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[Article]

A Regional Approach for Monitoring Salmonid Status and Trends: Results from a Pilot Study in Coastal Mendocino County, California

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Abstract.—In coastal California, many evolutionarily significant units (ESUs) of Chinook salmon *Oncorhynchus tshawytscha*, coho salmon *O. kisutch*, and steelhead *O. mykiss* are listed under the federal Endangered Species Act (ESA). Monitoring species status at the ESU or ESU subdivision scale requires specialized sampling. The purposes of this study were (1) to evaluate abundance estimated from a generalized random tessellation stratified (GRTS) design and compare the results with those from a more intensive stratified random monitoring program and (2) to evaluate the statistical power of the design to detect population trends. This 3-year pilot study considered five Mendocino County streams as an example region of coastal California to evaluate a two-stage sampling approach for monitoring regional escapement. Under this scheme, regional redd surveys (stage 1) were conducted in stream reaches in a GRTS sampling design. Ten percent of anadromous habitat was sampled in year 1 and 10–35% in years 2 and 3. Spawner : redd ratios were derived from smaller-scale census watersheds (stage 2) where "true" escapement was estimated using capture–recapture methods. Regional escapement was then estimated from expanded redd counts, calibrated by spawner : redd ratios. As an alternative, more intensive method for estimating escapement, three survey streams were also sampled in a stratified random design. The results, added to counts from the census basins, produced more rigorous "sum-of-streams" estimates for comparison with the GRTS sampling. Redd counts and the resulting escapement estimates were reliable for regional monitoring. The GRTS and sum-of-streams estimates overlapped, and the variation in the 95% confidence intervals did not change after 15%. Our results suggest that a sample size of 15% or 41 or more reaches (whichever results in fewer survey reaches) should have adequate precision and statistical power to detect regional trends in salmon populations. We recommend that this monitoring approach be applied at regional spatial scales consistent with ESA recovery planning efforts.

Recovery of Endangered Species Act (ESA)–listed salmonids centers on increasing their abundance (McElhany et al. 2000; Good et al. 2005), and the trend in abundance is the primary measure of recovery. In California watersheds north of Monterey Bay, Chinook salmon *Oncorhynchus tshawytscha*, coho salmon *O. kisutch*, and steelhead *O. mykiss* are listed under the U.S. Endangered Species Act (U.S. Office of the Federal Register 1999, 2000, 2005). Additionally, coho salmon are listed under the California Endangered Species Act (CDFG 2004). Delisting will depend on whether or not important populations have reached abundance thresholds (Spence et al. 2008), one of the four key components of the viable salmonid population concept (McElhany et al. 2000). Both the Recovery Strategy for California Coho Salmon (CDFG 2004) and the Steelhead Restoration and Management Plan for California (McEwan and Jackson 1996) identify population monitoring as critical to assessing the effects of recovery actions and determining whether recovery goals have been met.

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Game (CDFG) and NOAA–Fisheries completed an action plan for monitoring California's coastal salmonids (Boydstun and McDonald 2005). The action plan outlines a strategy for monitoring the status and trends of salmonid populations at evolutionarily significant regional spatial scales while providing population level estimates. The monitoring plan follows a sampling scheme similar to the adult component of the Oregon Plan (Stevens 2002; Firman and Jacobs 2000), where data to evaluate adult population status at a regional level are collected in a spatially explicit rotating panel design (Overton and McDonald 1998). Similarly, Boydstun and McDonald (2005) propose using a two-stage approach to estimate regional population status. Under this scheme, first-stage sampling consists of extensive regional spawning surveys to estimate escapement based on redd counts, which are made in stream reaches selected under a generalized random tessellation stratified (GRTS) survey design (Stevens and Olsen 2004; Larsen et al. 2008) with rotating panels at a survey level of 10% of available habitat each year. Second-stage sampling consists of producing escapement estimates in intensively monitored census streams through either total counts of returning adults or capture–recapture studies to estimate total abundance. The second-stage estimates are considered to represent true adult escapement and are used to calibrate first-stage estimates of regional adult abundance (Boydstun and McDonald 2005) by associating precise redd counts with true fish abundance.

