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ARTICLE

Using Spatial Resampling to Assess Redd Count Survey Length Requirements for Pacific Lamprey

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Abstract
Pacific Lamprey *Entosphenus tridentatus* has declined across its range along the West Coast of North America, and an understanding of all life history phases is needed to address population recovery. Spawning surveys (redd counts) are common tools currently used to monitor returning adult salmonids, but such methodologies are in their infancy for Pacific Lamprey. Our objective was to assess the minimum spawning survey distance required to detect the presence of Pacific Lamprey redds and obtain precise redd density estimates from these data. To do this, we statistically resampled existing spawning locations of Pacific Lamprey collected during spawning surveys in four streams of the Willamette River Basin, Oregon, during spring of 2013. We found that the minimum survey distance for Pacific Lamprey redd detection was inversely related to the observed redd density and was always less than 1.2 km. Survey distance requirements to obtain precise redd counts (±20% of observed redd densities) were also inversely related to redd density and habitat availability, and varied between 1.3 km and 13.7 km. Our results suggest that spawning surveys are a potential tool for monitoring adult Pacific Lamprey abundance, but the specific objectives of the monitoring programs and acknowledgment of unknowns must be considered prior to implementation into recovery plans.

Pacific Lamprey *Entosphenus tridentatus* is considered a cultural and ecological icon for native peoples of the Pacific Northwest (CRITFC 2011). The species has declined considerably across its range in western North America, and complete extirpation has occurred in multiple drainages (Moser and Close 2003). Between 1939 and 1969, Pacific Lamprey counts at Bonneville Dam on the Columbia River averaged over 100,000 adults but had declined to an average of less than 40,000 between 1997 and 2010 (Murauskas et al. 2013). The Columbia River is not the only location that has experienced a decline of Pacific Lamprey runs; annual abundance in 2009 and 2010 were estimated at less than 500 individuals at the Winchester Dam on the North Umpqua River, while historical adult abundance (1965–1971) was estimated at between 14,532 and 46,785 (Goodman et al. 2005). Despite the many important ecological and cultural roles of Pacific Lamprey (outlined in Close et al. 2002), conservation efforts have been hampered by numerous knowledge gaps in its biology (Luzier et al. 2011). Of the areas where the species has persisted, the Willamette River, Oregon, has one of the highest remaining adult abundances (Kostow 2002), and Willamette Falls (approximately 42 km upstream of the Columbia River confluence) currently supports one of the few remaining harvest locations for Pacific Lamprey. Although migrating adult populations can be monitored at natural and man-made barriers, little

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is known about Pacific Lamprey spawning distribution, characteristics (e.g., abundance, timing, habitat use), or populations within tributaries (CRITFC 2011).

To understand how Pacific Lamprey use available habitat in a large river system, it is important to develop methods for monitoring all life history stages, including the spawning stage. Redd surveys have been used for many years to monitor both anadromous and nonanadromous salmonid populations due to their nonintrusive nature, relatively low cost, and ability to survey large areas with little effort (Gallagher et al. 2007; Dunham et al. 2009). While redd count methods have been routinely implemented for salmonids, the development of standardized spawning surveys for Pacific Lamprey is in its infancy (Stone 2006; Brumo et al. 2009; Gunckel et al. 2009). In general, salmonid and Pacific Lamprey redds can be counted by using similar methods, but the assumptions related to redd counts, specifically redd detection rates, must be examined and addressed for Pacific Lamprey (Dunham et al. 2009).

Spawning surveys for Pacific Lamprey have traditionally been problematic for several reasons, including confusion of Pacific Lamprey redds with salmonid redds (Stone 2006), false identification in low- or high-density areas (Brumo et al. 2009), questions about redd longevity and loss (Stone 2006), and the relationship between redd counts and spawning adult numbers (Moser et al. 2007). Despite the potential sources of error, redd counts remain an efficient method to monitor populations and to assess Pacific Lamprey distribution, particularly with proper surveyor training (Wyss et al. 2013). For redd counts to be an effective monitoring tool, it will be important to ensure that surveys are conducted in a manner that both reduces bias and increases efficiency. Our objectives were to evaluate the required length (i.e., distance) of redd surveys for spawning Pacific Lamprey to allow for redd detection and to estimate redd density within an acceptable level of precision. To address this objective, we spatially resampled georeferenced spawning locations of Pacific Lamprey. By determining the suitable distance for surveying Pacific Lamprey redds, our analyses will increase surveying efficiency, allow sampling of larger spatial areas, and help address pertinent management questions.

