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Bias introduced by the non-random movement of fish in visual transect surveys

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Abstract

Non-random movement has been observed in a number of reef fish species but its effect on visual counts has not been previously examined. A simulation program Reefex was used to examine the relationship between the speed and approach angle of fish, and the degree of bias introduced in estimates of fish numbers from visual transects. Fish approaching at right-angles to the direction of the transect did not introduce a bias regardless of their speed. Fish approaching against the diver introduced a positive bias which increased linearly with fish speed. Fish moving in the direction of the diver created a negative bias, fish counts decreased linearly until fish speed matched that of the diver. This minimum value reflected the immediately visible portion of the entire transect that could be surveyed instantaneously by the diver when the survey began. Changes in the effective area surveyed determine bias. An equation is presented which relates bias to fish speed, angle of approach, diver speed, transect length and visibility.

Keywords: Bias; Diver survey; Fish movement; Transect; Visual survey

1. Introduction

Ecologists have used underwater visual census (UVC) techniques for recording fish densities on reefs since the 1950s (Brock, 1954; Barans and Bortone, 1983; Harmelin-Vivien et al., 1985). Recently this technique has been used to examine the effects of fishing on reef fish densities (Russ, 1985; Samoilys, 1988; Samoilys and Carlos, 1991).

The accuracy of visual surveys has frequently been questioned (i.e. Brock, 1982; Sale and Sharp,

1983; Andrew and Mapstone, 1987), though rarely tested (but see Brock, 1982; McCormick and Choat, 1987), because the bias has been difficult to measure. Several sources of bias have been identified, such as: the failure of an observer to notice individuals, the presence of the observer, observer experience, observer speed, and fish detectability (Sale and Sharp, 1983; Thresher and Gunn, 1986; Lincoln Smith, 1988).

As a relative measure of fish abundance a biased visual survey is not a problem if the bias remains constant. If the bias does not remain constant, however, visual estimates will not be consistent. Since the method has several advantages, notably being non-destructive and relatively quick to execute, potential problems of bias

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need to be evaluated. This is particularly relevant if visual surveys are to be used for fisheries stock assessment purposes.

The strip transect is one of the most frequently used visual survey methods (Thresher and Gunn, 1986). This technique involves a diver swimming a measured distance along the bottom while counting fish within a fixed width. The density of fish is the number counted within the defined area of the transect, expressed per unit area.

Accurate calculations of fish density from surveys should yield the same results as an instantaneous count. For many species the census area must be fairly large, and often extends beyond the range of visibility of the observer. Most users of transects for fish counts assume that the procedure is equivalent to an instantaneous count, and that the total count is equivalent to the sum of a series of instantaneous “snap-shots” taken as the diver moves along the transect. Consequently, the number of fish counted during the time taken to travel the length of the transect is assumed, on average, to be the same as the initial number of fish in the transect area. This assumes that reef fish move at random, their net movement is zero, and therefore density estimates made at any point along the transect will average the original transect density. It is not the movement of fish per se that is relevant here, but the net movement. If there is more movement in any one direction than in another, then the assumption of random movement does not hold.

Within the time frame of a visual transect, non-random or directional movement of certain reef fish species is likely. For example, the Carangidae are known to patrol along the reef slope when hunting, and this behaviour will change with time of day (Potts, 1980, 1981). Certain scarids are known to move up and down the reef with the tide (Choat and Robertson, 1975). Schooling behaviour can lead to directional movement. This behaviour is commonly observed in several reef fish species, for example many scarids (Choat, 1983). In addition, the movement patterns of fish may change with time or habitat, reflecting for example their foraging strategies (Thresher and Gunn, 1986).

If there is non-random movement, then the

number of fish counted in a transect area may differ from the initial number. It is important to know how much bias in the estimates of density arises from non-random fish movement. To investigate the bias associated with non-random movement by measuring fish speed and direction would be difficult in the field, but the question is well suited to investigation by simulation through computer modelling. Our purpose in this study was to produce a quantitative model of the effects of non-random fish movement on the bias of density estimates from visual transects.