The first purpose of this study was to evaluate abundance estimated from a GRTS survey design with 10% sampling as described by Boydstun and McDonald (2005) and compare the results with those from a more intensive stratified random monitoring program. The second purpose of the study was to evaluate the relationship between sample sizes over a range of values from 10% to 50% and the statistical power of the data for detecting population trends. In this 3-year pilot study, we considered five Mendocino County streams (Figure 1), as an example region of coastal California, to evaluate the reliability of a two-stage sampling approach for monitoring regional escapement. Regional escapement was estimated from redd surveys in five streams using a design-based GRTS survey with a 10% sample size in year 1 and sample sizes of 10–35% in years 2 and 3 (Figure 1), with survey counts calibrated using stage-two data. As an alternative and more rigorous method of estimating escapement, Little River, Hare Creek, and the main-stem and upper Noyo River (the survey streams; Figure 1) were also surveyed in an intensive stratified random design (Gallagher and Gallagher 2005). The results from these surveys were then added to the total counts from the census streams to produce "sum-of-streams" escapement estimates, which were subsequently used for comparison with the GRTS data. For second-stage sampling in both approaches, we used two of the five streams (Caspar and Pudding creeks) and the South Fork Noyo River (the census streams; Figure 1). We estimated escapement using capture–recapture methods and conducted redd count censuses in these streams and the resulting spawner : redd ratios were used to convert regional redd counts to escapement (Gallagher et al. 2010, this issue). Finally, to test the application of this approach to regional escapement monitoring (e.g., a population, diversity strata, or an entire evolutionarily significant unit [ESU]), we evaluated the impact of sample sizes on statistical power to detect trends in population abundance. The findings of this pilot study will help shape the long-term monitoring of California's coastal salmonids.

Study Area

The streams in our example region of coastal California (Figure 1) were selected based on the presence of coho salmon and steelhead, ease of access, and prior monitoring knowledge. In Little River, the main-stem Noyo River, and Hare Creek, only spawning survey sampling was conducted (Table 1). In Caspar and Pudding creeks and the South Fork Noyo River, we employed capture–recapture methods and conducted complete redd counts in all available spawning habitat. The main-stem Noyo River, which supports Chinook salmon, coho salmon, and steelhead, represents a large watershed that extends considerably further inland than many coastal Mendocino streams. Hare Creek and Little River are smaller coastal streams that support only coho salmon and steelhead. In Pudding Creek, there is a historic weir and fish ladder where fish can be captured, marked, and released. The Pudding Creek watershed is similar in size to those of the other two census streams. In the South Fork Noyo River, coho salmon and steelhead can also be marked and released at a historic weir and fish ladder. We chose Caspar Creek because many years of adult escapement, juvenile rearing, and downstream trapping data have been complied for this stream, it is a California Department of Forestry and Fire Protection experimental watershed, and it has a history of monitoring and restoration activities. These streams are dominated by coniferous redwood forests, range in drainage area from 13 to 296 km^2, flow directly into the ocean, and are groundwater fed with peak flows in winter following heavy rains.

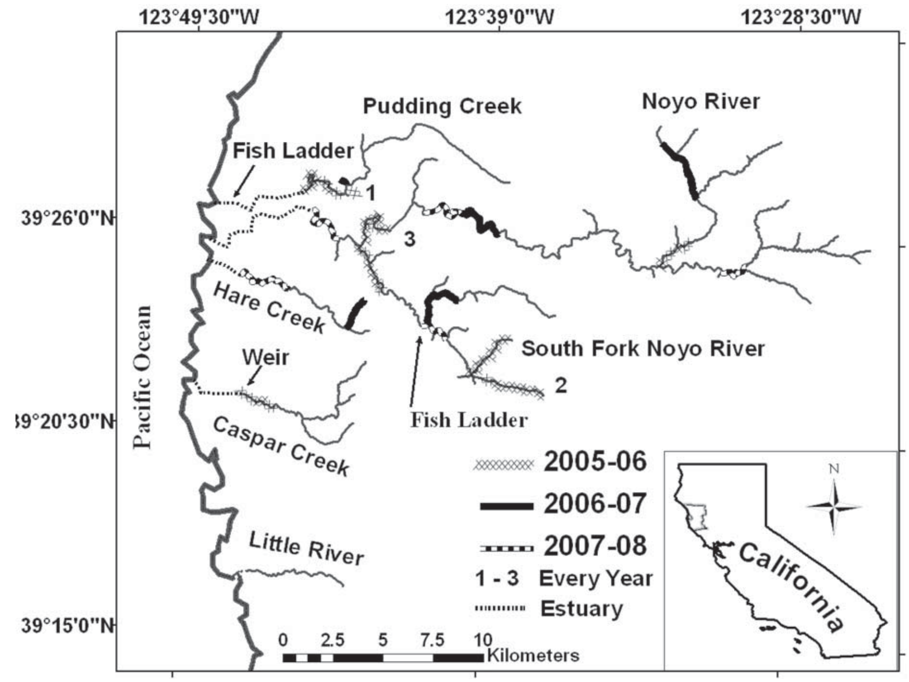

FIGURE 1.—Locations of the study streams in Mendocino County and the 10% regional generalized random tessellation sampling ordered steam reaches sampled each year of the study.

