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Absolute abundance estimates from shallow water baited underwater camera surveys; a stochastic modelling approach tested against field data

K.M. Dunlop [a,*], G.D. Ruxton [b], E.M. Scott [c], D.M. Bailey [a]

[a] Institute of Biodiversity, Animal Health and Comparative Medicine, University of Glasgow, Glasgow G12 8QQ, UK
[b] School of Biology, University of St Andrews, St Andrews, Fife KY16 9TH, UK
[c] School of Mathematics and Statistics, University of Glasgow, Glasgow G12 8QQ, UK

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ABSTRACT

Baited underwater cameras are becoming a popular tool to monitor fish and invertebrate populations within protected and inshore environments where trawl surveys are unsuitable. Modelling the arrival times of deep-sea grenadiers using an inverse square relationship has enabled abundance estimates, comparable to those from bottom trawl surveys, to be gathered from deep-sea baited camera surveys. Baited underwater camera systems in the shallow water environments are however, currently limited to relative comparisons of assemblages based on simple metrics such as Max_N (maximum number of fish seen at any one time). This study describes a stochastic simulation approach used to model the behaviour of fish and invertebrates around a BUC system to enable absolute abundance estimates to be generated from arrival patterns. Species-specific models were developed for the tropical reef fishes the black tip grouper (*Epinephelus fasciatus*) and moray eel (*Gymnothorax* spp.) and the Antarctic scavengers; the asteroid (*Odontaster validus*) and the nemertean worm (*Parbolasia corrugatus*). A sensitivity analysis explored the impact of input parameters on the arrival patterns (Max_N, time to the arrival of the first individual and the time to reach Max_N) for each species generated by the model. Sensitivity analysis showed a particularly strong link between Max_N and abundance indicating that this model could be used to generate absolute abundances from existing or future Max_N data. It in effect allows the slope of the Max_N vs. abundance relationship to be estimated. Arrival patterns generated by each model were used to estimate population abundance for the focal species and these estimates were compared to data from underwater visual census transects. Using a Bland–Altman analysis, baited underwater camera data processed using this model were shown to generate absolute abundance estimates that were comparable to underwater visual census data.

1. Introduction

Abundance estimates of marine populations, that are both accurate, close to the true abundance, and precise, repeatable under the same conditions, are important to understand changes in marine populations or communities (Farnsworth et al., 2007) and to help achieve sustainable management and effective conservation objectives (Collins et al., 2002). For marine fish and invertebrate populations the majority of this data has been collected using trawl surveys (Fitzpatrick et al., 2012; Johnson et al., 2012), which are difficult in abyssal environments and unsuitable in marine protected areas (Bailey et al., 2007). Baited underwater camera (BUC) systems have therefore been used in many studies to gather data on deep-sea scavenging fauna (Farnsworth et al., 2007) and fish assemblages in protected areas (Willis and Babcock, 2000; McLean et al., 2010). However, to use BUC data to produce absolute abundance estimates of fish and invertebrates requires a detailed understanding of the physical and biological parameters involved in the process of animals detecting and following the bait plume to the camera (Priede et al., 1994; Bailey et al., 2007).

Bait plume dispersal from a point source, its detection by fish or invertebrates and their arrival at the source, is influenced by a number of environmental and biological factors (Collins et al., 2002; Stoner, 2004). The odour from the bait disperses as a plume into the surrounding water on currents (Reidenbach and Koehl, 2011). The velocity and direction of currents will affect the length and lateral dispersal of the plume as well as its dispersal direction (Bailey and Priede, 2002; Dorman et al., 2012). The dispersal of odour plumes is also affected by turbulence within the aquatic environment (Meager and Batty, 2007), the topography over which it travels (Collins et al., 1999, 2002; Reidenbach and Koehl, 2011) and the characteristics and persistence of the bait (Bailey and Priede, 2002; Stoner, 2004). Fish and invertebrates have evolved olfactory organs with chemosensory abilities that

Abbreviations: BUC, Baited underwater camera; Max_N, Maximum number of individuals, of the same species, appearing on the field of view in any one frame over the whole deployment; $T_{arrival}$, Time to the arrival of the first individual from each species; T_{maxN}, Time to the maximum number of individuals observed at one time; UVC, Underwater visual census.

