North American Journal of Fisheries Management 32:823–831, 2012

ISSN: 0275-5947 print / 1548-8675 online
DOI: 10.1080/02755947.2012.703158

ARTICLE

Movement and Capture Efficiency of Radio-Tagged Salmonids Sampled by Electrofishing

Michael K. Young*
U.S. Department of Agriculture Forest Service, Rocky Mountain Research Station, 800 East Beckwith Avenue, Missoula, Montana 59801, USA

David A. Schmetterling
Montana Fish, Wildlife and Parks, 3201 Spurgin Road, Missoula, Montana 59804, USA

Abstract
Electrofishing-based estimates of fish abundance are common. Most population models assume that samples are drawn from a closed population, but population closure is sometimes difficult to achieve. Consequently, we individually electrofished 103 radio-tagged trout of two species, westslope cutthroat trout *Oncorhynchus clarkii lewisi* and brook trout *Salvelinus fontinalis*, in five streams in western Montana to quantify the influence of habitat and fish size on capture efficiency and movement related to electrofishing with unpulsed DC. First-pass capture efficiency was 46% and declined on subsequent passes. No variables were related to capture efficiency, and only the percentage of cobble or larger substrate was related to the probability that uncaptured fish would move during the first electrofishing pass. About 20% of the uncaptured fish did not move, and 95% traveled less than 18 m. We concluded that for these streams, the bias in abundance estimates from disregarding movement would be relatively minor.

Electrofishing is widely used for sampling fishes in small streams, and electrofishing catches are often coupled with mark–recapture or removal models to estimate fish abundance. Such models assume closed populations i.e., fish do not enter or exit a reach during sampling. Violating this assumption can lead to overestimates of abundance if marked fish leave the sampled reach between marking and recapture runs or to underestimates if any fish leave between removal runs (Ricker 1975). This is a problem for electrofishing-based estimates because some fish respond to the presence of an electrical field and electrofishing crews by fleeing the sampling area (Bohlin et al. 1989). To counter this behavior, biologists often deploy block nets at the upstream and downstream boundaries of sampling reaches (Peterson et al. 2005). But because block nets require considerable labor and time to install, can be dislodged when flows are high or debris-laden, and often permit some degree of fish movement (Temple and Pearsons 2007), biologists sometimes forego their use and accept the increased risk of violating the assumption of closed populations (Amiro 1990a; Heggenes et al. 1990). To what extent this compromises the validity of abundance estimates depends on the length of sample reaches, the proportion of fish that move, and the extent of their movements.

Many studies have demonstrated that certain habitat characteristics, such as wide or deep channels, extensive overhead cover, cobble or rubble substrates, or surface turbulence, are associated with reductions in electrofishing efficiency (summarized in Zalewski and Cowx 1990; Temple and Pearsons 2007). Such features may also influence fish movement during sampling. For example, if fish respond to electrofishing by seeking cover in locations where it is abundant, distances moved may be very short relative to the length of sample reaches, and fish movements will have a minor influence on abundance estimates (Bohlin et al. 1989). In contrast, if a scarcity of overhead cover encourages even modest numbers of fish to continually move to avoid the electric field, the resulting abundance estimates will be biased and confound comparisons of abundance among

*Corresponding author: mkyoung@fs.fed.us
Received January 18, 2011; accepted June 11, 2012

sites with varying amounts of cover (Persat 1991). A further issue is that not all species (or individuals within populations) sampled by electrofishing share the same level of catchability (Klein-Breteler et al. 1990; Dolan and Miranda 2003; Price and Peterson 2010), which may in part reflect whether and how much they move in response to this technique.