2. Methods and materials

2.1. Model description

A simulation model named Reefex was developed which provides a two-dimensional, animated simulation of the visual census process, depicting both the movement of fishes and of the diver. As the simulation proceeds, various statistics such as fish counts are displayed and recorded into data files.

Groups of fishes are defined which represent different species or different size groups within a species. For each group the user can control: fish density, the maximum distance from the diver that they can be seen (visibility), and the minimum distance that they will allow the diver to approach them or vice versa (approach distance). The user describes behavioural states which control individual fish movement and other responses for each fish group. For each behavioural state the user specifies: the probability of entering the state, an associated swimming speed of the fish, and the probability of moving in each of four directions in a horizontal plane (0°, 90°, 180°, and 270°). For example, for a fish group we might define three possible behavioural states: “stationary”, “random-movement”, and “cruising”. We might specify that any individual fish is in the “stationary” state for 50% of the time, in the “random-movement” state for 30% of the time, and the balance in the “cruising” state. For each of these three states we could then describe the direction and speed of movement. We would not

move fish while they are in the “stationary” state, however, while a fish is in the “random-movement” state we might allow movement with equal probability in each of the four directions at 2 m min^{-1} , and for the “cruising” state we could allow a greater probability of movement at 90° than in the other directions and at a faster speed, i.e. 4 m min^{-1} .

The length of the time steps used in the simulation can be specified. At each time step the behavioural state and the subsequent movement of each individual fish in each group is determined randomly by user-defined probability distributions. At each time step the new positions of the diver and the fish can be shown.

The total area of the reef represented in the simulation can be defined, as can the dimensions of the strip transect. All or only a portion of this total reef can be shown depending on the display scale chosen. For reference, grid lines can be displayed in any scale. If fish move out of the defined reef area, they are removed from the simulation, but are replaced on the opposite boundary so that the specified densities within the simulated reef are maintained.

The model allows for a count-saturation level to be defined for each fish group, that is the maximum number of fish in that group that a diver can count at any one time step. It is possible to create conditions where there is an established counting hierarchy within the fish groups, that is, the diver will attempt to count all of the highest priority species, and if time permits, proceed to the next group and so on. It is also possible to introduce error in the counting process either through allowing some fish to be missed or wrongly identified.

Fish within the transect boundaries when the simulation begins (time = 0) are registered as “original occupants”. A diver, however, can only observe fish within the circle of visibility (Fig. 1b), and will only count fish which are within the boundaries of the transect. Fish counted by the diver are classified as either “occupants” or “arrivals”, whether or not they have been previously registered as original occupants. Occupants are those which the diver observed within the transect boundaries at first sighting and, unlike arrivals, are used to calculate density estimates. Arrivals are those fish which the diver has ob-