Methods

Experimental design.—The objective of this study was to compare abundance estimates derived from a regional GRTS survey design with those from a more intensive stratified random monitoring program (Table 1) and to relate sample size to the statistical power of the data for trend detection. We calibrated regional stage-one redd surveys with stage-two spawner : redd ratios from census watersheds, where escapement was estimated using capture–recapture methods and redd counts (Gallagher et al., in press). Regional escapement was estimated from calibrated redd counts in all five streams using a survey-based GRTS design (Stevens and Olsen 2004; Boydstun and McDonald 2005; Jacobs et al. 2009) that surveyed 10% of anadromous fish habitat in the first year and 10–35% in the second and third. Total regional redd abundance was estimated by multiplying the mean redd density from the sample reach data by the total length of the streams in the sampling frame (Boydstun and McDonald 2005). We estimated 95% confidence limits using 1,000 bootstrap resamples (Boydstun and McDonald 2005). As an

TABLE 1.—Study design (regional five stream or sum of streams [see text]), sampling schemes, and parameter estimates for study streams in coastal Mendocino County. An x indicates inclusion.

		Sum of streams	
Variable	Regional five stream	Census streams	Survey streams
Sampling scheme	GRTS[a]	Mark–recapture estimates or total count	Intensive spawner survey
Parameter estimates	Mean redd density, expanded total redds, spawner : redd ratio escapement	True escapement estimate, total redd count, spawner : redd ratio	Accurate escapement estimate
Pudding Creek	x	x	
Main-stem Noyo River	x		x
South Fork Noyo River	x	x	
Hare Creek	x		x
Caspar Creek	x	x	
Little River	x		x

[a] Generalized random tessellation stratified design.

alternative method of estimating escapement, the survey streams were also sampled in a stratified random design (Gallagher and Gallagher 2005) and the results added to the total counts from the census watersheds to produce more rigorous "sum-of-streams" escapement estimates for comparison with the regional escapement estimate from the two-stage GRTS sampling (Table 1). This was done to allow comparison of total abundances from both designs across the entire region.

Spawning ground surveys.—For the regional GRTS sampling, all spawning habitat identified previously (Gallagher and Gallagher 2005) in the five streams was divided into uniquely identified reaches ranging in length from 0.26 to 3.79 km (D. McCain, Institute for River Ecosystems, Arcata, California, personal communication), resulting in a sampling frame with 76 reaches. We then produced a GRTS ordered sample of the 76 reaches using SDRAW (McDonald 2003). To achieve a 10% sample size, eight reaches were sampled each year. To improve the utility of the data set in tracking population trends, the first three reaches (GRTS order 1–3) were sampled each year. For each successive year of the study the next five reaches were added to that year's surveys (e.g., in 2005–2006 GRTS order numbers 1–3 and 4–8 were sampled and in 2006–2007 GRTS order numbers 1–3 and 9–13 were sampled; Figure 1). However, two reaches (9 and 12) were replaced with reaches 14 and 15 due to lack of access. The sampling scheme described by Boydstun and McDonald (2005) was designed to accommodate situations in which some reaches are unavailable for sampling.

To count redds in the census streams and selected reaches in the survey streams, we collected data during spawning surveys following Gallagher and Knechtle (2003) and Gallagher et al. (2007). We reduced over- and undercounting errors in redd counts following procedures we derived in our earlier studies on redd counts (Gallagher and Gallagher 2005). These efforts included a formal written protocol, training of field staff, pairing experienced and inexperienced observers, marking and reexamining marked redds, estimating observer efficiency for each reach, measuring redds, using predictive models to determine redd species, including a test category for ambiguous redds (these were removed from further analysis), and surveying biweekly (Gallagher et al. 2007). Surveys were conducted approximately fortnightly from early December to late April each year in all selected stream reaches. Redd density was calculated by dividing the bias-corrected redd counts by the reach length (km) for each survey segment.

Survey costs were estimated by multiplying the total person-hours for each reach by hourly wage estimates and then adding travel cost estimates. We recorded the start and end time of each survey, driving time and distance, equipment costs, and data analyst's time (Gallagher et al. 2007). Hourly wage estimates (with overhead) were based on the Pacific States Marine Fisheries Commission fisheries technician level (S. Allen, personal communication). Travel costs were estimated by multiplying the annual federal mileage rate by the distance to and from each reach and the number of surveys conducted in each reach.

Sample size and statistical power.—We combined data collected for this study with other reach density data for these streams from 2000 to 2005 (S. P. Gallagher, unpublished data) to examine sample sizes for using redd counts (in spawner : redd ratio expansions) for coastwide regional monitoring. These data (n = 144 [24 reaches over 6 years]) were examined following Krebs (1989) and were best described by the negative binomial distribution, as is common when fish data are clumped rather than randomly distributed (Lenarz and Adams 1980). We examined these data to determine whether they could be used to estimate regional sample sizes (n) by testing for trends. If these data show no temporal trends, they can be combined and used in the following equation to estimate sample sizes for different levels of desired precision (C. Gallagher, Clemson University, personal communication):

$$n = \frac{(100t_\alpha)^2}{r^2} \cdot \left(\frac{1}{\bar{x}} + \frac{1}{k}\right), \tag{1}$$

where n is the sample size needed from a negative binomial distribution with exponent k and mean $\bar{x}$ and variance $\bar{x} + \bar{x}^2/k$ to attain 95% confidence limits of $\bar{x} \pm r\%$ when an approximation of $t_\alpha = 2$ is used as the Student's t-value for the 5% significance level and there are $n - 1$ degrees of freedom (Krebs 1989). Throughout this paper, precision is defined as the half-width of the 95% confidence interval expressed as a percentage of the mean, just like r in this equation.