METHODS

Redd counts.—We monitored Pacific Lamprey spawning activity from late April through mid-June 2013 in four tributaries to the Willamette River Basin: Calapooia River, Luckiamute River, Marys River, and Thomas Creek (Figure 1). Our spawning survey methodologies were based on those used by other adult Pacific Lamprey studies (Stone 2006; Brumo et al. 2009; Gunckel et al. 2009) and included insights from preliminary spawning surveys conducted in the Willamette River Basin during 2011 (Clemens et al. 2012) and from redd counts for anadromous salmonid species (Gallagher et al. 2007). Survey locations were selected based on stream access, our ability to safely float in personal watercraft, and streams where larval Pacific Lamprey sampling was also conducted (Wyss et al. 2012, 2013). We selected survey segments to represent available habitat in each tributary; survey segments included all underlying geologic types present in each tributary (see below).

We conducted spawning surveys in multiple tributaries to the Willamette River to capture the spatial variability of spawning activity. Redd count surveys were initiated during 2012 to evaluate and refine survey methodology. These included two survey segments on both the Marys River and Thomas Creek; the Marys River had contiguous survey segments, whereas the survey segments on Thomas Creek were spatially discrete (Figure 1). In 2013, redd count surveys continued in those streams and we added single survey segments on the Calapooia and Luckiamute rivers (Figure 1). We had no a priori knowledge of the current distribution of Pacific Lamprey in these latter two rivers, except for radiotelemetric indications that adults had entered these streams near their confluence with the Willamette River (Clemens et al. 2012). We used only 2013 data for the analysis presented. In that year we surveyed these four streams with different habitats and peak redd densities, and all surveys were conducted with the same personnel that were trained to classify Pacific Lamprey redds. Additionally, relatively low water discharge and increased water clarity in 2013 increased our confidence in redd observation and counts.

All surveys were conducted by two surveyors in individual inflatable pontoon boats with each covering an area from stream bank to midchannel to observe the entire channel. We enumerated all Pacific Lamprey redds, live adults, and carcasses that were observed in each surveyed segment. Although subjectivity exists in redd surveys (Dunham et al. 2001), we defined redds as round depressions in the stream substrate that appeared to be actively excavated (Stone 2006). Larger rocks are frequently moved by Pacific Lamprey to the edge of redd depressions (Gunckel et al. 2009), an additional characteristic we used to differentiate Pacific Lamprey redds from those of other fishes. Additionally, the presence of actively spawning adult Pacific Lamprey in redds helped confirm our redd identification. Brook Lamprey *Lampetra richardsoni* (or *L. pacifica*) also spawn during the timeframe of Pacific Lamprey. However, median Brook Lamprey redd size (0.03 m^2) is much smaller than median Pacific Lamprey redd size (0.124 m^2; Stone 2006; Gunckel et al. 2009). If large areas of substrate appeared to be disturbed or redds appeared to overlap one another, as has been observed by Stone (2006) and Brumo et al. (2009), we counted each discrete depression as an individual redd.

Each segment was visited multiple times from April through June to capture temporal variability in spawning activity and to observe peak redd counts (i.e., the highest number of redds observed in all visits). Because no information is currently available related to the frequency of surveys needed for monitoring Pacific Lamprey redds, we attempted to visit each survey segment every 10–14 d, as is recommended in the salmonid literature (Gallagher et al. 2007). We considered our sampling recurrence appropriate to detect redds of various ages because median