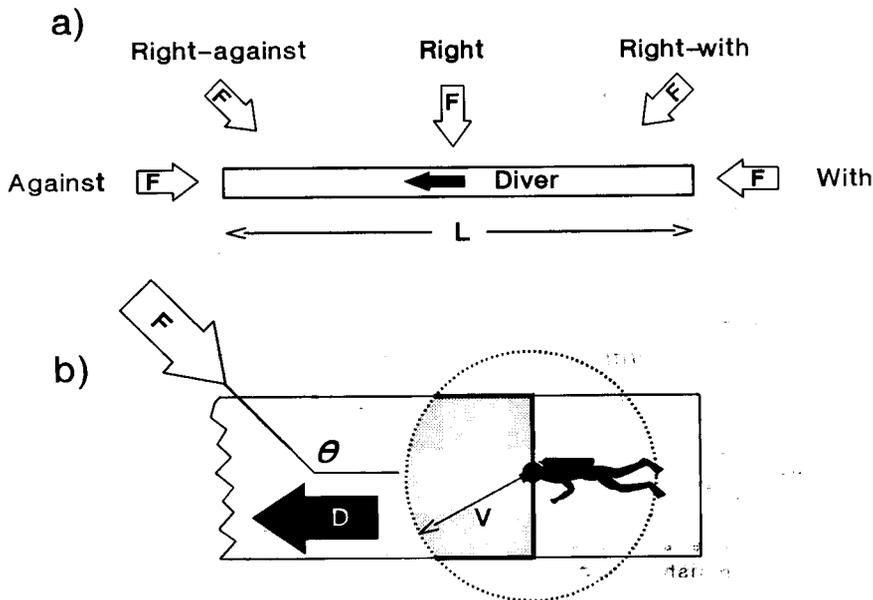


Fig. 1. Definition of simulation parameters including: (a) directions of fish movement and transect length (L), and (b) fish movement vector (F), diver movement vector (D), visibility (V) and fish approach angle (θ).

served crossing the side boundaries of the transect (projected forward to the extent of visibility), and those which overtake the diver within the two side boundaries (thus crossing thickened lines in Fig. 1b). By definition, therefore, fish can not be classified as both an occupant and an arrival.

2.2. Description of experiment

Our study was designed to investigate the bias introduced by the non-random movement of fish by altering the speed and approach direction of fish simulated in the model. In our simulation we used time steps of 10 s (trials were previously performed using time steps ranging from 1 to 30 s with little effect on outcomes). We used a simulated reef area measuring 250 m by 100 m. Our simulated transect was centred on this reef and measured 75 m in length (L , Fig. 1a) and 5 m in width. We used only one group of fish which were randomly distributed on the reef at a density of

150 ha^{-1} . These fish were observable by the diver at a distance of 10 m (V , Fig. 1b) without any error or limit to the numbers that could be counted in any one time step. The diver swam at a constant speed of 7 m min^{-1} (D , Fig. 1b) and the transect was complete when the diver could observe all the fish remaining in the transect (10 m from the end, the diver's visibility).

The fish speed (F , Fig. 1a) was varied between 1 and 19 m min^{-1} by steps of 2 m min^{-1} . For each speed, a series of approach angles (θ , Fig. 1b), with respect to the direction of the diver's motion, were examined. These are described as: "against" (opposite to the diver's direction, $\theta = 180^\circ$), "with" (in the same direction as the diver, $\theta = 0^\circ$), "right" (approaching at a right-angle from the diver's right side, $\theta = 90^\circ$), "right-against" (obliquely opposite to the diver's motion, $\theta = 135^\circ$) and "right-with" (obliquely in the same direction as the diver, $\theta = 45^\circ$) (Fig. 1a). Fifty trials were completed for each combination of

