches with the tracks calculated from HPFVMS. Logbooks give the single position where the vessel's largest catch was made each night. However, a night's fishing often extends beyond a single grid and therefore the routine VMS data for adjacent grids were also used to link the VMS and logbook data beyond the HPFVMS grids. The challenge was to combine all these data sets, which are recorded at different spatial and temporal scales. The result is that there is not enough information to determine which part of the catch was obtained within the trawl track.

The different spatial and temporal scales of the VMS and logbook data meant that the catch could not be accurately linked to the specific fishing grids chosen, but could only be associated with a larger, relatively loosely defined area that the vessel covered each night (based on its VMS plots). Furthermore, when plotting the position from HPFVMS data within the 6 nmi × 6 nmi grids that have catch allocated from the logbook data, the logbook position for the highest catch of the day did not always correspond to the vessel's position obtained from the VMS. Knowledge of the catch made within a specific area is required for biomass-depletion analyses.

These mismatches of VMS and logbook positions meant that the fishing areas to which the effort refers had to be carefully identified. As we described above, HPFVMS data were confined strictly to the three research grids. Often only

Table 2. Summary of track parameter estimates for the trawl tracks generated from GPS data.

| | Track area (km ²) | Total area trawled once (km ²) | Percent area passed once |
|---------|----------------------------------|--|-----------------------------|
| Mean | 3.92 | 2.84 | 73.00 |
| SD | 0.4 | 0.63 | 16.17 |
| Maximum | 4.71 | 4.07 | 99.94 |
| Minimum | 2.05 | 1.09 | 26.58 |

one record of a track fell inside the grid. To define the full area trawled by all fishers that entered the research grids in that day, we needed to define a new, bigger area. We used a convex-hull method to define the fished area using the HPFVMS with the linked VMS and logbook position data for the relevant tracks. The convex hull is the smallest convex polygon containing all the points (both VMS and logbook positions of vessels that entered the grid and its 3 nmi vicinity). This can most easily be visualized by imagining pins being inserted at all observed points and a tightly fitting rubber band placed to enclose all the points. However, single outlying points can easily double the size of the fishing area and often these points were the less reliable logbook positions. For this reason we finally defined the area more conservatively by using a one-peel convex hull. This means removing the points that defined the outer extent of the convex hull and using the convex hull of the next outer set of fixes instead. We selected logbook records (the number of vessels varied from 12 to 46 depending on area and year) from the database that fell into the convex hulls, allocated the catches along with the efforts estimated by HPFVMS, and calculated the target prawn CPUE to plot the graph of CPUE against cumulative catch to assess whether or not there was a depletion of the biomass with increasing cumulative catch.

Results

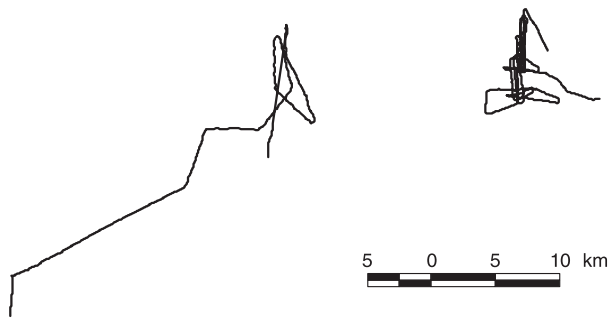
The grids chosen showed fishing that was either more randomly distributed (Fig. 1a) or heavily aggregated (Fig. 1b).

Accuracy of trawl tracks at various polling frequencies

The GPS data showed that the trawl tracks varied in shape, length, and degree of overlap (Table 2). These results can be explained by looking at examples of the trawl patterns. The "area trawled once" is only a small percentage of the convex-hull area. In general, a smaller area would be expected if tracks overlap (Fig. 2). In contrast, the track on the left-hand side of Fig. 2 is more open and extends across the diagonal and consequently has a much lower degree of overlap.

We calculated track areas and areas passed once. The mean values for track area and area passed once for all the tracks were plotted for each of the simulated polling intervals. Assuming that the values for 1-min-interval data are as accurate as possible, we have plotted the values for the other time intervals as proportions of the values for the 1-min-interval data. The results show that all simulated polling intervals underestimate the track area and area passed once,

Fig. 2. Two examples of fishing tracks from a single night of fishing obtained from vessel global positioning system (GPS) data. The track on the right has a high degree of overlap and the track on the left has a low degree of overlap.



and the error increases with time interval (Fig. 3). At a 30-min polling interval, the estimates are around 70% of the true (1-min-interval data) track. Moreover, when the polling interval was set at 20 min, both estimates are above 80% of the true track. However, at 2-h intervals, the estimates are as low as 30%–40% of the true track (Fig. 3) and the loss of precision is quite marked (Fig. 4). An example of the loss of information is shown in Fig. 4, where the points from one night's fishing, recorded by GPS plotter, were subsampled ("polled") at 30- and 120-min intervals. At the 120-min level of subsampling, all sign of the intensely aggregated part of the night's fishing effort has been lost.