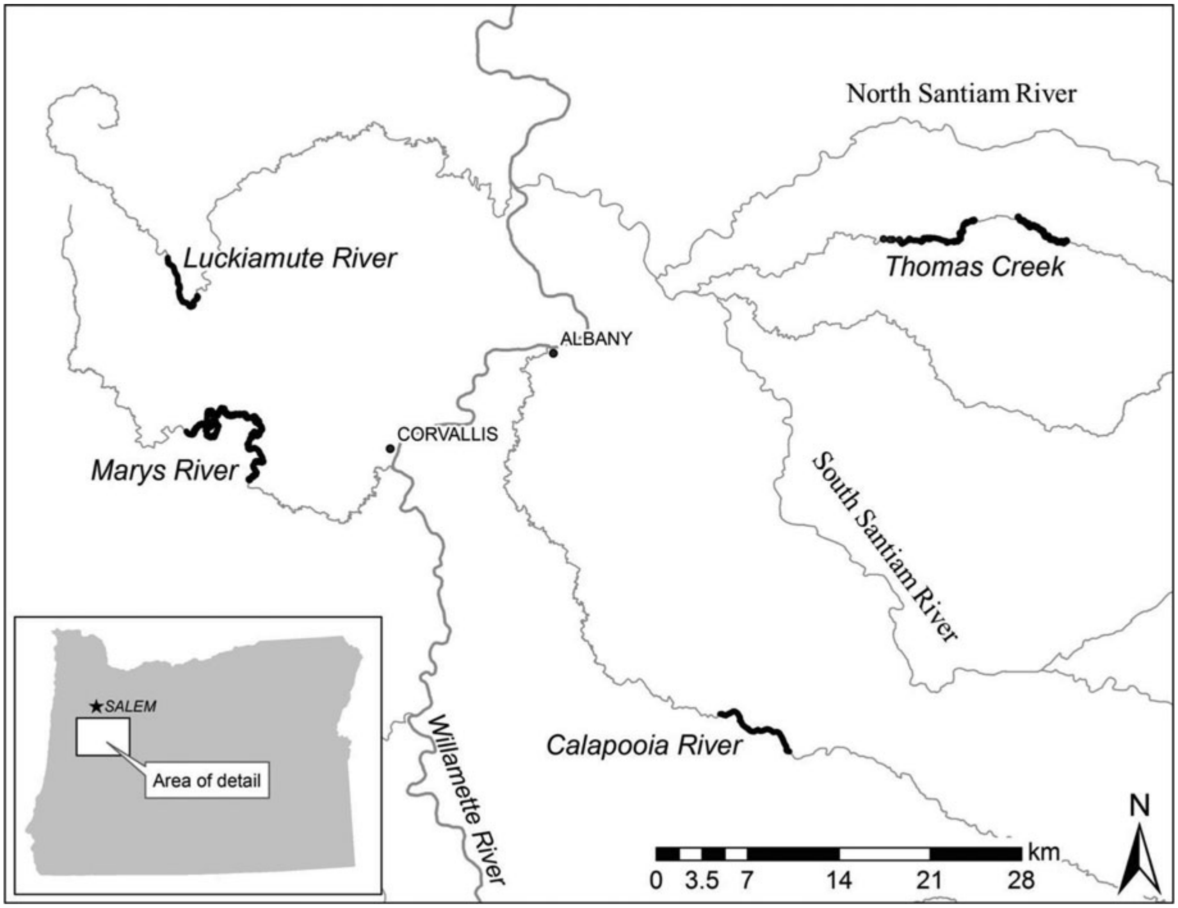

FIGURE 1. Pacific Lamprey spawning survey locations in four tributaries of the Willamette River, 2013. Segments of streams surveyed are in bold. Additional details on the distribution of redds within survey segments are shown in Figure 2.

longevity of Pacific Lamprey redds has been reported at 40 d with a minimum longevity of 10 d (Stone 2006). Occasionally, weather events and hydrologic conditions precluded completion of our surveys on schedule; those surveys were completed as soon as stream conditions permitted surveying.

We georeferenced all Pacific Lamprey redds identified during surveys using a hand-held global positioning system unit to generate redd distribution maps for each survey (Figure 2). We used linear referencing tools in ArcGIS version 10.1 (ESRI 2012) to determine the stream kilometer (as measured from the confluence of the tributary with a major river) of each redd location within a survey. We used existing geologic maps (Walker and MacLeod 1991) to calculate the percent of the stream survey distance with alluvial underlying geology in each survey segment. Alluvial geology, defined as underlying sediments that were deposited by moving water, included fine-grain alluvial, medium-grain alluvial, and Missoula Flood alluvial geologic types from geologic maps. In our related work (Schultz et al. 2014), we found that Pacific Lamprey selected for reaches with alluvial geology across the Willamette River Basin, and the resulting spatial distribution of redds (i.e., "clumpiness") was strongly related to these underlying geologic patterns. Our surveys encompassed a wide range of stream types and habitats on both the west and east sides of the Willamette Basin, with headwaters located in the Coast Range and Cascade Mountains, respectively (Table 1). We conducted several surveys in each segment at different times during the spawning season, but the peak redd density observed for each survey segment was used for analysis purposes, as is commonly done with redd count data analyses (Gallagher et al. 2007).