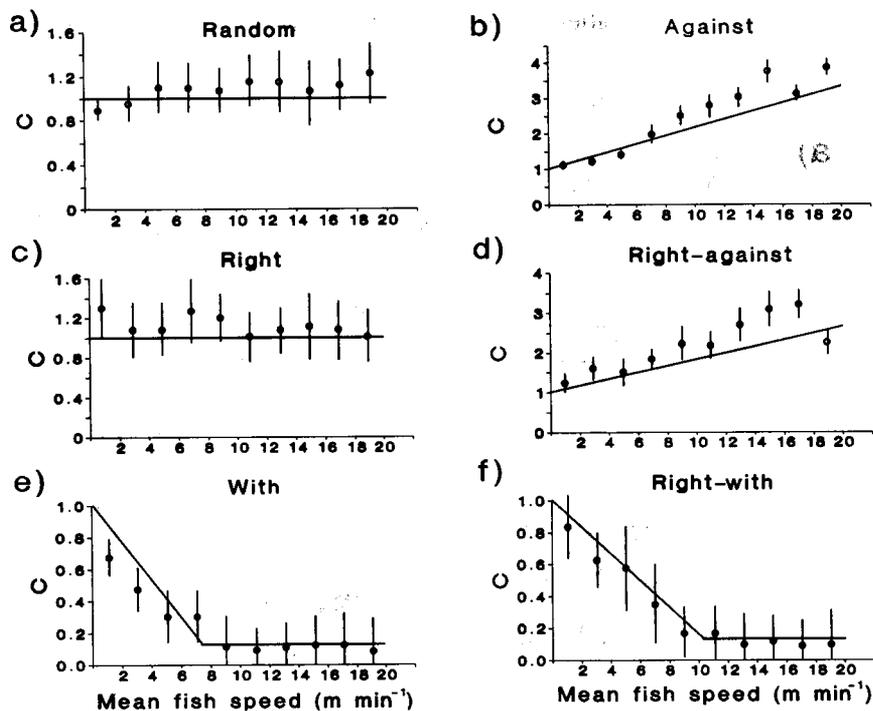


Fig. 2. Simulation observations (circles represent means and bars represent the 95% confidence limits), and predicted values (solid lines) of bias value C for a range of average fish speeds and approach angles with respect to the direction of diver movement: (a) random, (b) against, (c) right, (d) right-against, (e) with, and (f) right-with.

fish speed and approach angle. During each trial all fish were moved at the same nominated speed and direction at each time step. For simplicity, we have presented only the results for fish approaching from the diver's right – the results were the same when fish approached from the diver's left.

Records were kept of the number of occupants, arrivals and original occupants for each trial. Bias value (C) was defined as by the ratio,

$$C = \frac{\text{Occupants}}{\text{Original Occupants}}, \quad (1)$$

thus when $C = 1$ there is no bias in the estimation of fish numbers as an equal number of occupants are counted by the diver as there were original occupants of the transect (these need not be the same individual fish).

For each of the fifty trials of each combination of fish speed and direction an average C was calculated. We present the results of these simulations along with illustrations explaining how bias is created, and a formula which describes the relationship between bias and survey parameters.

3. Results

3.1. Simulation results

Random

There was no observed bias introduced by fish speed ($C = 1$) when the movement was random or on average non-directional (Fig. 2a) even at fish speeds of nearly three times that of the diver.

Against

As the speed of fish moving against the diver increased there was a linear increase in C (Fig. 2b). When the speed was 19 m min^{-1} , nearly three times the speed of the diver, the value of C was 3 to 4 times that of random fish movement.

Right

Changes in fish speed did not affect the value of C when the fish moved only at right-angles to the diver's motion. C remained equal to 1 while fish speed increased from zero to 19 m min^{-1} (Fig. 2c).

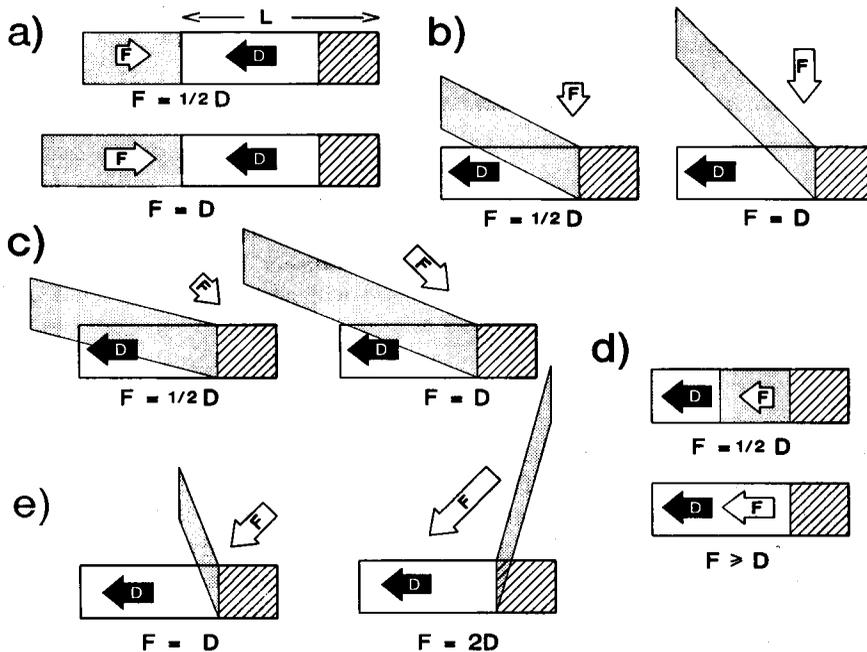


Fig. 3. Illustrated explanation of bias introduced by non-random fish movement from (a) against, (b) right, (c) right-against, (d) with, and (e) right-with (definitions of directions in Fig. 1).