Redd density data collected on 40 reaches during each of the 3 years of the study were used in the program MONITOR (Gibbs 1995) to examine the statistical power of this data for long-term monitoring. Temporal variance in the sample counts was calculated following Gibbs (1995). The model was set and run using one- and two-tailed tests with $\alpha = 0.05$ or 0.10. We then examined the power of the redd density data to detect trends with increasing sample sizes ($n = 8$–40) and increasing years of survey data ($n = 3$–18). For this study, statistical power of 0.80 or more was defined as reliable.

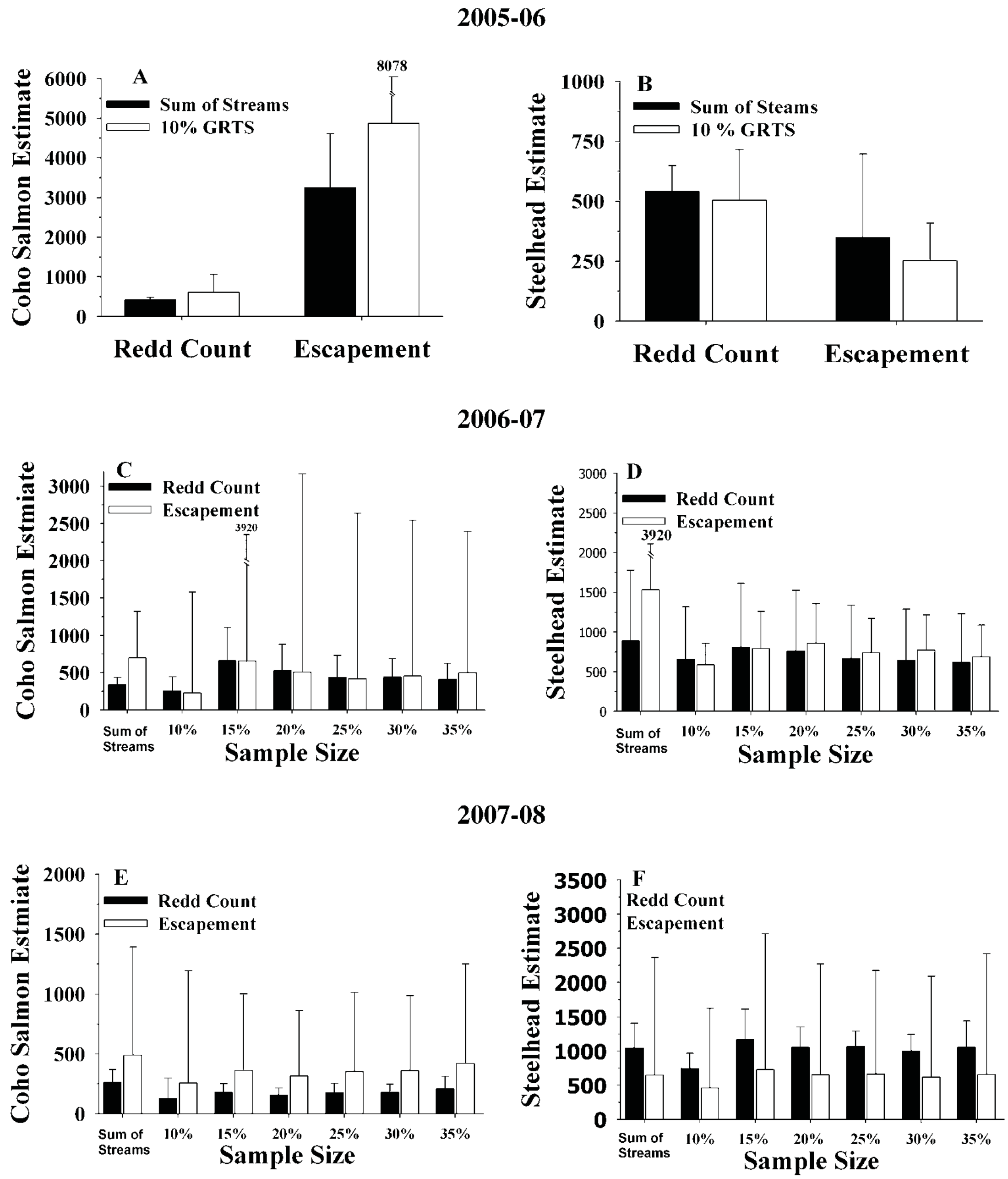

FIGURE 2.—Panels **(A)** and **(B)** show the redd counts and associated escapement estimates based on sum-of-streams and 10% generalized random tessellation stratified (GRTS) sampling for coho salmon and steelhead in coastal Mendocino County, 2005–2006. Panels **(C)** and **(D)** show the effects of sample size on the redd counts and associated escapement estimates for 2006–2007 and panels **(E)** and **(F)** the effects for 2007–2008. The thin lines are portions of the 95% confidence intervals.