Spatial resampling analysis.—We used spatial resampling of the georeferenced redd locations of each survey segment to evaluate suitable survey lengths (i.e., distance) in future sampling. A sequence of simulated subsample lengths was developed, beginning with 0.1 km and continuing by adding 0.1 km to every subsequent survey segment length until reaching a final subsample length of 1.0 km less than the total survey segment length (e.g., the Calapooia River survey was 7.3 km, so the subsample lengths we used varied from 0.1 to 6.3 km at 0.1-km intervals). For each subsample length, a continuous segment of that length was randomly selected from within our spatial data set of redd locations and the density of redds in that segment was calculated.

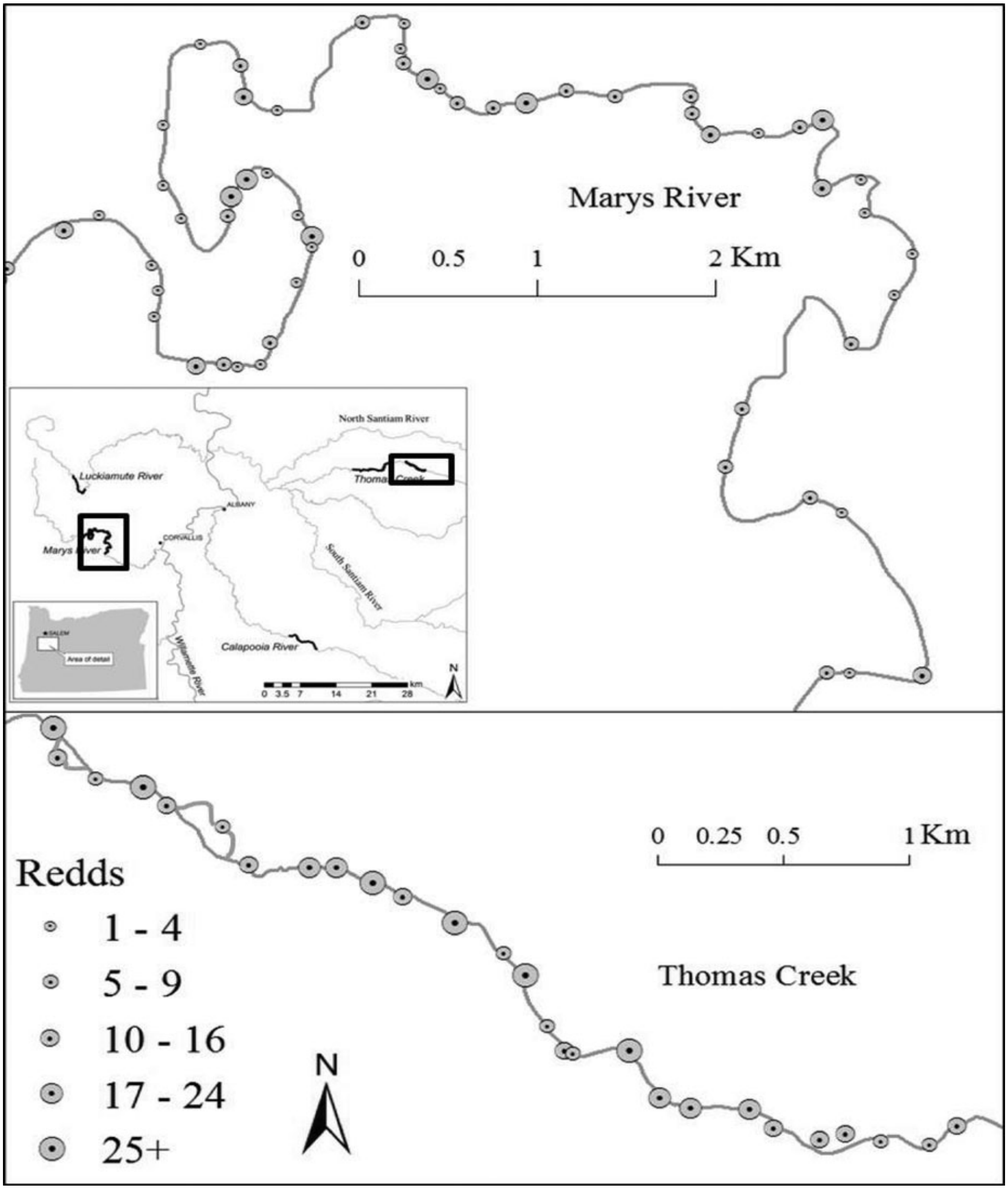

FIGURE 2. Distribution of Pacific Lamprey redds in the upper survey segment of Thomas Creek and in the Marys River, Oregon. For each location where redds were observed, the number of redds at that location is indicated by the size of the symbol, and the map indicates the degree of clumpiness of Pacific Lamprey redds for relatively high and low redd densities in upper Thomas Creek and Marys River, respectively. We spatially resampled from this observed distribution to assess minimum survey distance to detect redds and obtain redd densities within 20% of observed. Note: inset is Figure 1.

This procedure was repeated (with replacement) 10,000 times for each subsample length. Subsamples were restricted to be fully within the actual surveyed stream segment to ensure that no edge correction was needed. From each simulated subsample length, we determined the mean, maximum, and minimum redd density values from the 10,000 resamples. All resampling simulations were completed in Program R (R Core Development Team 2013).

TABLE 1. Observed peak redd density, percent alluvial geologic composition, and survey length requirements of three spawning activity metrics for survey segments in the Willamette River Basin. Survey length requirements were calculated from spatial resampling simulations to determine length needed to detect Pacific Lamprey spawning presence (>0.0 redds/km) and redd densities within acceptable error range (lower error level = 80% of observed, upper error level = 120% of observed). Mean stream width was measured during summer base-flow conditions.

					Survey length requirements (km)		
Survey	Segment length (km)	Observed peak (redds/km)	Mean stream width (m)	% Alluvial	Detection	80% of observed	120% of observed
Marys River	19.2	22.9	17.3	67	1.2	10.4	13.7
Luckiamute River	5.6	47.2	16.8	80	0.7	4.9	2.4