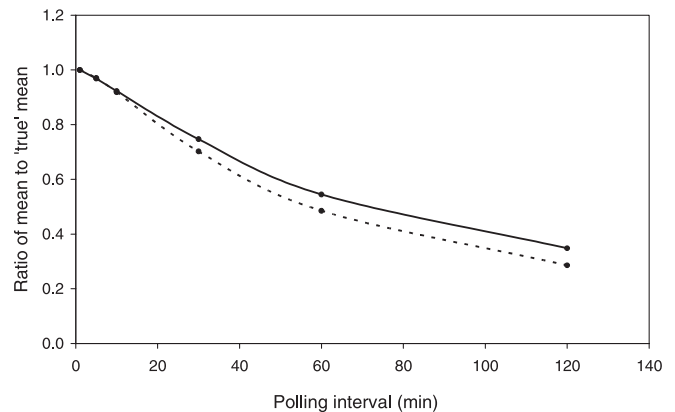
The distributions of "percent area trawled" against "number of passes" covered by a realistic number of trawl passes (100, 200, or 400) were calculated. The distributions for the "true" (1 min interval) estimate fitted the distribution most closely at the highest level of fishing effort (Fig. 5a). For the fishing effort at 100 trawls, the distribution of trawling intensities calculated from 120 min interval simulation underestimated the percent area trawled once, was close at 200 trawls, and overestimated with 400 trawls. The greatest proportion of the grid had not been passed even once (Fig. 5). As the effort in the grids increased, a greater proportion of the area had been trawled multiple times (Fig. 5d).

The results presented in this paper assume that the width of the trawl track corresponds to that of the trawl gear that follows a straight line between sequential polling points. The issue is that the assumption of a straight line between two closely polled points 2 h apart is less accurate than the same assumption made for points 2 min apart. Another method was attempted that calculated the swept area that would be covered in the polling interval and then adjusted the width accordingly (i.e., points that were closer together may have had a wider area of influence, as the vessel did not trawl in a straight line, whereas points that were farther apart in a short time would cover an area similar in width to the gear. These results are not presented, as the new method is computationally complex and did not change the results.

Trawling-intensity analysis

The spatial distribution of trawling intensity in the chosen areas highlights the changes in fishing patterns in the different years for the same grid. The spatial distributions of trawling intensity in grid A over the 2 consecutive years were similar, but the number of fishing tracks differed (134 in

Fig. 3. Comparison of track area (solid line) and area passed once (broken line) calculated from simulated VMS data polled at a range of frequencies up to 120 min.



1998, 82 in 1999). This suggests that prawn abundance remained above an economic threshold during the 2 years, although the fishing patterns in the first year were less aggregated than in the second year. In the other two areas, grid B and grid C, the spatial distribution of trawling intensities changed dramatically, as did the numbers of fishing tracks in the grids. The number of fishing tracks in grid B decreased from 239 to 4 and in grid C from 96 to 16 between 1998 and 1999. This suggests that biomass in these areas had declined significantly (Fig. 6).

Population-depletion analysis

Defining the "areas fished" when the VMS data and log-book data are spatially and temporally consistent is a critical factor for depletion experiments. In our study, we found that fishing patterns in grid A (Fig. 6) were aggregated during both 1998 and 1999, with relatively high levels of fishing effort. The depletion curve declined more slowly in 1998 than in 1999 and the total catch from this grid in 1999 was less than half of that in 1998. In 1998, the fishing pattern in grid B appeared aggregated and the level of effort was relatively high. The depletion trend shows the steepest decline among all of the curves. In 1999, grid B showed a dramatic decline in both fishing effort and CPUE, which might imply a heavy depletion of biomass in either 1998 or 1999. In grid C, the fishing pattern appeared to be less aggregated in 1998 and the depletion curves declined at a rate intermediate between those of grid A and grid B. In 1999, grid C exhibited the same problem of a large decline in fishing effort and CPUE (Fig. 7) and this result is not well summarized by a straight-line model.

Discussion

Accuracy of trawl tracks at various polling frequencies

HPFVMS can be used to accurately represent the trawl tracks of fishing vessels in the NPF, where fishing effort is often highly aggregated. However, the accuracy of the approach is limited by the polling frequency. This is because, at low polling frequencies, trawlers are unlikely to be travelling in straight lines between polling sites and so a straight-line linear interpolation may give incorrect estimates of the

Fig. 4. Original GPS track data recorded at a polling interval of 1 min (a) compared with simulated VMS tracks generated by subsampling the GPS track at polling intervals of 30 min (b) and 120 min (c).