Right-against

When the fish approached the diver obliquely the effect on the value of C was intermediate between that when the fish moved directly against the diver and that when they moved at right angles (Fig. 2d). As speed increased so did values of C , but not as rapidly as in the against case. When the fish were moving at 19 m min^{-1} , reaching three times the diver's speed the value of C was about three.

With

As the speed of fish travelling in the same direction as the diver increased, the value of C decreased in a linear fashion until the fish speed was approximately equal to that of the diver (Fig. 2e). When the speed of fish exceeded that of the diver, C approached a constant value of about 0.1.

Right-with

The effect of non-random fish movement from an angle behind and on the diver's right was intermediate between that obtained for those coming from the diver's right and those moving with the diver (Fig. 2f). The value of C decreased linearly until it reached about 0.1 to 0.15 at a speed of about 10 m min^{-1} , and remained constant at this value as speed increased further.

3.2. Illustrated model

In each situation described below, at the time that the transect swim begins (time = 0), visibility allows the diver to immediately count all fish within the cross-hatched portion of the transect (Fig. 3a–e).

Against

Moving along the transect the diver encounters and counts oncoming fish (Fig. 3a). These fish originate (location at time = 0) from within the remaining transect, and additionally from within the shaded area shown beyond the end of the transect. These additional fish add to fish counts introducing a positive bias ($C > 1$). As the speed of fish increases, and finally equals that of the diver's speed ($F = D$), the shaded area from

which additional fish can reach the transect equals the unshaded area of the transect, doubling the effective transect length if the cross-hatched portion is excluded. If fish speed increases still further, so will the shaded area and the associated bias.

Right

Fish which the diver encounters after time = 0 originate from the shaded area to the diver's right (Fig. 3b). As fish speed increases, the shaded area from which the counted fish originate, inclines away from the transect, but its area remains the same. This means that as fish speed increases the fish which the diver counts outside the cross-hatched area come from further and further away, but as they always originate from the same-sized area as the original transect there is no bias created.

Right-against

When fish speed is equal to diver speed but directed at 45° to the front, the diver instantly surveys the cross-hatched area and the remaining fish originate from the shaded area to the diver's right (Fig. 3c). The component of non-random fish movement against the diver causes this area to elongate and increase as speed increases producing a greater positive bias ($C > 1$).

With

As fish are moving in the same direction as the diver, some near the end of the transect will cross the transect boundary before the diver arrives, and will not be counted. In Fig. 3d the fish are initially moving at one-half the diver's speed. As a result, only those in the cross-hatched and shaded areas will be counted, the others will escape detection by leaving the area of the transect before the diver arrives. The resulting bias will be negative ($C < 1$). As fish speed increases, the shaded area becomes smaller and smaller. When fish speed matches the diver speed only those fish within the cross-hatched area will be counted. After counting these fish the diver will never encounter any new fish but will continue to travel with those already counted. As fish speed increases still further, fish overtake the diver,

however, these fish are arrivals, not occupants. Therefore, when $F \geq D$ only those fish within the limits of visibility at time = 0 (cross-hatched area) are counted.

Right-with

After the initial count of fish within the cross-hatched area, those subsequently counted originate from the shaded area stretching away to the diver's right (Fig. 3e). This area becomes reduced as the along-transect component of fish speed approaches that of the diver's until it becomes essentially a single line. After this component of fish speed exceeds that of the diver, fish will approach the diver from the rear, and are therefore counted as arrivals, not occupants. At this point only those fish initially present in the cross-hatched area will be counted as occupants.