Calapooia River	7.3	88.5	15.7	100	0.5	2.8	3.0
Thomas Creek, upper	4.2	116.2	19.6	100	0.3	2.4	1.3
Thomas Creek, lower	7.0	137.0	19.7	100	0.3	2.4	3.2

We used the mean, maximum, and minimum redd density values for each subsample to determine both the minimum survey distance necessary to detect Pacific Lamprey redds and the distance required to obtain precise redd density estimates. The minimum distance to detect redds was determined by identifying the survey length in which all simulations had a redd density greater than 0.0 redds/km. We considered redd density estimates to be precise if both the minimum and maximum redd counts for each simulated segment length were within ±20% of the observed redd density for the entire survey segment. We included this measure of error to account for surveyor-related differences in redd detection rates. Our experience with Pacific Lamprey redd surveys provided evidence that our redd counts were minimally biased, but it is likely that we and others might misidentify or omit redds during surveys. Although there is much variation in redd detection rates in the literature, we chose the 20% error based on the estimated detection rates of 0.83 from surveys of bull trout redds (Muhlfeld et al. 2006), but were slightly more conservative by rounding this to an estimated detection rate of 0.80. This estimate is conservative based on other salmonid redd counts, in which estimated individual detection rates ranged from 0.28 to 2.54 (Dunham et al. 2001; Gallagher and Gallagher 2005).

RESULTS

Redd Count Surveys

During the 2013 spawning season, we surveyed 43.3 km of stream habitat in locations throughout the Willamette River Basin, with individual survey lengths ranging from 4.2 km in upper Thomas Creek to 19.2 km of total continuous survey distance in Marys River (Table 1). Peak redd densities differed among streams, varying from 22.9 redds/km in the Marys River to 137.0 redds/km in the lower segment of Thomas Creek (Table 1). Although our sample size and the range of observed percentage of alluvial underlying geology were limited, variation in redd densities appeared to be related to the percentage of alluvial underlying geology; streams with lower observed redd densities (i.e., the Marys and Luckiamute rivers) had a lower proportion of alluvial geology, while the Calapooia River and Thomas Creek consisted entirely of alluvial geology and had much higher redd densities (Table 1). In the two streams with multiple years of survey data (i.e., the Marys River and Thomas Creek), the redd densities from 2013 were similar to those observed in previous years.