Data analysis.—The GRTS and sum-of-stream escapement estimates were compared using analysis of variance (ANOVA), treating years as replicates. Redd count and escapement estimates with narrower 95% confidence intervals (and thus smaller SDs) were deemed more precise and reliable than those with wider bounds. To determine the sample size for regional sampling, we examined the data using the negative binomial procedure of Krebs (1989). We accepted statistical significance at $P < 0.05$, although $P < 0.10$

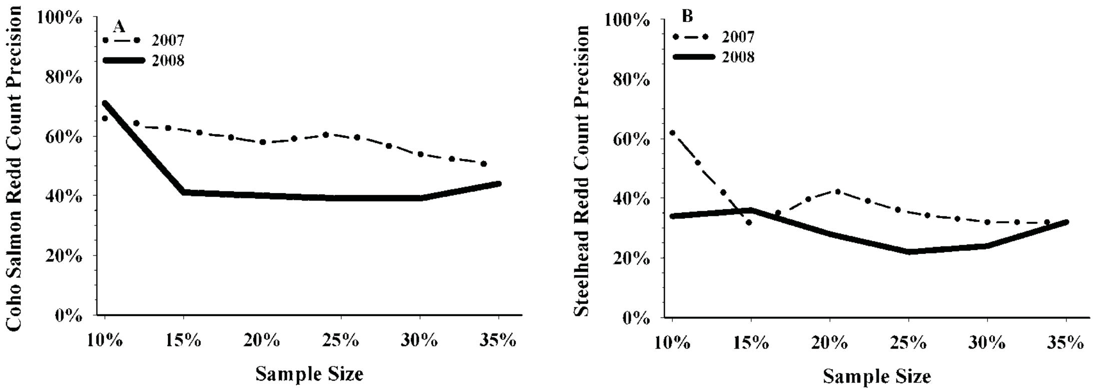

FIGURE 3.—**(A)** Coho salmon and **(B)** steelhead redd count precision (half-width of the 95% confidence interval expressed as a percentage of the mean) for GRTS sample sizes of 10% to 35%.

is often used in endangered species management (Good et al. 2005).

Results

Regional Escapement

The 10% GRTS sampling produced redd counts and spawner : redd ratio escapement estimates for coho salmon and steelhead that were not different from the sum-of-stream estimates during all 3 years of the study (Figure 2). Treating years as replicates, coho salmon redd counts were not significantly different between the 10% GRTS and the sum-of-streams samples (ANOVA: $F_{1,4} = 1.38$, $P = 0.58$). The power of this test was low ($\beta = 0.05$). Similarly, the redd count escapement estimates were not significantly different between the 10% GRTS and the sum-of-streams samples ($F_{1,4} = 0.06$, $P = 0.82$, $\beta = 0.05$). The same was true for the steelhead redd counts ($F_{1,4} = 1.38$, $P = 0.31$, $\beta = 0.08$) and the associated redd count escapement estimates ($F_{1,4} = 1.60$, $P = 0.27$, $\beta = 0.10$).

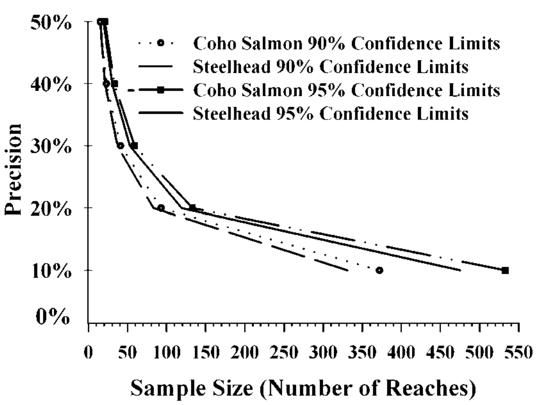

FIGURE 4.—Estimated sample sizes (number of reaches) to attain five desired levels of precision (10, 20, 30, 40, and 50%) in redd density.

We found that sampling 8 out of a total of 76 reaches in a GRTS design provided acceptable regional estimates; increased effort did not significantly improve the GRTS estimates relative to our sum-of-streams estimates. We also found that increasing the GRTS sample size above 10% did not improve the resulting redd count or escapement estimates (Figure 2C–F). The 10–35% GRTS redd counts and spawner : redd ratio escapement estimates overlapped the sum-of-streams escapement estimates for both species (Figure 2C–F), and the variation in the 95% confidence limits did not change substantially with samples greater than 15% (Figure 3). The coho salmon and steelhead GRTS redd count estimates had narrower 95% confidence intervals than the escapement estimates. This pattern was consistent over 2 years (Figure 2C–F).