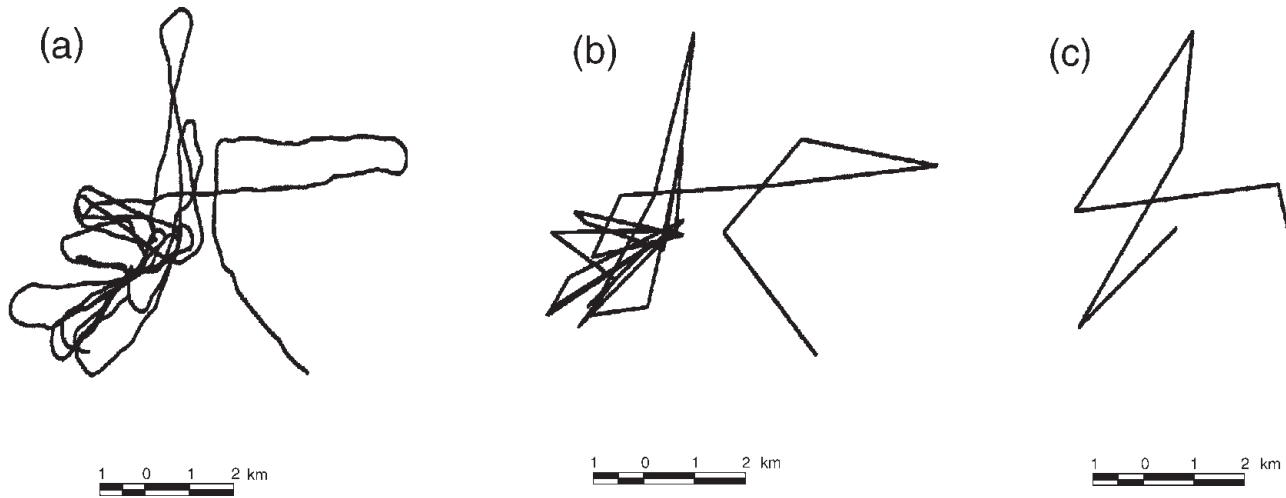
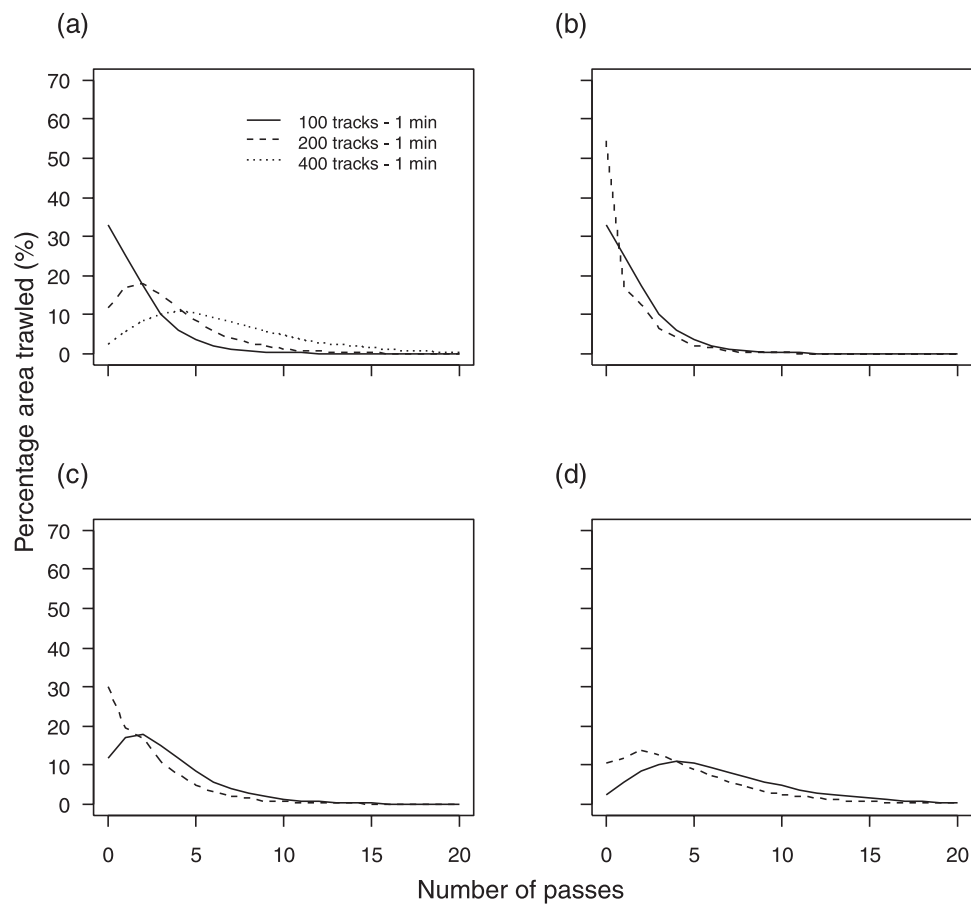