Spatial Resampling Simulations

We observed an inverse relationship between the minimum survey distance needed to detect Pacific Lamprey redds and observed redd density with our spatial resampling simulations. In the Marys River, the survey with the lowest redd density, a survey distance of 1.2 km was needed to detect redds (Table 1 and Figure 3). In contrast, in both sections of Thomas Creek, which had our highest observed redd densities, only 0.3 km was needed to detect redds (Table 1 and Figure 4). For the Luckiamute and Calapooia rivers, two streams with moderate redd densities, the survey lengths needed for detection were 0.7 and 0.5 km, respectively (Table 1 and Figures 3 and 4).

The survey length needed to obtain simulated redd densities within ±20% of observed redd densities generally decreased as observed redd density and the percentage of alluvial geology increased (Table 1). Because the minimum and maximum simulated redd density values were not symmetrical around the mean, the required survey lengths for each stream differed for the lower error level (80% of observed redd density) and the upper error level (120% of observed redd density); in our assessments, we used the longer survey length. The three surveys with the highest redd densities (upper and lower Thomas Creek and the Calapooia River) required minimum survey lengths of 2.4, 3.2, and 3.0 km, respectively, to obtain a subsample within ±20% of the observed redd density (Table 1 and Figure 4). In the streams with lower redd densities, a longer survey length was needed to obtain precise redd density estimates. For the Luckiamute River, a survey length of 4.9 km was needed to obtain precise redd density estimates, whereas the Marys River required a survey length of 13.7 km.

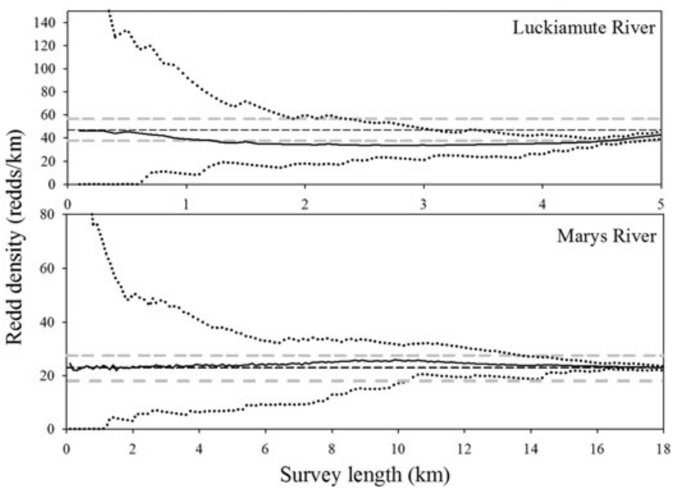

FIGURE 3. Spatial resampling simulation results of mean redd density (solid line), minimum and maximum values (dotted lines), and the observed mean redd density (dashed line) for study surveys in the Luckiamute and Marys Rivers, two streams with a mix of alluvial and nonalluvial underlying geology. Dashed gray lines indicate ±20% of the observed redd density, and the points where minimum and maximum values both lie within the dashed lines indicate the survey length requirements for obtaining a relatively precise redd density measurement. Note differences in scale of *y*-axes between panels.

