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Fish behaviour effects on the accuracy and precision of underwater visual census surveys. A virtual ecologist approach using an individual-based model

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ABSTRACT

Underwater visual census (UVC) methods are used worldwide to monitor shallow marine and freshwater habitats and support management and conservation decisions. However, several sources of bias still undermine the ability of these methods to accurately estimate abundances of some species.

The present study introduces FishCensus, a spatially-explicit individual-based model that simulates underwater visual census of fish populations. The model features small temporal and spatial scales and uses a movement algorithm which can be shaped to reflect complex behaviours and effects of diver presence. Four different types of fish were used in the model, featuring typically problematic behavioural traits, namely schooling behaviour, cryptic habits, shyness and boldness. Corresponding control types were also modelled, lacking only the key behavioural traits. Sampling was conducted by a virtual diver using four true fish densities and employing two distinct methods: strip transects and stationary point counts.

Comparisons with control fish have shown that schooling and bold behaviours induce positive bias and reduce precision, while cryptic and shy behaviours induce negative bias and increase precision, although shy behaviour did not have a significant effect on precision in transects. By looking at deviations from true density, however, schooling, shy and bold fish densities were strongly overestimated by both methods, while cryptic fish were slightly underestimated. Schooling and bold fish had the lowest precision overall, followed by shy fish. Fish rarity decreased precision, but had no effect on bias. Stationary points had less precision than transects for all fish types, and led to much higher counts, resulting in greater overestimation of density overall.

By modelling complex behaviour, it was possible to separate the contributions of detectability and non-instantaneous sampling on bias, and gain a deeper understanding of the effect of behavioural traits on UVC estimates. The model can be used as a tool for planning and optimization of monitoring programs or to calculate conversion factors for past or ongoing surveys, assuming behavioural patterns are well replicated.

1. Introduction

Methods to quantify the abundance of populations and communities are key in Ecology, determining the way a state or process of the system is perceived by observers (Zurell et al., 2010). When the entire area of interest or population cannot be surveyed, as is often the case, the choice of method and sampling design can be crucial, particularly if observations support conservation and management decisions (Blanchard et al., 2008; Pais et al., 2014).

Underwater visual census (UVC) methods are a cost-effective way to survey shallow marine and freshwater habitats. In addition, the fact that they are non-destructive makes them ideal choices for protected areas, supporting important management and conservation decisions worldwide, particularly on temperate and coral reefs (Colvocoresses and Acosta, 2007; Di Franco et al., 2009; Edgar et al., 2004; Henriques et al., 2013; McClanahan et al., 2007a,b). As with any sampling method, UVC methods estimate the true state of the observed system, but are affected by two kinds of uncertainty: precision and bias. Precision is the width of the dispersion of estimates around the mean and bias is the deviation of the mean from the true value we are estimating. Precision can be quantified by doing replicate measurements, and to a certain extent it can be reduced by

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increasing sampling effort (Pais et al., 2014), however, bias is very difficult to quantify and can only be minimised by changing sampling design, or applying a correction factor to field data (Kulbicki et al., 2010).

UVC methods are subject to several sources of bias, such as observer experience (Thompson and Mapstone, 1997), low detectability of organisms (MacNeil et al., 2008a), observer movement (Lincoln Smith, 1988), non-instantaneous sampling (Ward-Paige et al., 2010) and underwater visibility (Bozec et al., 2011). In fact, even if we ensure that divers are experienced and the sampling method is standardised across space and time, estimates may still be completely false, even if very precise (Sale and Sharp, 1983). While UVC methods are known for their tendency to underestimate due to imperfect detectability (Katsanevakis et al., 2012), Ward-Paige et al. (2010) used a simulation model to show that shark densities are systematically overestimated due to their high mobility. In either case, bias can have devastating effects, because managers and scientists may spend unnecessary resources to protect species which are not actually endangered, or may be unaware when population sizes reach threateningly low levels. Accurate estimates are particularly important for fisheries stock assessments (Jennings and Polunin, 1995), or to parameterise dynamic community and population models that support management decisions (Pelletier et al., 2008).

Several studies on UVC have concluded that bias is strongly linked to species behavioural traits (Bozec et al., 2011; Kulbicki et al., 2010; MacNeil et al., 2008a; Samoilys and Carlos, 2000; Willis et al., 2000). In fact, some traits such as cryptic habits (Christensen and Winterbottom, 1981; Willis, 2001), schooling behaviour (MacNeil et al., 2008a) and reaction to divers (Edgar et al., 2004; Kulbicki, 1998) have been pointed out as particularly difficult to deal with when using UVC.