Fig. 5. Percent area trawled versus the number of times each $11.7 \text{ m} \times 11.7 \text{ m}$ cell was trawled over a range of levels of effort and polling intervals. (a) Different track densities per grid. (b) 100 tracks per grid. (c) 200 tracks per grid. (d) 400 tracks per grid. In b, c, and d, the solid line represents the “true”, 1-min interval and the broken line represents the 120-min interval.



distribution of the effort. Even at relatively short polling frequencies (e.g., 30 min), biases occur and these biases increase as the polling frequency decreases. Calculations of the actual area trawled and the area trawled once or multiple times become progressively smaller than the most accurate estimates as polling frequency decreases. If analyses are

concerned with effects at small spatial scales, such as studies of the impacts of trawling on the benthos, VMS polling intervals >30 min will result in serious bias of the estimated track areas. The linear interpolation also results in some error in the calculation of track parameters, especially when there is a significant change in direction. When vessels turn

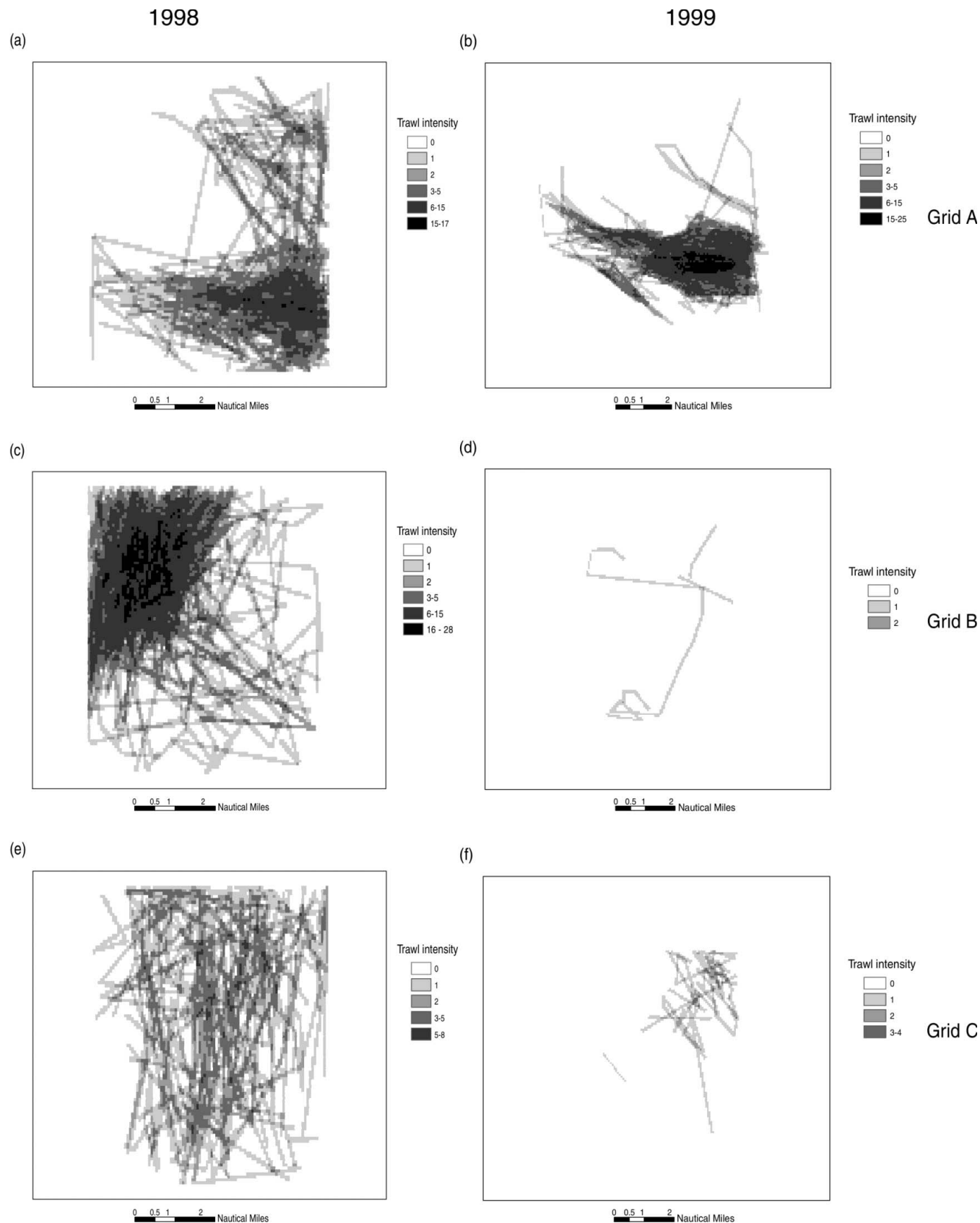
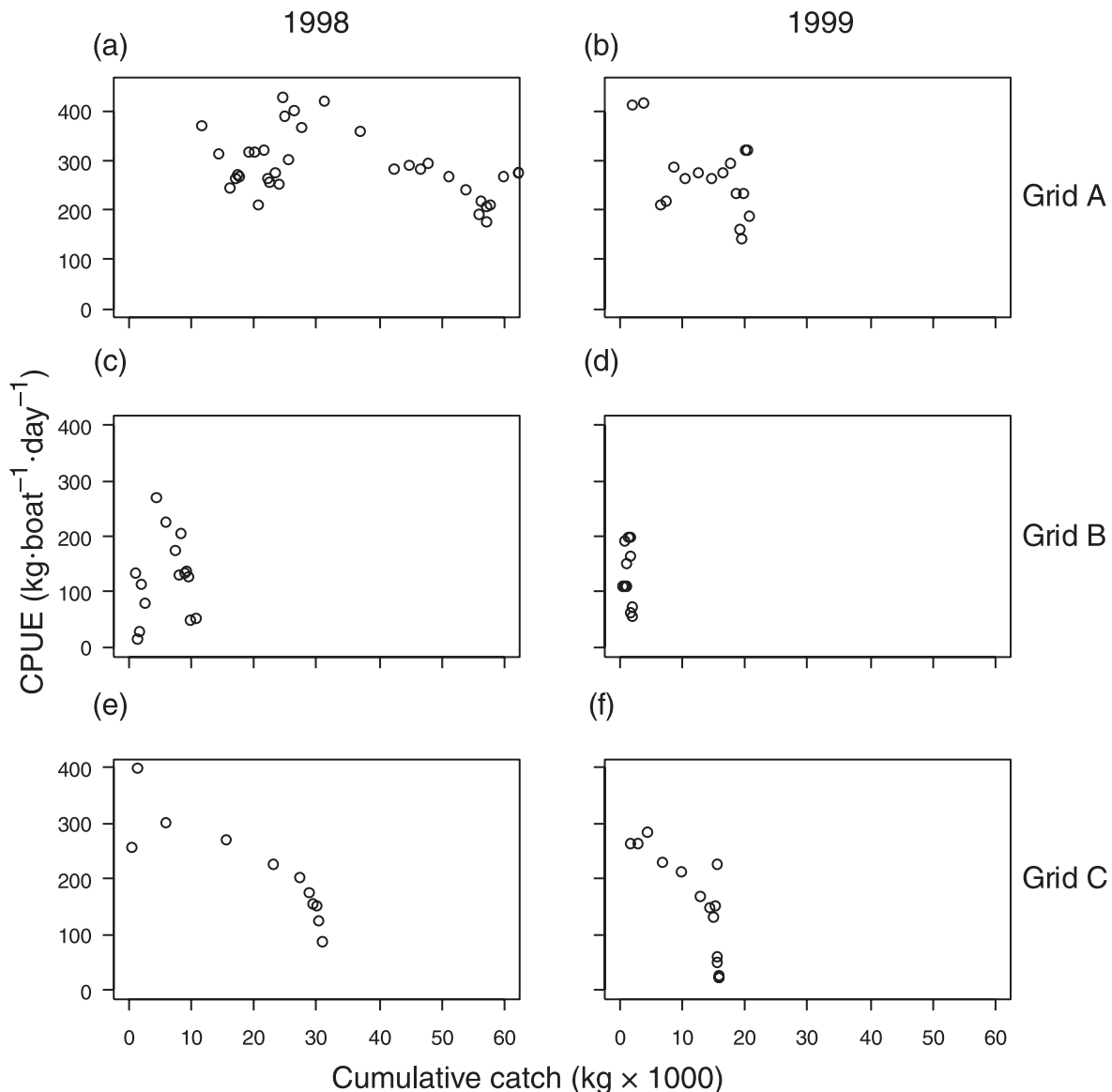
Fig. 6. Distribution of trawling intensities in grids A–C from high-polling-frequency VMS (HPFVMS) data in 2 consecutive years.