Electrofishing appears to have minor effects on long-term or population-scale movements (Nordwall 1999; Dunham et al. 2002; Young and Schmetterling 2004), but studies of trout movement during electrofishing have yielded mixed results. Bohlin et al. (1989) concluded that in small, turbulent waters, the absence of congregations of brown trout *Salmo trutta* near block nets was evidence that movements were limited and block nets unnecessary. Young and Schmetterling (2004) noted that few individuals from mixed populations of westslope cutthroat trout *Oncorhynchus clarkii lewisi*, bull trout *Salvelinus confluentus*, and brook trout *S. fontinalis* were captured in fish traps that barricaded the ends of electrofishing sections in two streams. In contrast, Peterson et al. (2005) concluded that the proportion of bull trout and rainbow trout *O. mykiss* escaping from electrofishing reaches substantially biased abundance estimates. However, each of these studies used different electrofisher settings and sampled very different basins. Moreover, that fish moved was only evident from their appearance in traps or beyond block nets at the reach boundaries; the patterns of individual fish movement were not described.

To more precisely quantify fish responses to electrofishing, Pine et al. (2003) and Peterson et al. (2005) suggested monitoring the behavior of radio-tagged fish during electrofishing. Grabowski et al. (2009) attempted this with radio-tagged robust redhorse *Moxostoma robustum*, but were unsuccessful because capture efficiency for this species was low. In contrast, electrofishing is a common and effective technique for sampling coldwater salmonids (Temple and Pearsons 2007; Dunham et al. 2009). Therefore, we used radiotelemetry to evaluate the movements of trout in response to electrofishing in small streams in western Montana. We used gastrically implanted transmitters inserted the previous day to monitor the locations of trout immediately before and after electrofishing. Our objectives were to assess how characteristics of radio-tagged fish and habitat influence the probability and extent of movement and probability of capture during electrofishing.

METHODS

Study area.—We examined electrofishing-related trout movement in two segments of one stream and one segment of four streams in western Montana from late July to mid-August 2005 (Table 1). The streams were typical of tributaries in this region that are sampled with backpack electrofishing gear to quantify fish abundance. Westslope cutthroat trout and brook trout were used in this study because they were relatively abundant in the study streams and are species typically monitored by biologists conducting population surveys.

Field sampling.—Fish capture and monitoring typically required 2 d for each stream segment. On the first day we captured trout by angling to ensure that recent exposure to electrofishing would not influence fish behavior from electrofishing-induced stress (Mesa and Schreck 1989; Barton and Dwyer 1997) or injury (Snyder 2003) or produce a sample of fish predisposed to capture by electrofishing (Bohlin and Sundström 1977; Carrier et al. 2009). Each captured fish was anesthetized with clove oil, weighed (g), measured (total length [TL], mm), and gastrically implanted with a transmitter. Transmitters weighed 0.9 g in air, were 11 mm long, and had cross-sectional dimensions of 4 × 5–7 mm (the larger size reflected the battery end). We used a polyethylene tube as a plunger to insert a transmitter into each fish's stomach. The antenna protruding from each fish's mouth was trimmed to 10 cm and crimped at the corner of the mouth to align parallel with the body; the antenna did not extend past the caudal fin. Transmitters constituted 0.5–7.5% of fish body weight. Fish were held for a few minutes in freshwater to recover from anesthesia and to ensure that they did not immediately regurgitate the transmitter, then were released where they were captured. The regurgitation rate for the first 40 transmitters inserted was high (39%). Thereafter, we added a

TABLE 1. Characteristics (means and ranges) of fish (westslope cutthroat trout and brook trout) and study streams in western Montana. The habitat of origin is where a fish was observed just before the first electrofishing pass. Mean temperature and mean conductivity were based on 1–3 point measurements. Gradient was estimated from map-based sources. Species: WCT, westslope cutthroat trout; BKT, brook trout.

