A Stepwise Approach to Assess the Occupancy State of Larval Lampreys in Streams

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Abstract

Pacific Lamprey Entosphenus tridentatus is an ecologically and culturally important anadromous species of conservation concern for which fisheries managers use information on occupancy state in streams to assess species status and inform stream management decisions. Here we developed a stepwise approach that incorporates the potential for nondetection and a preselected expected maximum probability of stream occupancy if field crews do not document larval Pacific Lamprey during sampling. Our approach includes seven steps: define the occupancy question; select the maximum acceptable probability of occupancy, if the species is not documented during sampling; define an assumed detection probability for the target organism; calculate required sampling effort; select sampling units; conduct sampling; and interpret sampling results into probabilistic occupancy conclusions. We examined detection probability of our approach for larval lamprey using data from multiple occupied streams in the Pacific Northwest. We illustrated our approach by evaluating Balm Grove Dam as a barrier to Pacific Lamprey migration in Gales Creek, Oregon. Bayesian estimates of detection probability in occupied streams ranged from 0.15 to 0.94, with an overall median of 0.70 (95% credible interval: 0.60–0.79). Assuming detection probability is at least 0.15 (i.e., lowest estimate), 19 reaches are required for the expected maximum probability of occupancy to be not more than 0.05, if the species is not documented through our sampling approach. Although detected downstream, we detected no larvae upstream of Balm Grove Dam; thus, we conclude that the maximum probability of occupancy upstream of Balm Grove Dam was not more than 0.05 at an assumed detection probability of 0.4, suggesting the dam as a barrier to adult migration. We provide an occupancy assessment tool with standardized sampling requirements that incorporates the potential for nondetection and the flexibility to select an expected maximum probability of occupancy if researchers document no larvae, to aid management and restoration in a single stream.

Keywords: occupancy method; Pacific Lamprey; larval lampreys; streams; Bayesian; dams

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Introduction

It is often essential for fisheries managers to assess whether a stream area is occupied (occupancy state = 1) or unoccupied (occupancy state = 0) by a fish species of conservation concern before initiating research, development, or restoration projects in the area. If crews detect the species in question through field sampling, managers know the occupancy state is one. If they detect no individuals, it is unclear whether the stream is truly unoccupied or if, by chance, zero individuals were collected from an occupied stream. If the fish species truly occupies the area, increasing effective sampling would decrease the probability of nondetection, but even intensive and extensive sampling cannot reduce the probability of nondetection to zero. The inability to differentiate between the two states can be problematic, but understanding the expected probability of occupancy in case researchers do not document the species can aid area and species management decisions.

Pacific Lamprey *Entosphenus tridentatus* is an ecologically and culturally important anadromous species of conservation concern for which fisheries managers use information on occupancy state in streams to assess species status and inform stream management decisions. Pacific Lamprey import marine-derived nutrients into rivers and streams and are prey for freshwater and marine predators (Beamish 1980; Close et al. 2002; Riemer et al. 2011; Clemens et al. 2019). Native American tribes harvest Pacific Lamprey in freshwater for spiritual, subsistence, and medicinal purposes (Close et al. 2002; Wang and Schaller 2015; Noble et al. 2016). Pacific Lamprey have experienced declines in distribution partially due to migration barriers, such as dams. Dams impede migration and could be one major threat to Pacific Lamprey persistence (Close et al. 2002; Wang and Schaller 2015).

We developed a stepwise sampling approach to improve standardization and incorporate the potential for nondetection to address the question “what is the probability that a specific stream area is occupied by Pacific Lamprey if none are documented after sampling?” to aid species conservation and stream management. After describing the stepwise approach, we estimate detection probability of the approach in multiple streams in the Pacific Northwest and then illustrate use of the approach to assess the probability of occupancy both above and below a potential passage barrier for Pacific Lamprey in Gales Creek, Oregon. We selected a barrier assessment as an example of the approach since questions about whether specific barriers block Pacific Lamprey migration are common and vital for decisions regarding dam removal and passage in streams. Researchers could apply this stepwise sampling approach to other species and habitats; however, they must consider assumed values and field methods on a habitat- and species-specific basis. Similarly, we used a barrier assessment as an example, but others could apply the approach to a variety of occupancy questions relevant to larval lampreys, including, but not limited to, those discussed herein.