Fig. 7. Comparison of depletion curves in three grids during the 1998 and 1999 fishing seasons. Each point on the graphs represents daily CPUE for each grid.



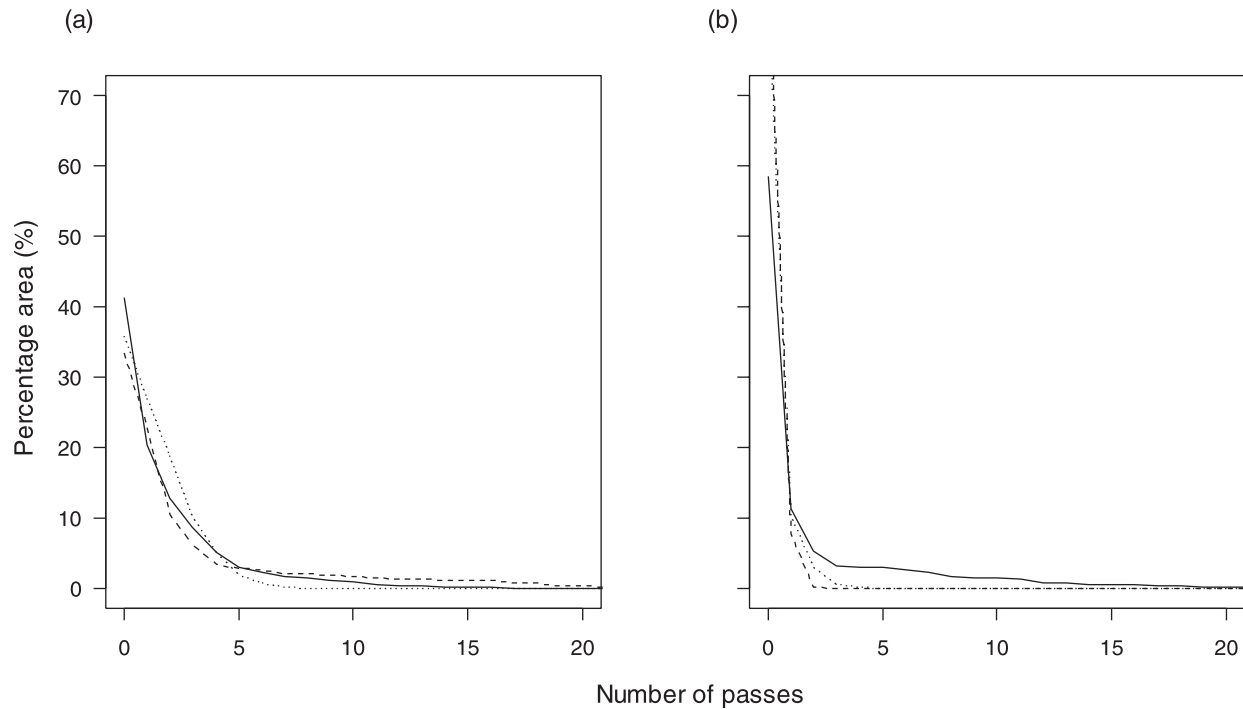
sharply, points are not allocated to the outside of the turn and although effort was made to exclude double counting of cells along the inside of the track, not all cases were eliminated. By assigning points to cells, we also limited the resolution of the estimation to around 12 m.

In most instances, fishers in the NPF vary their trawling patterns daily, depending on the degree of aggregation of the prawns and the success of the skipper in finding the aggregations. The relationship between the real trawl track and that estimated from low-frequency VMS polling depends largely upon the trawl pattern, so the track area and other parameters cannot be predicted from an estimate of the initial position and low-frequency VMS fixes (>30 min). In cases when the polling interval exceeded 30 min, enough information is lost for the characteristics of the trawl track to be significantly distorted. This suggests that the current VMS data collected routinely in the NPF cannot be used directly to estimate trawling-behaviour parameters.

It is difficult to advise as to one polling interval at which the results become significantly biased in all situations. If a polling interval was to be recommended, other factors including cost, physical polling limitations, form of data storage, and purpose of data collection must also be considered. Also, the scale at which the polled data were to be used would be an important determinant. However, we have shown that combining high- and low-polling-frequency data can enhance the accuracy of the analyses and increase the number of applications for which these data could be useful.