Stream	Latitude (°N)	Longitude (°W)	Species	*n*	Total length (mm)	Captured on first pass (%)	Distance moved on first pass by uncaptured fish (m)	Temperature (°C)
Chamberlain-1	46.980	113.262	WCT	14	161 (125–212)	50	4.1 (0–13.1)	11.3
Chamberlain-2	46.990	113.250	WCT	11	190 (136–243)	45	11.3 (1.5–28.9)	9.3
Elk	46.880	113.380	BKT	19	171 (140–227)	42	7.8 (0–20.9)	13.9
O'Brien	46.852	114.169	WCT	20	181 (117–262)	45	7.5 (0–26.1)	10.0
Surveyors	46.845	114.695	WCT	21	151 (119–187)	48	3.0 (0–8.0)	8.3
WF Butte	46.747	114.300	BKT	18	184 (151–218)	44	4.7 (0–12.8)	12.0

5-mm band of latex surgical tubing to the battery end of most transmitters (Keefer et al. 2004; Rivinoja et al. 2006), which reduced the regurgitation rate to 4%. For fish smaller than 125 mm ($n = 4$), no band was added because we judged the transmitter diameter to be adequate to ensure retention. We acknowledge that the high transmitter weight : fish weight ratio may have reduced swimming stamina for the smallest fish (Adams et al. 1998), and that gastrically implanted transmitters tend to reduce growth and survival in fish in long-term studies (Hall et al. 2009). For short-term studies, however, effects of gastrically implanted transmitters on fish behavior or movement are thought to be negligible (Martinelli et al. 1998; Bridger and Booth 2003), and we assumed that the transmitters did not influence the relations between electrofishing and fish movement or capture efficiency.

The day after initial capture, one person located each fish and monitored its position (typically within 0.5 m; Schmetterling 2001) throughout sampling activities by using a Lotek SRX 400 telemetry receiver and a three-element Yagi antenna. Next, an electrofishing crew—with several seasons of experience—consisting of one person operating a backpack electrofisher (Smith-Root LR-24) and 1–2 people netting entered the stream 20 m downstream from the fish or at the base of the preceding habitat unit, whichever was closer. The location of the radio-tagged fish was not revealed to the electrofishing crew, who also refrained from noting the position or actions of the person monitoring fish locations. The crew used a diamond-shaped anode and trailing cable cathode provided with the electrofishing unit, and fished with DC adjusted using the unit's auto-setting feature (voltage range, 120–375 V). On several occasions, this setting was too low to efficiently capture fish and voltage was increased until we judged efficiency to be acceptable; i.e., after exposure to electrofishing, most fish that we observed (the majority of which were untagged) exhibited directed swimming, tetany, or narcosis with little evidence of internal hemorrhaging (cf. Habera et al. 2010). Crews electrofished upstream as though conducting an abundance estimate, netting stunned trout, and continued through the habitat unit containing the radio-tagged fish. If the radio-tagged fish was captured, electrofishing ceased. If the fish moved upstream but remained within the habitat unit where first detected, electrofishing continued until the fish was captured or the crew reached the head of the habitat unit after passing the radio-tagged fish. If the fish was not captured on the first pass or left the habitat unit where first detected, the electrofishing crew targeted the radio-tagged fish based on a triangulated estimate of its position for up to five additional passes. After each attempt to capture a radio-tagged fish, its location was marked with flagging or otherwise noted to permit movement measurements. Crews attempted recaptures at 5–10-min intervals, but this was sometimes longer if fish moved a substantial distance. Fish not caught after the sixth pass were continually pursued until captured or sometimes captured on subsequent days. Except in the cases when captures were on later days, each radio-tagged fish was pursued and captured before another radio-tagged fish was targeted. In nine habitat units, two to four radio-tagged fish were simultaneously present, although never immediately adjacent (<1 m) to one another. We electrofished these units as described above, with the position of each fish being monitored until capture. All capture attempts were conducted between 0900 and 1730 hours.