The quantification of sampling bias can be very useful, not only because it can be used to reshape sampling designs to better suit our subject, but also because it allows us to apply correction factors to existing data, or to standardised long-term monitoring programmes (Christensen and Winterbottom, 1981; Pierucci and Cózar, 2015; Sale and Sharp, 1983). This of course requires that we know the true density of fish at a given time, which is a challenge that many have tried to overcome. The majority of studies dealing with bias in UVC used an alternative method (usually more destructive) to represent the true state of the system, which include traps (Edgar et al., 2004) or fish poisoning in an enclosed pool (Christensen and Winterbottom, 1981) or caged area (Willis, 2001). Other approaches include distance sampling (Bozec et al., 2011; Buckland et al., 2012) and predictive models that use data from different transect widths and extrapolate to a zero-width theoretical scenario (Sale and Sharp, 1983). However, these alternative methods have their own bias (Mahon and Hunte, 2001), and some can seriously affect or kill fish from the assemblages of interest, defeating the purpose of a non-destructive method.

Another alternative approach is to use a controlled environment, which can be a fish tank or even a natural enclosed area, where a known number of fish are introduced (e.g. Biro, 2013). Of course, the logistics of such an approach hinder its use, but even if feasible, fish behaviour can be affected by conditions in captivity and artificial gathering of fish near walls can affect counts if the tank is too small.

A third alternative is to use computer simulation. This requires the effort of programming the model, but can ultimately meet the requirements of being cost-effective and non-destructive, while also continuing to serve as a tool for future use and improvement. A suitable modelling approach to answer sampling-related questions is what has been labelled by Zurell et al. (2010) as the "virtual ecologist" approach. In such models, more realistic output values can be drawn by also modelling the data collection procedure, where a "virtual ecologist" records measurements and observations in a similar way a real ecologist would do in the field. For the specific case of UVC, two models have been built to study observation bias, both opting for a spatially-explicit individual-based model of fish movement, with divers added as agents responsible for observing and recording the number of fish according to pre-determined rules and limitations. The Reefex model was developed by Watson et al. (1995) to study the influence of fish speed and approach angle on transects and stationary point counts. It featured grid-based fish movement and a time step of 10 s. While the movement model was simplified, many complex processes were included, such as fish avoidance, different behaviours with pre-defined frequencies and observation error.

More recently, Ward-Paige et al. (2010) studied the effect of bias due to observer speed and non-instantaneous sampling in UVC of sharks, creating a new model that improved on some of the limitations faced by the Reefex model to answer these questions. The resulting AnimDens model uses a correlated random walk for sharks and a much smaller time step of 1 or 2 s. Because the movement model is simplified down to two parameters, speed and maximum turning angle, it is meant to be generically adaptable to visual counts of any moving animal.

While these two previous models succeed at answering specific questions about UVC bias, the representation of fish behaviour in either of them is very simplified. It is impossible or very difficult to accurately represent the movement of a fish species with complex behaviours such as schooling and shoaling, diver avoidance/attraction or cryptic habits. This can lead to bias estimates from these models being more accurate for certain species than for others, depending on how the real species fits the grid-based or correlated random walk assumptions.

In the present study, a new individual-based model is presented, building upon some of the concepts behind the Reefex and AnimDens models but featuring complex fish movement and behaviour. The FishCensus model can have a very small time step (0.1 s) to allow for precise modelling of fish reactions to their surroundings, and can be used to simulate counts using the most common UVC methods. This study focuses on four behavioural traits which are typically problematic for UVC, namely schooling behaviour, cryptic habits, shyness and boldness towards divers. Four generic fish types representing these key traits were simulated and placed in the environment at four densities. Virtual divers performed strip transects and stationary point counts and reported an estimated density, which was used to calculate accuracy and precision. The isolated effect of each behavioural trait was also calculated using control fish types. The FishCensus model is proposed as a tool to aid in sampling design for monitoring and research, and to calculate correction factors for densities of species estimated with standardised methods.

2. Materials and methods

2.1. Model description

The FishCensus model was programmed in NetLogo version 5.3.1 (Wilensky, 1999). The latest model versions are freely available at https://www.openabm.org/model/5305/. Model version 1 was used in this study. A full description following the ODD (Overview, Design concepts, Details) protocol for describing individual-based models (Grimm et al., 2010, 2006) is available as supplementary material (S1).

2.1.1. Purpose

The FishCensus model simulates how different fish behaviours affect density estimates in common underwater visual census