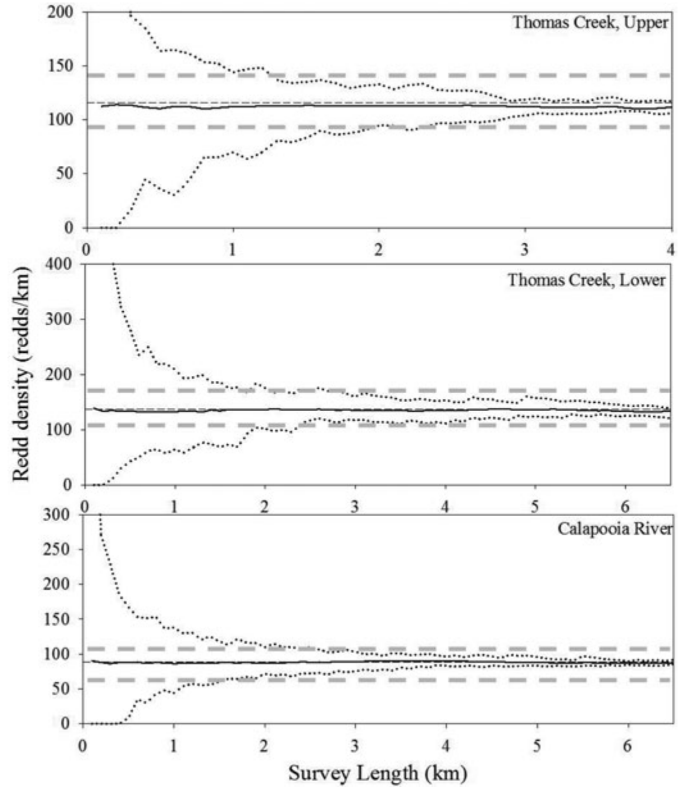

FIGURE 4. Spatial resampling simulation results of mean redd density (solid line), minimum and maximum values (dotted lines), and the observed mean redd density (dashed line) for study surveys in Thomas Creek and the Calapooia River, two streams consisting of entirely alluvial underlying geology. Dashed gray lines show ±20% of the observed redd density, and the points where minimum and maximum values both lie within the dashed lines indicate the survey length requirements for obtaining a relatively precise redd density measurement. Note differences in scale of *y*-axes between panels.

DISCUSSION

Our spawning survey efforts have incorporated methods and findings from previous Pacific Lamprey spawning surveys in the Pacific Northwest (Stone 2006; Brumo et al. 2009; Gunckel et al. 2009) to learn more about monitoring the spawning phase of the Pacific Lamprey life cycle. Our findings suggest survey length requirements for detecting and evaluating the abundance of spawning adult Pacific Lamprey and can be used in the development of monitoring programs. Furthermore, these data may be used to assess the relative precision of spawning surveys that have already been completed and adapt survey methodology and biological interpretations accordingly. Our spatial resampling approach may also be applied to existing data sets from spawning surveys for other fishes to optimize fieldwork efficiency. Although redd surveys are generally considered an imprecise measure of Pacific Lamprey abundance (Moser et al. 2007), redd counts may facilitate trend assessments of status more accurately than have traditional measures of adult abundance such as counts at dams, which are often poor reflections of escapement (Moser and Close 2003; Lampman 2011). However, addressing several key uncertainties might allow using redd counts to compute population metrics for Pacific Lamprey.

Although we only used survey data from 1 year, which had relatively good spawning survey conditions, the stream segments we surveyed had a range of redd densities and geologic composition, and our results indicate how survey length relates to these factors. Except for the Luckiamute River, our resampled mean redd density showed very little bias relative to what we observed in our spawning surveys. In the Luckiamute River survey, however, there was an aggregation of several redds right at the end of the survey segment. The negative bias that we observed in that survey was probably because these redds were often not included in resamples. Our use of the minimum and maximum observed values (of 10,000 observations) rather than other statistics of variance (e.g., 95% confidence intervals) from our resampling techniques provided the most conservative survey length recommendations possible from our data. Because of our approach, our results can be applied to inform survey methods in other basins with a mix of hydrologic conditions, alluvial and intrusive geology, stream flow regimes, and anthropogenic impacts. However, in such other basins, similar techniques should be used to validate spawning survey lengths and refine monitoring methodologies.

Implementation of spawning surveys for Pacific Lamprey can be informed by our analyses, but clearly outlining the objectives of a monitoring plan for Pacific Lamprey spawning activity will dictate the logistics of conducting surveys. If detection of Pacific Lamprey is the study goal, our spatial resampling analyses suggest that completing short spawning surveys (of at least 1.2 km) over a large spatial scale may be the most effective way to meet objectives. If monitoring redd density, temporal trends, and other spawning characteristics is desired, our results indicate that available spawning habitat and underlying geologic structure are important to consider to obtain relatively precise estimates of redd density. Although our survey segments contained a relatively narrow range of percent alluvial underlying geology, some of our related work suggests that Pacific Lamprey select for areas with these underlying sediments (Schultz et al. 2014). Stream segments with alluvial underlying geology, in addition to providing a source of suitable spawning gravel, are also more likely to retain these sediments than are areas with bedrock streambeds (May and Gresswell 2003), particularly in streams that have experienced historic habitat degradation (e.g., splash dams; Miller 2010) and loss of large wood (Sedell and Froggatt 1984). In other areas, particularly river basins with little alluvial geology, examining the relationship between underlying geology and redd density will be important for developing and refining spawning survey methodology.