Stepwise approach description

**Step 1: define the occupancy question.** It is important for researchers to consider if an occupancy approach is appropriate to meet study or management purposes. Table 1 lists some potential purposes specific to Pacific Lamprey (not exhaustive) that researchers could address using our approach. One common example relevant to Pacific Lamprey could be to assess whether a specific dam is a barrier to upstream migration of adults. Researchers may accomplish this by evaluating the expected probability of occupancy in the stream both upstream and downstream of the dam. If field crews document Pacific Lamprey downstream, but not upstream, managers could use the expected probability that the area upstream is occupied to infer whether the dam is a barrier. It is essential to define what “occupied” means. Herein we use the simplest definition—at least one larval Pacific Lamprey.

**Step 2: select the maximum acceptable probability of occupancy, if researchers do not document the species during sampling (Mo).** If researchers document the species, the probability that Pacific Lamprey occupy the area is one. If they do not document species, the probability that the area is occupied ranges from zero to one, since nondetection can occur regardless of sampling techniques and effort. However, increased sampling effort and increased capture efficiency of sampling methods reduce the probability that Pacific Lamprey occupy the area (with no detections) and increase the probability that the area is truly unoccupied. Before sampling, we suggest managers and other stakeholders discuss what they consider the maximum acceptable probability of occupancy if field crews do not document the species during sampling (Mo). For this approach, selecting a lower value for Mo results in higher confidence that the area is unoccupied if no individuals are documented by sampling, but also means higher sampling effort requirements.

**Step 3: define an assumed detection probability for the target organism (d).** Herein, we define d as the probability that researchers detect the species in a sampling unit, given that the stream area of interest is occupied. Our definition for detection probability is different from that of standard occupancy approaches (MacKenzie et al. 2006) in that we do not sample repeatedly within units, so our d is a function of capture probability and density, but also distribution in the stream. Specifically,

\[ d = U \left( 1 - (1-C)^I \right) \]  

(1)

where U is the proportion of occupied sampling units, I is the number of individuals of the species in an occupied unit, and C is the capture probability of one individual. For our approach, an expected value of d must be assumed prior to sampling to calculate sampling effort. Ideally, the assumed value of d would be based on an empirical estimate calculated using similar field methods.
in an occupied stream with similar habitat. For example, assume 16 field units are sampled in an occupied stream with similar habitat and the species was detected in 12 units, the expected value of \( d \) could be estimated as the proportion of occupied units or 12 divided by 16 (i.e., 0.75).

**Step 4: calculate required sampling effort.** If researchers do not document the species by sampling, they can calculate the expected probability of occupancy (\( P[F(c_o)] \)) using a model developed from Bayes’ theorem and described by Peterson and Dunham (2003; also see MacKenzie et al. 2006; Jolley et al. 2012; Sethi and Benolkin 2013):

\[
P[F|c_o] = \frac{P(c_o | F) \cdot P(F)}{P(c_o | F) \cdot P(F) + P(c_o | \sim F) \cdot P(\sim F)}
\]

(2)

where \( P(F) \) is the prior probability of presence and \( P(\sim F) \) is the prior probability of absence (i.e., 1− \( P(F) \)). In general, we set \( P(F) \) and \( P(\sim F) \) to 0.5 suggesting that there is equal probability that the stream is occupied or not occupied before sampling (i.e., uninformed), but environmental factors, historical occupancy, and rarity in the region could inform these values (Peterson and Dunham 2003; Wintle et al. 2012). \( P(c_o | \sim F) \) is the probability of not detecting the species when the area is unoccupied. \( P(c_o | \sim F) \) is often set to one, indicating that detecting the species in an unoccupied area is not possible. However, if species misidentification is possible, \( P(c_o | \sim F) \) could be set to less than one. Researchers can accurately identify larval Pacific Lamprey greater than about 60 mm total length by caudal pigmentation while smaller individuals are more difficult to differentiate, but can be identified using genetic markers (Goodman et al. 2009; Docker et al. 2016). \( P(c_o | F) \) is the probability of not detecting the species in an occupied system and is a function of unit detection probability (i.e., \( d \)) and the number of interchangeable units sampled (\( n \); i.e., effort). \( P(c_o | F) \) is always 0–1 and is estimated as \((1 - d) ^n \). Thus, we can calculate a \( P[F|c_o] \) curve as a function of different levels of \( n \) to identify the number of sampling units needed to assess the probability of occupancy, if the species is not documented. Figure 1 illustrates examples of \( P[F(c_o)] \) curves for different assumed values of \( d \). The number of units to sample also depends on \( Mo \) (see Step 2). We include a script in Program R (R Core Team 2013) to calculate the \( P[F(c_o)] \) curve and to identify the number of units that need to be sampled to achieve \( Mo \) (Text S1, Supplemental Material).

