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Empirical and simulation evaluations of an abundance estimator using unmarked individuals of cryptic forest-dwelling taxa

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ABSTRACT

Conservation and management programs use populations of sentinel taxa, such as stream-associated amphibians, as indicator species due to their perceived sensitivity to environmental change. Estimating population size with traditional tools such as mark–recapture estimators may be impractical for forest-dwelling stream-associated amphibians, many of which are cryptic and have low detection probabilities. In addition, sampling techniques can alter habitat conditions, particularly with repeat sampling, and compromise inferences about management impacts. We used simulated and empirical data and *N*-mixture models to estimate detection probabilities and abundances for two amphibian genera, giant *Dicamptodon* and torrent *Rhyacotriton* salamanders, sampled with a less-invasive approach than other methods. We surveyed forested headwater streams located in western Washington, USA, for salamanders 7 July–27 August 2008. We assessed model sensitivity to changes in animal abundance (5 and 15) and detection probability (0.05–0.5), as well as study design alternatives including number of sample plots (50–150) and number of sampling visits (2–4). We also evaluated the effects of stream temperature and stream order on detection probability using data collected from forested streams in Washington, USA. Precision of detection probability estimates improved as the number of plots and sampling occasions increased. Variability of estimated population sizes decreased with higher detection probability, although species abundance had little effect on precision of detection probability estimates. Detection probability estimated from empirical data ranged from 0.07 to 0.65 for giant salamanders and 0.06–0.67 for torrent salamanders. Giant salamander detection probability was positively associated with stream temperature regardless of stream order, and was higher in second- and third-order streams than first-order streams. Detection probability for torrent salamanders varied with stream temperature, order, and the interaction of those covariates, with detection increasing with temperature for second- and third-order streams but showing a flat or decreasing trend for first-order streams. *N*-mixture models, paired with careful consideration of study design alternatives, can produce robust estimates of abundance and obviate the traditional reliance on indices of relative abundance for many rare and sensitive taxa. Use of a less invasive technique for sampling stream-associated amphibians resulted in sufficient animal captures for suitable model performance. Our simulation results can inform study design and direct efficient allocation of field effort.

1. Introduction

Indicator species are used to monitor changes to forest environments due to natural and anthropogenic disturbances (Lawler et al., 2010; Pearce and Venier, 2005; Relyea, 2005). Often, these "sentinel" taxa possess behavioral or physiological traits that make them acutely sensitive to comparatively minor changes in environmental conditions (Grove et al., 2009; van der Schalie et al., 1999). Amphibians are a prominent example, as many species have experienced reductions in local abundance and range contractions as a result of disease, competition with introduced species, and habitat degradation and conversion (Sparling et al., 2001; Stuart et al., 2004). Species that occur in forested environments can respond negatively to management practices that reduce structural complexity of aquatic and terrestrial habitats (Corn and Bury, 1989; Kroll, 2009).

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Stream-associated amphibians are considered sentinel taxa because of their dual life histories, restricted dispersal abilities, and explicit microhabitat and physiological requirements (Lawler et al., 2010; Welsh and Ollivier, 1998). However, reliable inference about these, and similar, taxa is often challenging due to their low detection probabilities (Bailey et al., 2004a; Mazerolle et al., 2007). Moreover, changes in detection probabilities may be confounded with variation due to ecological processes (Pollock et al., 2002; Schmidt, 2004). As a result, inferences about population status and trends may be inaccurate. The resulting uncertainty can confound research and monitoring efforts to conserve viable populations and communities of these species (Kroll, 2009).

To address this issue, researchers may implement sampling protocols to limit the variation in detection probability associated with certain covariates (e.g., time, temperature, and weather). These protocols assume that, under the range of prescribed sampling conditions, detection probability is constant. In practice, this assumption is often violated (Mazerolle et al., 2007; Pollock et al., 2002; Schmidt, 2004). The use of mark–recapture or removal sampling to estimate detection probability represents a valuable improvement for making inference since detection probabilities frequently vary among species (Bailey et al., 2004a; Price et al., 2011), life stages (Price et al., 2011; Sagar et al., 2007), habitat types (Kroll et al., 2008), and sampling methods (Bailey et al., 2004b; Quinn et al., 2007). However, the use of mark–recapture and removal sampling can be impractical for stream-associated amphibians (Jung et al., 2000; Welsh and Hodgson, 2009).