* Corresponding author at: Monterey Bay Aquarium Research Institute, 7700 Sandholdt Road, Moss Landing, CA 95039, USA.
E-mail address: kdunlop@mbari.org (K.M. Dunlop).

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allow them to detect odour plumes and follow them to their source (Reidenbach and Koehl, 2011). The area within the odour plume where the odour concentration is above the threshold which organisms can detect is known as the 'active space' (Sigler, 2000; Stoner, 2004). The probability of the fish entering the active space of the bait plume will be dependent on their search behaviours (Dorman et al., 2012), including their swimming speed and position in the water when foraging (Stoner, 2004), as well as the abundance and distribution of the population (Armstrong et al., 1992). Once the plume has been detected, the fish will decide whether to follow it based on the feeding motivation that the bait provides (Dorman et al., 2012). The time that individuals remain at the bait will be determined by the availability of food within the environment (Charnov, 1976) as well as the competition and interactions with other scavengers at the bait (Armstrong et al., 1992; Bailey and Priede, 2002; Dunlop et al., 2014a).

The process of bait plume detection, attraction and arrival of the deep-sea grenadier *Coryphaenoides armatus* at a BUC was modelled using an inverse square relationship:

$$n = c/t_{\mathrm{arr}}{}^2$$

where n is the number of fish per square kilometre and c is a constant, dependent upon the current velocity and through water swimming speed of the fish towards the BUC system (Priede et al., 1990; Priede and Bagley, 2000). t_{arr} represents the time elapsed between the beginning of the camera deployment and the arrival of the first fish. The model was developed by Priede et al. (1990) to allow scavenger density to be estimated from their arrival rates at the BUC in conjunction with information on the odour plume spreading characteristics, current velocities and fish swimming speed. The staying time of deep-sea grenadiers at the BUC can be estimated using the relationship:

$$N_\beta = \frac{\alpha_0}{x}\left(1 - e^{-\beta x}\right)$$

where N_β is the maximum number of fish present after a certain period of time, α_0 the initial rate of fish arrival at time zero, e the exponential constant and x a constant representing the decay of the odour plume from dilution and bait consumption (Priede et al., 1990). Arrival rates are of interest as a bait placed amongst an abundant scavenger population has a greater chance of being reached by an individual quickly (Bassett and Montgomery, 2011). The arrival times of deep-sea grenadiers at a BUC in two sites in the North Atlantic were modelled in the above manner to produce estimates of abundance which were comparable to those from bottom trawl surveys from approximately the same area and time (Armstrong et al., 1992; Priede and Merrett, 1996). However, when applied to fish arrival times on the Mid-Atlantic Ridge there was no correlation between BUC generated abundances and those estimated from trawls (Bailey et al., 2007).