**Step 5: select sampling units.** The definition of a sampling unit could depend on multiple factors including, but not limited to, species and life stage, stream habitat, and field gear. We limit potential units to those in the third-order portions of the stream to help eliminate units in unsuitable habitat for larval Pacific Lamprey (i.e., small or seasonally dry portions) or inaccessible habitat to backpack electrofishing (i.e., deep or fast flowing). There are many sampling schemes, including purely random or random stratified. Herein, we use a generalized random-tessellated stratified (GRTS) approach to delineate points

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**Table 1.** Study or assessment objectives that are important to Pacific Lamprey *Entosphenus tridentatus* research, management, and conservation, as well as the specific occupancy question addressed, and occupancy sampling requirements.

| Study or assessment objective | Management or research question addressed | Occupancy sampling methods |
|------------------------------|------------------------------------------|---------------------------|
| Evaluate a potential barrier to upstream migration | Are the areas upstream and downstream of the barrier occupied? | Sample upstream and downstream of the barrier |
| Evaluate if recolonization occurred after barrier removal or passage structure placement | Is the area upstream of the barrier occupied following removal or passage structure? | Sample downstream and upstream of the barrier, both before and after barrier removal or passage structure construction, potentially multiple times to examine recolonization timing and patterns |
| Determine stream candidacy for development (e.g., culvert installation), stream management (e.g., dredging), restoration (e.g., woody material placement), or recolonization (e.g., translocation) | Is the potentially affected area occupied? | Sample to assess probability of occupancy |

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**Figure 1.** Solid lines represent calculations of the expected probability of occupancy, if researchers do not document the species, by the number of reaches sampled, for multiple examples of detection probability (given \( P[F] \) and \( P[\sim F] \) are 0.5 and \( P(c_o | \sim F) \) is one). The dark grey dashed lines illustrate the number of 50-m reaches needed for the probability of stream occupancy by Pacific Lamprey *Entosphenus tridentatus* to be a maximum of 0.05 if detection probability is assumed to be 0.4 (i.e., example in Gales Creek, Oregon).
to use as sample units. The GRTS approach uses a reverse hierarchical ordering procedure to generate numerically ordered points that are random and spatially balanced (Stevens and Olsen 2004). We include a script in Program R to use GRTS to delineate points in the area of interest at an average rate of one point for every 500 m of stream (Text S2, Supplemental Material). Here we defined the GRTS points as a 50-m-long sample reach, a sample unit convention adopted from previous work used to assess Bull Trout Salvelinus confluentus occupancy in wadeable streams (USFWS 2008). If we are not able to sample a reach (due to safety concerns, lack of access, dewatered conditions, etc.), we replace it with the next lowest numbered reach; this does not violate the spatial balance. We suggest use of a spatially balanced design to ensure spatial coverage and improve precision when compared to simple random sampling, especially when a species exhibits a clumped distribution (Lawrence et al. 2015; Liermann et al. 2015; McGarvey et al. 2016), as observed for larval lampreys (Torgersen and Close 2004; Stone and Barndt 2005).

Step 6: conduct sampling. Similar to sampling units, field sampling methods also depend on factors such as stream habitat and catchability of the species. Researchers have assessed larval Pacific Lamprey occupancy by backpack electrofishing (Dunham et al. 2013; Reid and Goodman 2015). Herein, we conducted backpack electrofishing with an AbP-2 electrofisher (ETS Electrofishing Systems, Madison, WI). This electrofisher produces two pulse frequencies: the primary output is pulsed direct current in a 3:1 pattern (every fourth pulse deleted) which stimulates larvae to emerge from the sediment; the secondary output is a higher-frequency standard direct current (30 Hz) activated to induce muscle tetany once larvae have emerged (Weisser and Klar 1990; Bowen et al. 2003). This electrofisher was designed to capture larval lamprey (Weisser and Klar 1990) and capture probability averages ~0.28, but is highly variable (Harris et al. 2016). Sampling can cease when all selected reaches are sampled or an occupancy state of one is confirmed.