Comparing distributions of trawling intensities made from HPFVMS data (Fig. 8) and GPS data, the patterns of HPFVMS data were similar to the patterns from the analysis of the 1-min-interval method. This implies that the HPFVMS data themselves and the method used to analyse them were close to the true situation. For the grids sampled, the more aggregated the sample, the greater the proportion of highly trawled areas (Fig. 8). This suggests that specific areas within

Fig. 8. Distribution of trawling intensities based on HPFVMS data for 1998 (a) and 1999 (b). The solid line represents grid A, the broken line represents grid B, and the dotted line represents grid C.



each grid are being targeted. Also, greater fishing effort coverage causes the distribution to flatten out.

Trawling intensity and population-depletion analysis

We found that we could realistically calculate trawling intensity only when the polling frequency was less than 20 min. However, the cost of obtaining and processing such large volumes of data for a large number of vessels is prohibitive. This makes it extremely difficult to undertake large-scale trawling-intensity studies with this approach. Rather, a more realistic approach to assessing trawl impacts on seabed biota would be to combine HPFVMS of areas of affordable size with repeat trawl experiments in the same area.

Three grids (6 nmi \times 6 nmi) of HPFVMS data were collected during this study. Establishing reliable links between the VMS and logbook data was a complex operation because the two data sets have different spatial and temporal scales. Daily positions recorded in logbooks represent the locations of the highest catch on a specific fishing day, whereas the VMS records vessel locations (but no catch) at preset polling times. Generally, we found that there were four potential types of relationship between logbook data and HPFVMS records for one vessel on one day. These varied from complete compatibility to the case where the logbook placed the vessel in the nominated grid but the VMS showed that the vessel was elsewhere. We analysed 1999 logbook records falling inside the three 6 nmi \times 6 nmi grids. In grid A, 64 of 70 logbook records matched HPFVMS records and 6 records not at all. In grid B, 4 of 5 matched and 1 not at all, and in grid C, 21 of 32 matched and 11 not at all. There are cases where the vessel's logbook location is too far away from the HPFVMS grid for a single night's trawling.

In cases where there were minor disagreements between VMS and logbook locations, this imprecision might not af-

fect the accuracy of the analysis because the logbook records were very close to the "grid" and might represent partial input from the area fished. For cases where there is no agreement, the logbook position is either a mistake or a deliberate misrepresentation by the skipper. However, it is not possible to use only the HPFVMS data from specific grids because a night's fishing usually extends beyond a 6-min-interval grid.

To better define the spatial coverage of a night's fishing by vessels that entered the grid, we added the routine VMS records of relevant vessels. Furthermore, we added untrawled fishing ground information to the GIS in order to better understand the fishers' behaviour in the grid. The combination of routine VMS, logbook, and HPFVMS data was used to define the area fished. Since this area need not be square, we used a convex-hull method to define the outer boundary of trawled areas. A one-peel convex hull was applied to remove the effect of outliers, such as logbook records that placed the vessel very far from the assumed correct VMS records of that vessel. We found that only by combining the logbook, routine VMS, and HPFVMS data could we adequately solve this problem. These difficulties in defining the depletion area would be common to many fisheries in Australia and the world.

The results of our depletion analysis did not always conform to the commonly held assumption of a linear relationship between CPUE and available biomass (Hilborn and Walters 1992). This relationship is widely assumed in many fishery-stock assessments. We have also shown a difference in depletion rate between highly aggregated and non-aggregated fishing patterns. This could be due to differences in biomass or habitats in each area, or to migration, but also may be related to trawling intensity. Although there are several scale issues in applying the depletion analysis, the point

is that these data are useful. Clearly there are difficulties with using a single data source, especially logbook data. We show that VMS data would therefore greatly enhance any depletion analyses.

The rates of depletion of two neighbouring fishing grids were often very dissimilar. However, the amount of effort in a grid is a major factor in the success of these analyses, as there needs to be enough effort to cause a population decline. In these two grids, fishing effort in 1998 was sufficient for an effective depletion experiment to be undertaken. The absolute CPUE is generally lower in grid B and its CPUE is also low early in the season. The decline rate of depletion was much higher in grid B than in grid C. One reason for this higher decline rate could be the highly aggregated fishing as per our hypothesis. The effort levels in these two grids in 1999 were not sufficient to yield useful results in a depletion analysis.

The fishing pattern in grid A in 1998 and 1999 indicates that trawling was aggregated. The decline rates of depletion in this grid during both years have similar trends but different extents. The decline rate of depletion was steeper in 1999 than in 1998. There are two possible reasons: either the fishing pattern was more highly aggregated in 1999 than in 1998 or the tiger prawn biomass was reduced between 1998 and 1999. Considering that effort dropped significantly between years (from 134 to 82 days), the decrease in the decline rate of depletion is most likely attributable to a reduction in prawn biomass.