An additional consideration prior to implementing monitoring programs is the site-specific statistical power of redd counts for population monitoring. By acknowledging a potential error rate of $\pm 20\%$ in redd counts, the statistical ability to detect small temporal changes in populations based on spawning activity is greatly reduced and may not even be possible (Maxwell 1999; Wagner et al. 2013). If greater statistical power is desired to be able to detect changes in spawning populations, it will be necessary to increase survey length to capture a larger sample of spawning activity and increase precision of redd counts. The spatial pattern of Pacific Lamprey redds is often "clumped" and can deviate significantly from a completely random spatial pattern (Schultz et al. 2014); as a result, some reaches consist of short segments with many redds tightly packed in gravel of suitable size for spawning as well as long segments with no redds. Even in stream segments with relatively high redd densities, longer (i.e., distance) surveys may be needed to account for this habitat patchiness. Because redds are often clumped and the relationship between redd density and adult abundance is uncertain (Schultz et al. 2014), it may be more effective to use approaches that account for detection probability and abundance (e.g., a multistate occupancy model; Nichols et al. 2007) to evaluate trends in adult populations.

Using redd counts to monitor temporal trends in populations with any amount of statistical power requires the reduction of bias, particularly bias associated with redd detection (Maxwell 1999; Wagner et al. 2013). Proper training of personnel conducting spawning surveys is essential to ensure the most accurate redd counts possible (Dunham et al. 2009). Our spawning surveys were conducted by two individuals; one person had extensive salmonid spawning survey experience and the other had 1 year of Pacific Lamprey spawning experience. While Pacific Lamprey redds are often located in similar habitat types (i.e., pool tailouts, riffles) as salmonids, they generally tend to be much smaller than anadromous salmonids (Stone 2006; Gunckel et al. 2009; Clemens et al. 2012; Wyss et al. 2013); moreover, Pacific Lamprey typically place excavated substrate pieces at the upstream end of redds (Stone 2006). Redd superimposition is an additional issue that we and other researchers (e.g., Al-Chokhachy et al. 2005; Brumo et al. 2009; Gunckel et al. 2009) have observed during redd surveys and might lead to an underestimation of redd counts. False identification of redds may also be more likely to occur in areas with low redd densities (Muhlfeld et al. 2006). Clearly specifying a priori what characteristics constitute a counted redd will greatly increase the precision of redd counts between observers and time conditions (Wyss et al. 2013). Environmental conditions can also affect the ability to accurately detect redds; in wet years, it is more likely that redds will be washed out between surveys (Jones 2012) or that low visibility levels will reduce probabilities of redd detection.

Pacific Lamprey population metrics and trend assessments derived from spawning surveys should also be interpreted with caution (sensu Maxwell 1999). For spawning surveys to provide cost-effective measures of redd density across stream segments, the relationship between redds counts and adult abundance, factors that influence variability between surveyors, and male-to-female sex ratios must be examined (Dunham et al. 2001, 2009; Parsons and Skalski 2009). While some assumptions of redd identification error can be obtained from salmonid studies, many factors are unknown for Pacific Lamprey, including how many redds are constructed per adult and the proportion of test redds constructed. Stone (2006) observed one female build multiple redds with several males, a characteristic that we frequently observed during our surveys. These types of spawning characteristics must be further investigated before Pacific Lamprey redd counts can be used for monitoring with more statistical power.

Despite the unknowns in Pacific Lamprey spawning behavior, redd counts remain useful as a means of understanding the distribution of this anadromous fish across its range and can easily be integrated with existing spring spawning surveys. Pacific Lamprey redds are often encountered during steelhead *Oncorhynchus mykiss* spawning surveys, but the surveys usually end before peak Pacific Lamprey spawning has occurred (E. Brown, Oregon Department of Fish and Wildlife, Oregon Adult Salmonid Inventory and Sampling Project, personal communication). Extending these steelhead surveys through June would probably capture the majority of the Pacific Lamprey spawning season. Logistical constraints would dictate the feasibility of walking or floating surveys, but we have documented spawning activities in rivers as small as 3–5 m wide (base flow) to as large as 100–150 m wide (Schultz et al. 2014). However, the ability to accurately observe all available spawning habitat in wide stream segments (>25 m wide) is greatly compromised relative to smaller habitats. Redd counts also have considerable potential value as a coarse measure of adult Pacific Lamprey abundance. Our results provide a starting point for developing a monitoring design using redd counts for Pacific Lamprey populations. These monitoring plans will provide an informative tool for monitoring the response of the spawning life history stage to management actions and help address the ongoing decline of Pacific Lamprey.

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