Each reach was surveyed on average 10 times during a season (December to early April), or approximately every other week. We estimated an average annual cost of US$3,000 to survey one reach for an entire season. The costs ranged from $850 to $5,400 per reach; shorter reaches took less time to survey and were therefore less expensive.

Sample Size and Statistical Power

Coho salmon redd densities did not exhibit significant trends between 2000 and 2007 ($r = 0.16$, $P = 0.70$, $n = 8$). Similarly, steelhead redd densities did not exhibit significant trends between these years ($r = 0.25$, $P = 0.54$, $n = 8$). Therefore, the annual redd density data for each species were combined in equation (1) to examine sample size for monitoring salmonids in coastal California. Our results suggest that a sample of 41 reaches would produce redd-based escapement

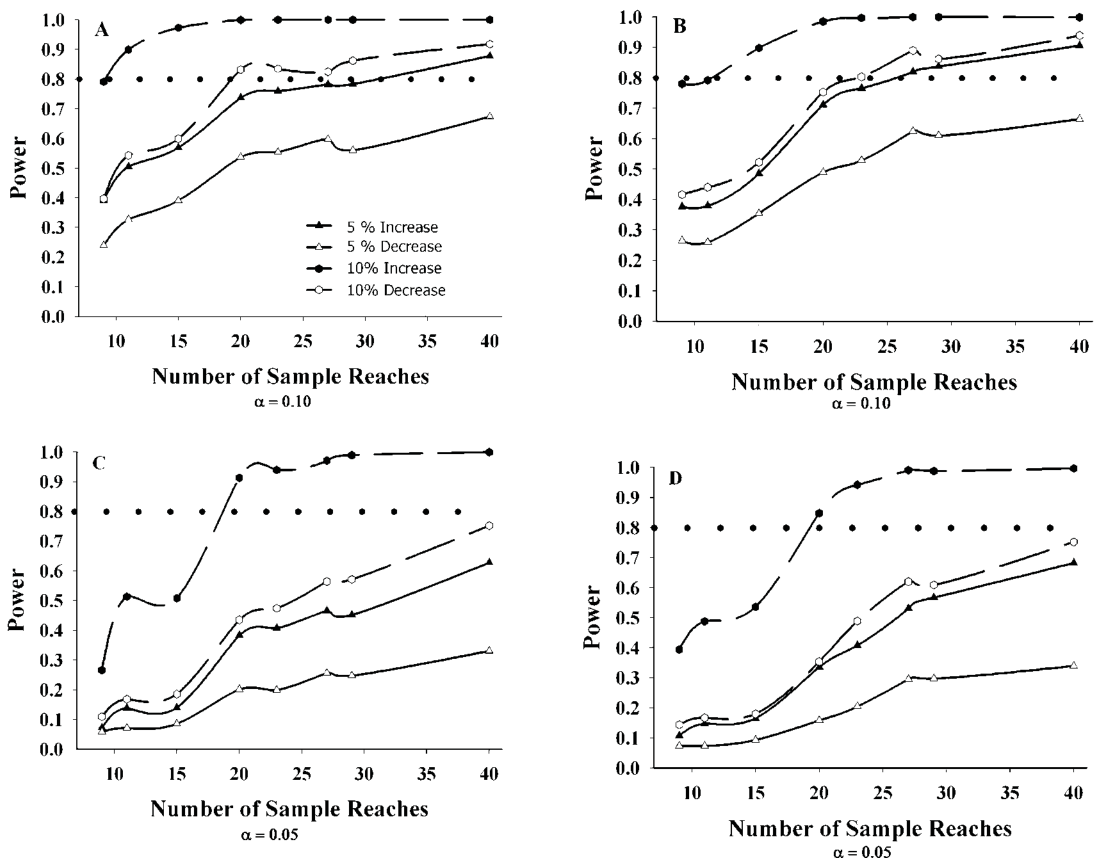

FIGURE 5.—Number of sample reaches and estimated power to detect trends in **(A)** and **(C)** coho salmon and **(B)** and **(D)** steelhead populations based on redd densities. Panels (A) and (B) show the results of one-tailed tests with $\alpha = 0.10$, panels (C) and (D) the results of two-tailed tests with $\alpha = 0.05$. The dotted lines indicate a power of 0.80.

estimates with 90% confidence limits of ±30% of the mean. Increased precision would require larger sample sizes, which would result in higher costs (Figure 4).