Step 7: interpret sampling results into probabilistic occupancy conclusions. Conclusions should refer to study objectives and assumptions and are probabilistic in nature. For example, “a larval Pacific Lamprey was identified during sampling; thus, the stream is occupied with a probability of one.” Alternatively, “zero Pacific Lamprey larvae were identified during sampling; thus, the expected maximum probability of occupancy is 0.05 at an assumed d of 0.4.”

Detection probability for larval lampreys

To examine expected values and variability in d among streams and to identify expected sampling effort for future studies in streams of unknown occupancy state, we estimated d and the P(F|C0) curves for eight occupied stream areas in the Pacific Northwest (Figure 2; Ostberg et al. 2019; Data S1, Supplemental Material). We examined the efficiency of our approach by examining the range in expected values of d and P(F|C0) curves among streams. Variability in d and the associated P(F|C0) curves elucidate implications of poor assumptions of d; most notably, selection of an expected value of d that is too high would result in an underestimate of the probability of occupancy, if the species was not documented. We sampled using our approach for 6–16 50-m reaches in each occupied stream. We included only third-order portions of each occupied stream considered accessible to Pacific Lamprey (i.e., downstream of known migration barriers). We estimated d using a binomial model for each stream separately (i.e., to examine for variation among streams) and then overall including data from all streams combined (i.e., to produce a median estimate).

For each estimate of d, we calculated the P(F|C0) curve (Step 4: sampling effort). We estimated d and the P(F|C0) curves using Bayesian analysis methods with JAGS software (Plummer 2003) called from Program R. We used Package jagsUI with function autojags (Kellner 2017) for three chains with 2,000 adaption iterations, 5,000 burn-in iterations, and we saved enough iterations (increments of 25,000) to reach convergence as assessed by Rhat scores of 1.1 or less for all estimated parameters (Gelman and Hill 2007; K´ery and Schaub 2012). Priors for d were beta distributions with both shape parameters set to one (i.e., all were beta (1,1) distributions). We reported each expected value as the median of the posterior distribution and precision as the 95% credible interval (95% CI) on the posterior distribution.

Approach application

We applied our approach to assess if Balm Grove Dam is a complete barrier to upstream migration of Pacific Lamprey in Gales Creek, Oregon. Gales Creek is a third-order tributary of the Tualatin River. Pacific Lamprey occupy lower portions of Gales Creek and other streams in the Tualatin River basin (Schultz et al. 2016). However, Balm Grove Dam, located about 20 km upstream of the confluence, is a potential barrier to upstream migration and occupancy upstream of the dam is unknown. We assumed that the presence of larval Pacific Lamprey upstream of Balm Grove Dam would indicate that the dam was not an impediment to spawning migration for adults. We used empirical estimates of larval Pacific Lamprey detection probability from streams in Washington and Oregon (Data S1) to guide the selection of a detection probability value for Gales Creek.

Results

Detection probability for larval lampreys

We estimated d and the P(F|C0) curves for Pacific Lamprey in eight streams in the Pacific Northwest (Figure 3; Data S1). Estimates of d ranged from 0.15 (95% CI: 0.02–0.41) to 0.94 (95% CI: 0.71–1.00). Ranges for 95% CI were generally large, but still did not overlap for all example systems suggesting that d differs among third-order streams for larval lamprey (Figure 3). Depending on d,
Figure 2. Map illustrating the stream occupancy sampling locations for larval Pacific Lamprey *Entosphenus tridentatus* in Washington and Oregon: Washougal River, Gales Creek, Cedar Creek, Newaukum River, Skookumchuck River, Black River, Wynoochee River, and Wishkah River (highlighted by darker blue). Sampling was conducted from 2008–2016 to assess expected values and variability in detection probability and the expected probability of occupancy if researchers do not document Pacific Lamprey larvae.
Figure 3. Estimates of detection probability \( (d) \) with 95% credible intervals (in parentheses) and the expected probability of occupancy associated with those estimates of detection probability, if researchers do not document larvae, for Pacific Lamprey *Entosphenus tridentatus* in eight occupied Pacific Northwest streams. The eight occupied streams sampled from 2008–2016 were Washougal River, Gales Creek, Cedar Creek, Newaukum River, Skookumchuck River, Black River, Wynoochee River, and Wishkah River (see Figure 2 for stream locations). Black lines illustrate the median estimates of probability of occupancy and the grey lines indicate the 97.5% and 2.5% credible intervals.
We developed a stepwise approach including sampling methods, effort needed, and unit selection, to

Step 2: select the maximum acceptable probability of occupancy, if researchers do not document the species during sampling (Mo). We set Mo at 0.05 for demonstration purposes. Researchers must select the Mo for each study individually based on stakeholder input regarding the appropriate maximum acceptable probability of occupancy, if researchers do not document the species during sampling.