3.3. Equation

From the illustrated model (Fig. 3) we see that the number of "occupants" counted by the diver is proportional to the area actually sampled. This is equal to the sum of the area initially visible (the cross-hatched area of Fig. 3, which is constant if visibility and transect width remain the same), and the projected area sampled during the remainder of the survey (shaded area of Fig. 3, which is variable and depends on fish speed and direction). The relationship describing the change in the area sampled as the fish speed and direction change is:

$$A = WV + W \left((D - F \cos \theta) \frac{(L - V)}{D} \right), \quad (2)$$

where A is the resultant sampled area, W is the transect width, V is visibility, D is diver speed, F is fish speed, θ is the approach angle and L is the transect length. The area of the initial count (cross-hatched in Fig. 3) is WV , and the projected area (shaded in Fig. 3) is

$$W \left((D - F \cos \theta) \frac{(L - V)}{D} \right). \quad (3)$$

The projected area (Eq. 3) is calculated by multiplying the transect width by the distance

that the shaded area (Fig. 3) extends in the direction parallel to the transect. Note that since movement at right angles to the transect does not produce any bias, extension of the shaded region in this direction has no effect on its area. The distance that the shaded area extends parallel to the transect is derived from the product of the relative speed component between fish and diver in this direction or $D - F \cos \theta$, and the time available for sighting occupant fish. This opportunity occurs only when new areas of the transect become visible and is therefore limited by the time taken for the diver's range of visibility to reach the end of the transect, expressed as $(L - V)/D$.

The source of "original occupants" is, by definition, that area encompassed by the transect boundaries, or

$$WL, \quad (4)$$

Thus by replacing Eq. 1 with the relevant area expressions, Eqs. 2 and 4, the effect of transect width is removed and the value of C is described by:

$$C = \frac{V + (D - F \cos \theta) \frac{(L - V)}{D}}{L} \quad (5)$$

For illustrative purposes the response of C to fish speed and approach angle is presented in Fig. 4.

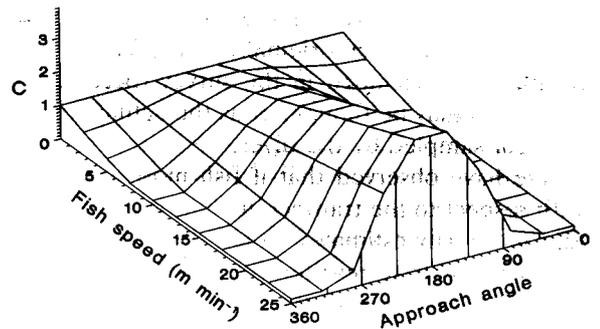


Fig. 4. Plot of surface representing the predicted relationship between fish speed, approach angle and bias value C for all angles and for speeds from 0 to 25 m min^{-1} based on equation 5 (diver speed = 7 m min^{-1} , transect length = 75 m, visibility = 10 m).

4. Discussion

Our simulation model demonstrated that during a visual census the non-random movement of fish can induce significant errors in a diver's estimates of fish density. Essentially, if there is an "against" component of movement of fish with respect to the diver, the visual counts will overestimate density. An underestimation of density occurs when there is a "with" component of fish movement with respect to the diver. This positive or negative bias increases with increasing speed of fish.

As the transect lengths necessary to sufficiently sample fish densities are usually relatively long compared to underwater visibility and diver speed, counts are not instantaneous estimates of fish density but rather an integrated count of the transect area. Poor visibility can greatly restrict the portion of the transect that the diver can view at any one time. It is unlikely that all individuals counted as occupants are ever present in the transect area simultaneously. Fish counts are comprised of a combination of original transect occupants, and those which enter the transect when they are out of the observer's visual range.

Visual transect surveys can not be regarded as approximations of instantaneous counts when an unknown portion of fish not originally present in the transect are counted as occupants, while others, seen entering the transects (arrivals) are excluded from density estimates. The relationship between a visual count and a true instantaneous count is related to the ratio between the transect area, and the area originally occupied by fish counted and included in the survey (occupants). The latter may be thought of as the actual area of the reef sampled by the diver.

We have observed that if fish move randomly with respect to the transect, no bias is introduced; that is, density estimates do not differ from those which would have resulted from an instantaneous count. This is because the area actually sampled by the divers is the same size as the transect area.