The statistical power of redd monitoring increased with sample size for both coho salmon and steelhead (Figure 5). Sampling 25 or more reaches and using a one-tailed test with $\alpha = 0.10$ appears sufficient (power ≥ 0.80) to detect increases in abundance exceeding 5% (Figure 5A–B). Decreases in abundance appear more difficult to detect. We found that even with a sample of 40 reaches and a one-tailed test with $\alpha = 0.10$, we would only detect decreases exceeding 10% with a power greater than 0.80. Using a two-tailed test and $\alpha = 0.05$, we would only detect increases of 10% or more and would need to sample at least 40 reaches to achieve a power greater than 0.75 for detecting such decreases (Figure 5C–D). Monitoring 25 reaches and using a one-tailed test with $\alpha = 0.10$ would enable us to detect population increases greater than 5% in 9 years (Figure 6A–B) and decreases greater than 5% in 12 years. Monitoring 25 reaches and using two-tailed tests with $\alpha = 0.05$ would provide sufficient statistical power to detect increases in coho salmon and steelhead redd density of 10% or more after 10 years (Figure 6C–D). Using these parameters, it would take 18 years to detect population decreases of more than 5%.

Discussion

Regional Escapement

We found that the use of second-stage spawner : redd ratio sampling to calibrate the first-stage regional redd GRTS sampling produced cost-effective and reliable annual salmonid escapement estimates. It was surprising that sampling 8 of 76 reaches produced estimates comparable to those from more intensive sampling of the entire region (e.g., the sum-of-streams estimates) and that increasing the sample size above 15% did not change this outcome. Jacobs et al. (2009) found similar

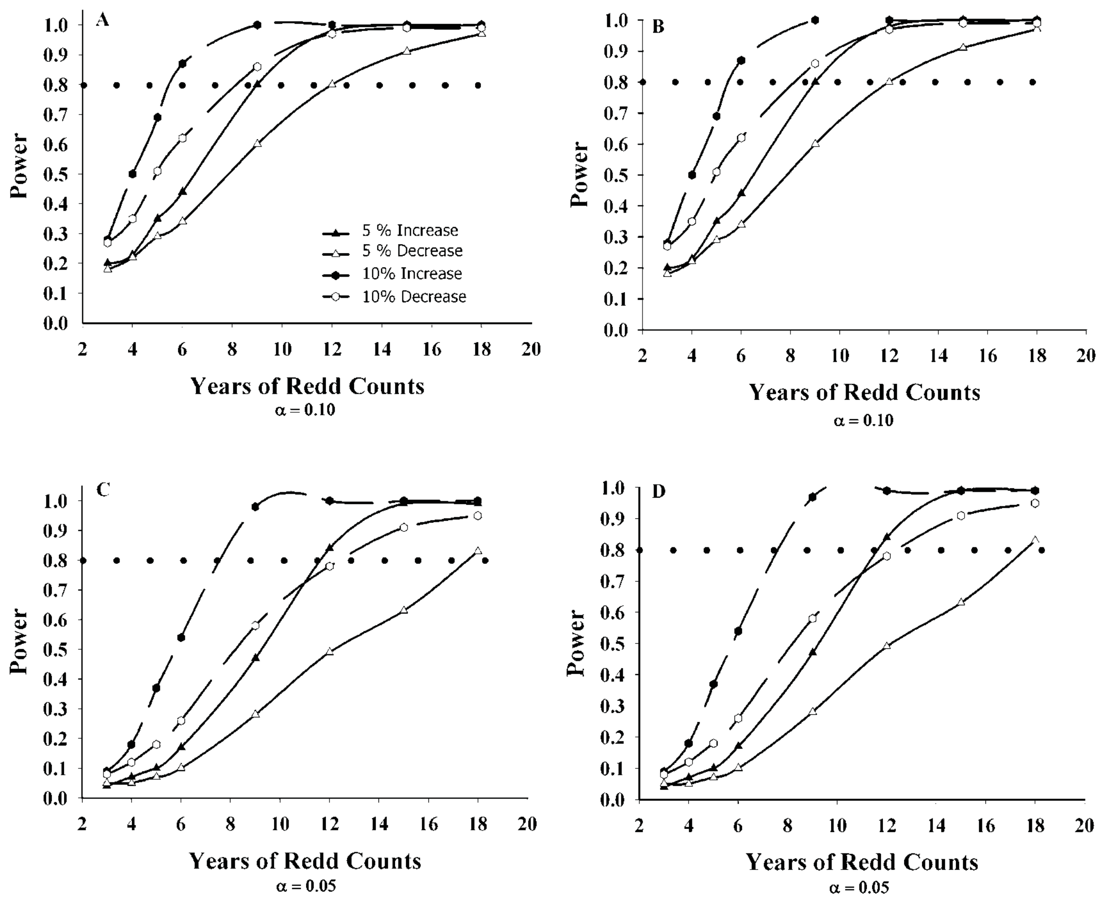

FIGURE 6.—Power of trend detection with 25 reaches of **(A)** and **(C)** coho salmon and **(B)** and **(D)** steelhead redd densities sampled over 18 years. Panels (A) and (B) show the results of one-tailed tests with $\alpha = 0.10$, panels (C) and (D) the results of two-tailed tests with $\alpha = 0.05$. The dotted lines indicate a power of 0.80.

results in a GRTS simulation study of bull trout *Salvelinus confluentus* in the Columbia River plateau. Our GRTS estimates were within 25% of—and overlapped—the "true" sum-of-streams estimates. This is well within the range of ±25% precision needed for management purposes (Krebs 1989) and within the ±28% precision that Jacobs and Nickelson (1998) found for coastwide monitoring of coho salmon in Oregon.