Step 3: define an assumed detection probability for the target organism (d). We assumed d was 0.4 for Gales Creek. This value was substantially more conservative than the median estimate we produced for Pacific Lamprey (Figure 4). We assumed a conservative detection probability estimate because our examination of detection probability suggested variability in d among streams (Figure 3) and reduced upstream passage at Balm Grove Dam (during all or some years) could lead to lower density or a more patchy distribution of larvae than in other locations without a potential barrier.

Step 4: calculate required sampling effort. We used inputs of 0.05 for Mo and 0.4 for d to calculate the expected P(F_{C}) curve (Text S1). The model indicated that we should sample six 50-m reaches both downstream and upstream of Balm Grove Dam (see dashed lines in Figure 1).

Step 5: select sampling units. We used GRTS to delineate sample points in Gales Creek (Data S2, Supplemental Material). The third-order portion of Gales Creek is just over 33.5 km in length, so we scripted Program R to delineate 67 sample points for an average rate of one point for every 500 m of creek (Text S2, Supplemental Material). We gave the six lowest numbered reaches below Balm Grove Dam and the six lowest numbered reaches above the dam the highest priority for sampling. We defined the sample points generated by GRTS as the downstream boundaries of the 50-m-long sample reaches, which is where we would begin electrofishing sampling for each reach.

Step 6: conduct sampling. We sampled the six selected reaches in each area using electrofishing field methods described above. We stopped sampling in a reach if a larval Pacific Lamprey was documented.

Step 7: interpret sampling results into probabilistic occupancy conclusions. We detected larval Pacific Lamprey (n = 33) in all six reaches downstream of Balm Grove Dam and zero of six reaches upstream of the dam. Pacific Lamprey occupy Gales Creek below Balm Grove Dam with a probability of one. Since we did not detect any individuals, the expected maximum probability of occupancy of Gales Creek upstream of Balm Grove Dam is the predefined Mo value of 0.05 at an assumed detection probability of 0.4. Our results support the suggestion that Balm Grove Dam is a barrier to upstream movement of adult Pacific Lamprey.

Discussion

We developed a stepwise approach including sampling methods, effort needed, and unit selection, to
help researchers identify the occupancy state of larval lamprey in a stream to support Pacific Lamprey management and conservation. Most occupancy methods focus on estimating the proportion of occupied sites in a larger occupied area of interest (MacKenzie et al. 2006). These occupancy studies require repeated sampling of some occupied sites over time to adjust for nondetection and to differentiate environmental patterns in occupancy from environmental patterns in detection. The main purpose of such studies is to understand what impacts occupancy and detection patterns across a landscape (MacKenzie et al. 2006; Benoît et al. 2018). In contrast, the goal of our approach is to delineate the sampling needed to meet a selected maximum probability of occupancy in a specific stream, if zero individuals are detected during sampling, without sampling in multiple streams. Researchers using the method identify the maximum level of effort needed and the actual sampling locations before sampling (i.e., in case zero individuals are detected), but may cease sampling as soon as they have identified the occupancy state as one (i.e., one individual is detected). Researchers can include previous information by modifying prior probabilities of occupancy or species misidentification, if needed (Peterson and Dunham 2003; Wintle et al. 2012). Although we have illustrated our approach for larval Pacific Lamprey sampled by backpack electrofishing in a stream, researchers could apply the general stepwise approach to other species and systems, although they must make careful consideration with regard to assumptions about detection probability and interpretation.