When fish movement becomes directional, the counts made from the area of the transect beyond the initially visible area of the count are subject to bias. This bias can range from trivial to signifi-

cant depending on the relative fish speed and the direction of approach. When the approach angle of fish is perpendicular to the transect, the areas of the transect and the original location of the occupant fish, the area actually sampled, are equal. Bias is associated only with the component of relative fish movement parallel to the diver's direction of motion, therefore changes in the width of the transect have no effect on the bias of estimates.

Unfortunately, there is little information on the patterns of movement of reef fish with which we can assess the significance of our findings. Based on studies of fish behaviour, non-random or directional movement of reef fish is likely. One would expect the direction of fishes' movements to correspond with environmental gradients, schooling behaviour, home ranging behaviour, etc.

During our simulation we moved all fish at the same speed and in the same direction to reduce variability. This may seem unnatural, but for the purposes of our study this has no effect as bias is not introduced by the net movement of individual fish but by the net movement of all fish sampled. Members of a fish school may at any given moment appear to be travelling in different directions, and individuals may change direction from moment to moment, yet the school as a whole may move considerable distance. It is this net movement of all fishes which induces bias.

The effect of bias due to movement can be reduced by the careful orientation of transects. Where mobile species are to be surveyed, transects are best aligned at right angles to the direction of movement, which usually means placement of transects across habitat zones. This may, however, cause sampling problems if habitats change rapidly, or if the required transects are long.

The magnitude of bias is also proportional to the amount of time taken to cover the area of the transect. The risk of bias is reduced if the time taken to complete the survey is decreased. This can be achieved by either shortening the length of the transect or by increasing the diver's speed. These two factors must be implemented with respect to the characteristics of the species and the practicalities of the habitats sampled. Length

of transect must be sufficient to maintain an adequate census area (a function of density and dispersion). Speed must allow for adequate search and recording time for the species and habitat.

It has been shown that slower speeds result in higher estimates of abundance of cryptic species (Lincoln Smith, 1988). Following the assumption that visual counts generally underestimate (Sale and Sharp, 1983), slower speeds have been deemed more appropriate by these authors. Such a conclusion may be misleading if a similar result were obtained from surveys of mobile species, as in this case the higher density estimates with slower diver speeds could have resulted from greater movement-induced bias.

Visibility has a similar effect as speed and transect length, in that it changes the time required to cover the area of transect beyond the range of initial visibility. If all boundaries were observable when the survey begins then an instantaneous count would be approximated. This ideal situation is approached when either the visibility is exceptionally good (greater than the transect length) or when the transect length is kept within the limits of visibility. For practical reasons, however, this is usually impossible with the transect method, as the total area encompassed would be too small for sampling the distributions of many less abundant species.

Counts made while the diver is stationary (Bohnsack and Bannerot, 1986) may offer some advantages when fish are highly mobile. Because the entire survey area is within the range of visibility there is no bias introduced by fish movement. This method, however, requires sufficient visibility for an adequate area to be surveyed from one diver position. This can be a limitation for species with low densities. This is usually accomplished by a diver surveying a circular area from its centre. As in all counting methods which demand finite time, it is still necessary to classify individuals as either occupants or arrivals. Compared to a transect count there is less uncertainty in this classification because the entire area and its boundary is always observable. This factor confers other advantages on a stationary count. Different search strategies can be employed over the same area, which is useful when surveying

both cryptic and mobile fish. The count units are also compact in linear extent and therefore fit well into areas with sharp habitat gradients.

We have demonstrated how simulation modelling can be used to investigate sources of survey biases which are difficult to examine in the field. By defining suites of behavioural patterns with associated probabilities we can incorporate sufficient details to allow even complex interactions to be examined. Such a simulation allows study of many other interesting sources of bias such as diver–fish interactions and count saturation. Our work allows estimation of the relative magnitude of bias induced by non-random fish movement. It will undoubtedly be difficult for biologists to accurately measure fish speed and approach direction in the field and therefore calculate the associated bias, however, through careful planning the risk of sufficient bias can be reduced.

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