The use of BUC systems in shallow waters has enabled relative comparisons of both fish and invertebrate assemblages in the tropical (McLean et al., 2010; Moore et al., 2010), temperate (Willis et al., 2003) and the Antarctic environments (Smale et al., 2007) between areas of different protection status (Willis and Babcock, 2000; Westera et al., 2003), habitat type (Moore et al., 2010) and disturbance pressure (Smale et al., 2007). The majority of studies have used the maximum number of individuals, of the same species, appearing in the field of view in any one frame over the whole deployment (Max_N) as an index of relative abundance (Willis and Babcock, 2000; Stoner et al., 2008). Max_N avoids the repeated recording of individuals that leave and re-enter the camera field of view and is usually less than the count of all animals visiting the bait (McLean et al., 2010; Harvey et al., 2012). Some surveys have also used the time to the arrival of the first individual from each species ($t_{arrival}$) and time to the maximum number of individuals observed at one time (t_{maxN}) (Willis and Babcock, 2000; Jones et al., 2003). In the shallow water environment however, the development of models of the process of fish or invertebrate arrival at BUCs has been limited (Stoner et al., 2008; Langlois et al., 2012). Heagney et al. (2007) investigated whether abyssal scavenger arrival models could be applied to shallow mid-water baited underwater video data. Existing models appropriate for deep-sea BUC studies with long soak times and where scavengers approached more slowly, were found unsuitable for shallow water BUC studies with much shorter soak times and which attract many fast moving species (Heagney et al., 2007). Rapid arrival patterns of shallow water fish result in overestimated abundance due to the inverse square law of the abyssal model (King et al., 2006; Stobart et al., 2007). Compared to the shallow water environment, currents in the abyss are relatively constant, so an assumption of a constant current speed and direction is more suitable (Heagney et al., 2007; King et al., 2008). The assumptions of deep-sea models also cannot be applied to describe the foraging behaviours of shallow water fish species, which also use sight, as well as chemoreception, to find food (Ellis and DeMartini, 1995; Stobart et al., 2007). The time related metrics used in the deep-sea such as, $t_{arrival}$ and t_{maxN}, have not correlated well with other survey methods in some shallow water BUC surveys (Stoner et al., 2008; Willis and Babcock, 2000).

The area sampled by the active space of the odour plume is largely unknown in shallow BUC surveys. Concerns have been raised regarding the effect of localised environmental conditions, such as topography and current conditions, on plume dynamics making it difficult to make comparisons between areas (Taylor et al., 2013; Watson et al., 2009). Surveys assume that a comparable area is sampled by each deployment, however, this will often be untrue if current conditions vary (Heagney et al., 2007). The importance of the currents on the dynamics of bait plume dispersal and subsequent fish arrival patterns has been highlighted in several studies in the mid water (Heagney et al., 2007) and demersal environments (Dorman et al., 2012). The unknown sample area of shallow water BUC surveys also makes it difficult to make comparisons with abundance estimates from other survey methods. Several studies have investigated the differences in fish and invertebrates recorded by BUC and UVC surveys (Langlois, 2006; Watson et al., 2010), however, conclusions regarding comparisons have been difficult as the area sampled cannot be directly compared (Langlois et al., 2010).

A model to determine the absolute measures of shallow water fish or invertebrate abundance from arrival patterns at a BUC would involve developing an area based bait dispersion model using in-situ measurements of current speed and direction (Heagney et al., 2007). The mechanistic models outlined by Priede et al. (1990) to estimate the abundance of deep-sea demersal fish from first arrival times are deterministic. However, the arrival rate of fish is stochastically related to population abundance and the factors governing aspects of shallow water fish movement are often assumed to be well represented by random distribution (Farnsworth et al., 2007). This means that it is important to include stochastic elements to mechanistic models. The physical factors, current distribution and velocity, observed around the camera system also have a random distribution within a particular range. Therefore it is important to introduce this random aspect into models to describe fish attraction and arrival at a BUC system. Stochastic models that incorporate both the predictable and random aspects of a process, are increasingly being used to build our understanding of complex natural ecosystems (Brown and Kulasiri, 1996). Farnsworth et al. (2007) also modelled the arrival process of deep-sea demersal scavengers at the BUC using the addition of stochastic elements to deterministic models. Farnsworth et al's models unfortunately did not include a mechanism to reverse the process and calculate abundances from arrival patterns. The models also required a very large number of assumptions and parameters, making them difficult to implement for many BUC users.

The primary objective of the present study was to develop a stochastic modelling approach to enable the estimation of the absolute abundance of fish and invertebrates using arrival data collected using a shallow water BUC system. This involved the development of species-specific models for two fish and two invertebrate species observed in tropical