Species-level detection is the probability of detecting occupancy, whereas individual detection is the probability of detecting a single individual and is used to model abundance. In the Pacific Northwest, stream-associated amphibians have been shown to have low to moderate individual detection probabilities. Sagar et al. (2007) estimated moderate individual detection probabilities of 0.48 and 0.59 for larval coastal giant salamanders *Dicamptodon tenebrosus*, dependent on age. Conversely, McIntyre (2003) estimated low individual detection probabilities ranging from 0.02 to 0.09 for Van Dyke's salamanders *Plethodon vandykei*. The cryptic nature of forest-dwelling stream-associated amphibians coupled with relatively low individual detection probabilities can demand an intensive field effort to mark and recapture a sufficient number of animals so that models perform adequately. These limitations can be overcome with an increased number of sampling occasions and sampling intensity. However, intensive, repeated sampling of the same sample units may introduce the unwanted side effect of habitat degradation and may not be feasible with limited resources.

N-mixture models are an alternative to mark–recapture and removal sampling and have been utilized to estimate species abundance in several studies (Chelgren et al., 2011; Dodd and Dorazio, 2004; Kéry et al., 2005; McKenny et al., 2006; Price et al., 2011). These models provide an attractive alternative as they allow sampling approaches that are comparatively less invasive than some other amphibian sampling methods (e.g., rubble rouse sampling, Quinn et al., 2007) and preclude the need for costly special handling of individuals. Furthermore, because sampling unmarked individuals is less time-consuming per site than relocating marked individuals, more sites can be sampled overall. More sample sites frequently results in smaller variances in derived population estimates and greater statistical power to detect population trends (Dodd and Dorazio, 2004). However, these models have yet to be statistically evaluated for performance with taxa that have low individual detection probabilities and comparatively low numbers of plot-level observations. Evaluation of the performance of *N*-mixture models for variable animal abundance, detection probability, number of sample plots, and number of sampling visits can encourage inclusion of these techniques in research and monitoring programs, and support effective conservation decisions.

Our objectives were to evaluate the performance of the *N*-mixture model (1) using simulations for variable animal abundance (5 and 15) and detection probability (0.05–0.5), as well as study design alternatives including number of sample plots (50–150) and number of sampling visits (2–4) and (2) with empirical data for two amphibian genera, giant *Dicamptodon* and torrent *Rhyacotriton* salamanders, sampled using the less invasive light-touch method (Quinn et al., 2007). These stream-associated amphibian taxa are distributed across headwater environments in the Pacific Northwest, USA, and may be sensitive to forest harvesting impacts (Corn and Bury, 1989; Kroll, 2009; Steele et al., 2003). We evaluated the effects of two covariates, stream temperature and stream order, on detection probability for both genera. Temperatures can vary broadly even in undisturbed headwater streams, and the amount of variation may differ significantly by stream order. Stream orders may differ in drainage area, flow rate, and habitat conditions, among other factors. Our results provide important information that can guide population assessments for sensitive, cryptic taxa that are the focus of conservation concerns but which pose significant challenges to commonly applied sampling and estimation methods.

2. Materials and methods

2.1. Study sites

We established 18 study watersheds throughout western Washington, USA, as part of an ongoing experimental study examining the effectiveness of alternative riparian management zone prescriptions on non-fish-bearing stream basins (Hayes et al., 2005). Each watershed was a perennially flowing, non-fish-bearing, first-, second- or third-order stream basin (sensu Strahler, 1952) located along the Clearwater, Humptulips and Wishkah Rivers in the Olympic Mountains; the North, Willapa, Nemah, Grays and Skamokawa Rivers and Smith Creek in the Willapa Hills; and the Washougal River and Hamilton and Trout Creeks in the southern Cascades (N45°48.42′-N47°38.87′, W122°15.88′-W124°12.07′, elevation 22–730 m). Watersheds occurred in managed Douglas-fir *Pseudotsuga menziesii* Franco- and western hemlock *Tsuga heterophylla* Sargent-dominated second-growth forests on private, state and federal timberlands. Watersheds ranged from 12.5 to 76.1 ha (measured utilizing a Geographic Information System (GIS), specifically ArcMap (ESRI, 2004)) and were dominated (⩾84% of total watershed area) by forest stands with ages ranging from 32 to 80 years. Prior to this work, we verified the presence of stream-associated amphibians (Washington Department of Fish and Wildlife, unpublished data) and absence of fish (using electroshocking, B. Fransen, Weyerhaeuser Company, unpublished data) at all watersheds. We grouped watersheds into five blocks based on geographic distribution and other watershed-specific covariates to minimize variability (McIntyre et al., 2009).

2.2. Sample plot locations

We distributed sample plots to ensure that we had at least one plot per stream order within each study watershed for a total of 40 plots (18 first-, 16 second- and 6 third-order plots). We sampled watersheds located in the northernmost block first and worked our way south, sampling plots located within a watershed concurrently. We chose a 30-m plot length to maximize the likelihood of detecting the focal amphibian genera. Previous research using the same sampling method demonstrated that one of our two focal amphibian genera is detected with high confidence when approximately 20 m of stream length is surveyed (Quinn et al., 2007). Based on reconnaissance prior to sampling we randomly located