Our results suggest that monitoring at greater than a 15% GRTS does not provide any substantial improvement in either the ability to detect differences in abundance (the true positive rate) or the ability to identify estimates as the same (the true negative rate). Based on their experience, Boydstun and McDonald (2005) suggested that a sample size of 10% be used for regional monitoring. Our results generally corroborate this, as we found that increasing sampling above 10% did not improve estimates. However, the precision of the estimates was improved by sampling at 15% and it did not substantially decrease with increased sample size (Figure 4). Our spatially balanced sampling design (i.e., GRTS) contributed to these results. Lenarz and Adams (1980) found the same result for fish trawl surveys. For regional escapement analysis, our results coupled with the findings of others (Courbios et al. 2008; Jacobs et al. 2009) suggest that low-intensity surveys with wider spatial coverage provide greater precision and accuracy than more intensive surveys in fewer locations.

Sample Size and Statistical Power

Our evaluation of sample size suggests that producing regional escapement estimates for California's coastal salmonids may require a lower level of effort than anticipated by Boydstun and McDonald (2005). Their estimated 10% sample draw for coastal Mendocino County would result in an annual sample size of 203 reaches if the variance between reaches that we observed in our five-stream example region is representative of coastal northern California, whereas coastwide (e.g., diversity strata or ESU level) escapement estimates would require a much smaller number of survey reaches, perhaps fewer than half their estimate. At $3,000 to survey one reach over the course of one season, the cost difference is substantial. Further examination of reach variance and its effect on sample size over other coastal areas is an important next step in implementing a GRTS-based regional monitoring program for California's coastal salmonids.

Regional monitoring of California's coastal salmonids will presumably occur at different population structural levels, ranging from localized watersheds (for evaluation of issues such as hatchery effects and habitat restoration) to individual independent–dependent population units and entire ESUs (for recovery planning) (Spence et al. 2008). Sampling 25 or more reaches in each of these smaller segments should result in ESU-level samples much larger than our results suggest are necessary, thus balancing the need for sufficient statistical power and precision in the estimates. Further evaluation of the power of monitoring salmonid population trends should be conducted while examining reach variance effects on sample size.

Boydstun and McDonald (2005) recommend using the normal approximation to estimate 95% confidence bounds for regional GRTS-based escapement estimates if there are more than 30 reaches. A 10% GRTS sample at the scale of the coast of California (or the Central California Coast Coho Evolutionarily Significant Unit) would likely result in a sample draw consisting of more than 30 reaches, which is consistent with their recommendation. Thus, the effect of using bootstrap simulation and the neighborhood variance estimator (Stevens 2002) to estimate confidence bounds relative to cost and sample size should be evaluated. Finally, the use of standardized data collection procedures and well-trained staff (Gallagher et al. 2007) will also contribute to increased precision in regional escapement monitoring.

The results of this study suggest that a sample size of more than 25 reaches would have sufficient statistical power to detect regional trends in less than 9 years. Jacobs et al. (2009) needed a sample size of 150 survey reaches to attain sufficient statistical power to detect a 30% change in bull trout redds on the Columbia River plateau. Maxell (1999) found it necessary to use one-tailed tests and $\alpha = 0.20$ to obtain a statistical power of at least 0.80 for detecting 50% declines, which took up to 15 years of monitoring bull trout redds in Idaho. He suggested that the statistical power of the monitoring would improve if errors in redd counts were identified and reduced. Dauwalter et al. (2009) found it necessary to monitor at least 30 sites over 8 years and set $\alpha = 0.20$ to detect a 5% decline in trout populations. Al-Chokhachy et al. (2009) required a 48% sample, $\alpha = 0.10$, and 15 years of data to detect a 25% decline in bull trout populations. We reduced errors in redd counts as described above and found that with a sample size of 25 reaches using one-tailed tests with $\alpha = 0.10$ we could detect increases of 5% or more and decreases of 10% or more with sufficient statistical power. Decreasing α to 0.05 and using two-tailed tests had statistical power to detect increases of more than 10%, which further suggests that we have sufficiently reduced the error in redd counts.

We found that spawning surveys of between 25 and 41 reaches give estimates that can be used in a California Regional Monitoring Plan for sample units varying from small to large. We recommend that regional salmon escapement monitoring be conducted in a GRTS design that surveys a minimum of 41 reaches or 15% of the sampling universe, whichever results in a smaller number of reaches. This is a larger number of reaches—but a smaller percentage—than the Oregon Plan's adult coho salmon survey sampling goal of 30 reaches or 30% of the total number of reaches (ODFW 2007) for a population. Our results provide strong confidence that these regional monitoring approaches can be applied at varying spatial scales to assess ESA recovery efforts.

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