Our estimate of the number of repeat trawls allows us to quantify the effects of repeat trawling on benthos. This is an important issue in any trawl fishery (Jennings et al. 2001). Our data show that trawlers target some areas heavily, so there is the potential for impacts on both the target species and sessile benthos to occur. Many fishing activities involving bottom trawling can cause chronic and widespread disturbance to the seabed in shelf seas (Schratzberger and Jennings 2002). Trawling and dredging can alter, remove, or destroy the complex, three-dimensional physical structure of benthic habitats by the direct removal of biological (e.g., sponges, hydroids, bryozoans, amphipod tubes, shell aggregates, and sea grass) and topographic (e.g., sand depressions and boulders) features (Turner et al. 1999; Jennings et al. 2001). According to Poiner et al. (1998), the average depletion rate of one trawl was 7% for all sessile benthos classes, 9% for mobile benthos, and 10% for fish. It is noticeable that in some grids we found that fishing was extremely intensive in some areas (up to 28 trawls over the same ground). This suggests that most benthos has probably been removed from some areas, based on the level of impact found by Poiner et al. (1998) (Table 3). However, Poiner et al.'s (1998) study was based on the Great Barrier Reef, in areas with a lot of sessile epibenthos, and much of the NPF has soft, unstructured sediments with different benthic assemblages. Thus, the effects of trawling on these assemblages may be quite different. The less stable the substrate, the less likely it is that the impacts of trawling would be severe, because the species assemblages there are more likely to be opportunistic species that colonize quickly following natural disturbances.

In summary, we found that VMS polling at an interval of less than 20 min represents an acceptable estimate of the

Table 3. Estimated rate of removal of nontarget organisms in each of three NPF fishing grids (A, B, and C) based on the results of repeated trawl experiments in similar habitats (Poiner et al. 1998).

| Year and grid | Trawling intensity (N) | Percent area trawled | Total removal rate (%) | | |
|---------------|------------------------|----------------------|------------------------|----------------|-------|
| | | | Sessile benthos | Mobile benthos | Fish |
| 1999 | | | | | |
| A | 1 | 27.1 | 7 | 9 | 10 |
| | 2 | 12.9 | 14 | 17 | 19 |
| | 3–5 | 22.0 | 20–30 | 25–38 | 27–41 |
| | 6–15 | 32.6 | 35–66 | 43–76 | 47–79 |
| | 16–25 | 5.5 | 69–84 | 78–91 | 81–93 |
| B | 1 | 99.0 | 7 | 9 | 10 |
| | 2 | 1.0 | 14 | 17 | 19 |
| C | 1 | 74.7 | 7 | 9 | 10 |
| | 2 | 21.1 | 14 | 17 | 19 |
| | 3–4 | 4.2 | 20–25 | 25–31 | 27–34 |
| 1998 | | | | | |
| A | 1 | 34.8 | 7 | 9 | 10 |
| | 2 | 21.7 | 14 | 17 | 19 |
| | 3–5 | 28.4 | 20–30 | 25–38 | 27–41 |
| | 6–15 | 14.9 | 35–66 | 43–76 | 47–79 |
| | 16–17 | 0.2 | 69–71 | 78–80 | 81–83 |
| B | 1 | 34.2 | 7 | 9 | 10 |
| | 2 | 15.9 | 14 | 17 | 19 |
| | 3–5 | 18.7 | 20–30 | 25–38 | 27–41 |
| | 6–15 | 38.8 | 35–66 | 43–76 | 47–79 |
| | 16–28 | 5.7 | 69–87 | 78–93 | 81–95 |
| C | 1 | 42.2 | 7 | 9 | 10 |
| | 2 | 29.5 | 14 | 17 | 19 |
| | 3–5 | 26.8 | 20–30 | 25–38 | 27–41 |
| | 6–8 | 1.6 | 35–44 | 43–53 | 47–57 |

real track of a trawl without substantial bias. HPFVMS data have greatly increased our ability to monitor fishing activity and are particularly valuable when calculating trawl intensities for fine-scale analysis of fishing impacts. We have also shown that by combining fishery logbook catch records, HPFVMS data, and routine VMS data, a localized population-depletion analysis can be undertaken. Our depletion analyses hint towards supporting the hypothesis that the rate of depletion will be more rapid in highly aggregated fishing areas than in randomly fished areas. It is difficult, though, to scale this result to the whole fishery, but it does suggest that trawl-fishery CPUE and available biomass may not be directly proportional when fishing effort is highly aggregated. Even so, VMS data are essential to the success of this analysis. Finally, the VMS data have demonstrated that a large number of repeated trawls can occur in productive areas and that the effect of this trawling may be quite marked and should be investigated.

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