Our approach makes an a priori assumption about detection probability and interpretation should reflect that assumption. Our results suggest that detection probability for larval lamprey varies among streams and assuming different values for detection probability can affect the identified number of reaches to sample to assess the probability of occupancy, if the species is not documented (Figure 3). True detection probability is affected by capture probability, as well as species density and distribution in the stream. Electrofishing capture probability is affected by environmental factors (e.g., water temperature, turbidity, conductivity, etc.), sampling techniques, and personnel (Price and Peterson 2010; Benejam et al. 2012; Rodtka et al. 2015). By standardizing field sampling methods and seasonal periods, and by training field crews, researchers can reduce variability in capture efficiency. For example, we typically sample in summer and early fall, when water currents and depths are at their lowest and visibility is at its highest, to maximize electrofishing capture probability. Detection probability is also impacted by larval density and distribution. Adult Pacific Lamprey build redds in gravel and cobble substrates (Gunckel et al. 2009; Mayfield et al. 2014) and larvae prefer to burrow in fine sediments (Torgersen and Close 2004; Stone and Barndt 2005; Figure 5). Thus, quantity and distribution of gravel and fine sediments may affect larval density and distribution. Detection probability estimated by sampling in similar streams with known occupancy state of one can provide information about detection probability in a stream with unknown occupancy state. Given variability in distribution, habitat, and capture probability, as well as environmental and demographic stochasticity, evaluating effort needs over a range of potential detection probability values before sampling and assuming a conservative (i.e., low) value for detection probability may be optimal. Even assuming the lowest observed estimate of detection probability, researchers would need to sample only 19 units for the probability of occupancy to be not more than 0.05, if they detect no individuals. Sampling in up to 19 units would likely be practical (i.e., acceptably low level of effort in terms of time and money) as part of an assessment plan conducted to aid decisions about future development, translocation, or restoration projects in a stream. Research examining factors that affect detection probability would help inform effort in future studies.

Despite variability among streams, our results suggest that detection probability for Pacific Lamprey larvae associated with our approach is high for most occupied streams (Figure 3). Our Bayesian estimates of detection probability in Pacific Northwest streams ranged from 0.15 to 0.94 and the overall estimate including all streams was 0.70 (95% CI: 0.60–0.79). Our

Figure 5. Upper panel: Adult Pacific Lamprey Entosphenus tridentatus on spawning substrate (photo credit: Jeremy Monroe at Freshwaters Illustrated); lower panel: larval Pacific Lamprey burrowed in sand (photo credit: David Herasimtschuk at Freshwaters Illustrated).
results suggest that, for many streams, researchers need to complete relatively little sampling to obtain a low (i.e., <0.05) expected probability of occupancy, if they do not document the species by sampling. Pacific Lamprey are highly fecund (Clemens et al. 2013) and larvae disperse in a mostly downstream direction (Quintella et al. 2005; Moser et al. 2015). Thus, larvae may be extensively distributed downstream of spawning areas if habitat is acceptable. In experimental studies, Liedtke et al. (2015) found that larval Pacific Lamprey burrowed less than 15 cm below the sediment surface and Harris et al. (2016) estimated average capture probability of our backpack electrofishing protocol at 0.28. As a result of biology, dispersal, and relatively high catchability of backpack electrofishing, detection probability for larval lamprey is usually high (Dunham et al. 2013; Reid and Goodman 2015; Ostberg et al. 2019).

We designed our approach to address questions about occupancy state of larval Pacific Lamprey to make informed decisions about restoration, translocation, passage, and land use in a stream (see Table 1). Our approach requires managers to assume a value for detection probability and to select the maximum acceptable probability of occupancy to ensure they achieve the level of certainty needed for the specific stream management objectives. Although the estimate of median detection probability is 0.70 (95% CI: 0.60–0.79), we recommend carefully considering the potential range for detection probability and assuming a conservative value; thus, the probability of occupancy will be no more than the maximum acceptable value, if researchers do not document the species during sampling. For example, dredging a stream bottom for navigation might only be acceptable if results suggest that the expected probability of occupancy by Pacific Lamprey is less than 0.01 at a conservative detection probability of 0.1; this would require sampling 44 50-m units. Alternatively, installation of a passage structure might be considered if the probability of occupancy is one downstream of the barrier, but only 0.1 upstream of the barrier at a detection probability of 0.3; this would require sampling seven 50-m units. We did not collect Pacific Lamprey larvae above Balm Grove Dam; thus, we conclude that the maximum probability of occupancy upstream is the selected $Mo$ value of 0.05 at the assumed detection probability of 0.4. Our results suggest that Balm Grove Dam is a barrier to upstream migration of adult Pacific Lamprey and managers can use this information to evaluate the potential benefits of dam removal or construction of a lamprey passage structure in Gales Creek. Although we evaluated specific field methods and estimates of detection probability for larval lamprey in streams, researchers could apply the overall stepwise approach to other species and systems, although the researchers may need to modify field methods and estimates of detection probability. Ultimately, this approach allows users to design a sampling plan to assess the occupancy state of an area that incorporates the potential for nondetection to meet project-specific targets to guide species conservation and area management projects.

**Supplemental Material**

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**Data S1.** Data used to estimate detection probability of larval Pacific Lamprey *Entosphenus tridentatus* in the Pacific Northwest, by stream name and river basin. Data include the number of 50-m reaches we sampled by electrofishing in each stream (R) and the number of 50-m reaches from which we identified at least one Pacific Lamprey larvae (L). We conducted sampling 2008–2016 using the approach (and all associated methods), as described in the text. The eight streams sampled were Washougal River, Gales Creek, Cedar Creek, Newaukum River, Skookumchuck River, Black River, Wynoochee River, and Wishkah River. Figure 2 is a map illustrating the geographical locations of the sampled streams.

Found at DOI: [https://doi.org/10.3996/112018-JFWM-107.S1](https://doi.org/10.3996/112018-JFWM-107.S1) (16 KB DOCK).

**Data S2.** Shapefiles (zipped) for the third-order portion of Gales Creek, Oregon, that we used to order reaches for sampling both below and above Balm Grove Dam. Data for Gales Creek (projected: UTM NAD83 Zone 10, meters) are from a stream layer in the National Hydrography Dataset.

Found at DOI: [https://doi.org/10.3996/112018-JFWM-107.S2](https://doi.org/10.3996/112018-JFWM-107.S2) (231 KB ZIP); also available at [https://www.usgs.gov/core-science-systems/ngp/national-hydrography/national-hydrography-dataset?qt-science_support_page_related_con=0#qt-science_support_page_related_con](https://www.usgs.gov/core-science-systems/ngp/national-hydrography/national-hydrography-dataset?qt-science_support_page_related_con=0#qt-science_support_page_related_con).

**Text S1.** Code to calculate the probability of occupancy curve and to identify the number of units that need to be sampled to meet a selected maximum acceptable probability of occupancy, in case a species is not documented by sampling. The code is a script for Program R. The user must specify values for INPUT PARAMETERS. Current values for INPUT PARAMETERS are those we used to estimate the number of sampling units needed to assess Balm Grove Dam (on Gales Creek, Oregon) as a potential barrier to upstream migration by Pacific Lamprey *Entosphenus tridentatus*. BLACK LINE indicates the probability of occupancy, if the species is not documented. BLUE LINE indicates the number of units (i.e., 50-m reaches) to sample. RED LINE indicates the maximum acceptable probability of occupancy, if researchers do not document the species.

Found at DOI: [https://doi.org/10.3996/112018-JFWM-107.S3](https://doi.org/10.3996/112018-JFWM-107.S3) (3 KB R).

**Text S2.** Code to order and provide coordinates and shapefiles for stream reaches by generalized random-
tessellated stratified (GRTS) approach. User must have linear shape files (zipped) for stream of interest and label files accordingly. User must know the total length of the stream area of interest in kilometers (KM). The code is a script for Program R. User must install and run specified R libraries. Current values and labels in INPUT SECTION are those we used to order sampling reaches needed to assess Balm Grove Dam (on Gales Creek, Oregon) as a potential barrier to upstream migration by Pacific Lamprey *Entosphenus tridentatus*. To run this R script, Data S2.zip (Data S2, Supplemental Material) must be included in the working directory file, along with this R script.

Found at DOI: https://doi.org/10.3996/112018-JFWM-107.S4 (3 KB R).

**Reference S1.** Liedtke TL, Weiland LK, Mesa MG. 2015. Vulnerability of larval lamprey to Columbia River hydropower system operations—effects of dewatering on larval lamprey movements and survival. U.S. Geological Survey Open-File Report 2015-1157, Reston, Virginia.

Found at DOI: https://doi.org/10.3996/112018-JFWM-107.S5 (1.04 MB PDF); also available at https://pubs.usgs.gov/of/2015/1157/ofr20151157.pdf

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