After each radio-tagged fish was captured, a single observer measured several characteristics of the habitat unit occupied by the radio-tagged fish during the first electrofishing pass. We classified the unit as a pool or riffle and measured its length, width (nearest 0.1 m), and maximum depth (nearest 1 cm). We made visual estimates of the percentage of cobble or larger substrate and percentage of overhead or instream cover (nearest 5%) (Bain and Stevenson 1999). We did not measure the characteristics of the habitat unit in which each radio-tagged fish was eventually captured (unless caught on the first pass), but did classify the unit as a pool or riffle.

All statistical analyses were conducted in R (version 2.11.0, R Development Core Team 2010) and we regarded $\alpha \leq 0.05$ as indicating statistical significance. Data for all segments were pooled because habitats and fish sizes were similar; fish movement after the first pass (but before subsequent passes) did not differ among segments (one-way ANOVA: $F_{5,50} = 1.87$, $P = 0.12$; Table 1). We used an array of logistic and linear regression models to explain patterns in capture probability and fish

TABLE 1. Extended.

		Habitat of origin				
Conductivity (μS/cm)	Gradient (%)	Length (m)	Width (m)	Maximum depth (cm)	Cover (%)	Cobble (%)
137	1.8	9.3 (6.4–14.4)	3.1 (2.1–4.3)	57 (43–70)	36 (10–85)	17 (1–60)
171	2.2	7.4 (1.7–16.8)	3.2 (1.3–4.8)	47 (24–64)	23 (10–50)	22 (3–60)
324	2.2	6.7 (1.9–20.9)	2.9 (1.8–4.0)	47 (26–76)	32 (15–70)	26 (3–80)
266	2.5	4.3 (2.0–6.5)	2.5 (1.3–4.9)	36 (15–73)	31 (2.5–70)	6 (0–70)
190	3.7	4.9 (2.7–7.9)	3.3 (1.7–5.2)	47 (25–81)	29 (10–70)	9 (0–50)
35	3.0	8.5 (3.7–21.9)	3.3 (1.6–5.2)	43 (25–60)	31 (15–65)	7 (0–25)

movement. We used a two-step process to guide variable inclusion in these regressions. First, we constructed a correlation matrix to assess collinearity among independent variables. No pairwise comparisons had correlation coefficients exceeding 0.3, so all covariates were considered for inclusion in models. Second, we tested all univariate relations between the dependent variable and the suite of covariates considered for each model. Those covariates that were not significantly related to the dependent variable were excluded from that model. Model fit was examined using goodness-of-fit tests (logistic regression) or inspection of residuals (linear regression) and judged to be adequate for all models.

We used logistic regression to relate the probability that fish would be captured on the first electrofishing pass to the habitat of origin's length, width, maximum depth, arcsine-transformed percentages of substrate >150 mm in diameter and overhead or instream cover (not considering substrate), and to fish TL. For those fish not captured on the first pass, we used logistic regression to evaluate the probability of movement ≥ 1 m with respect to the same set of covariates. In practice, electrofishing reaches are often extended to the head of an individual habitat unit. Therefore, we repeated the aforementioned analyses but used the probability that fish would move from the habitat unit occupied during the first electrofishing pass as the dependent variable.

Linear regression was used to relate the distance moved between the first and second passes by uncaptured fish to this suite of variables. We also used linear regression to relate the number of electrofishing passes needed to capture radio-tagged fish to these variables and to fish movement during the first pass. Because we targeted fish for capture after the first electrofishing pass and continually electrofished after the sixth pass, this analysis only included fish captured during passes 2–6. In addition, we examined the relation between the total distance moved by those fish caught on any pass after the first one and the aforementioned variables.

RESULTS

We implanted radio transmitters in 81 westslope cutthroat trout and 41 brook trout (mean TL, 172 mm; range, 117–262 mm and mean weight, 53 g; range, 12–168 g). Of these, 19 fish regurgitated their tags. We used the remaining 103 fish for analyses of movement and capture efficiency.

On the first electrofishing attempt, 47 radio-tagged fish were recaptured, and seven of these moved 0.5–5.0 m upstream before being captured. One of these fish moved 1.0 m upstream to a different habitat unit, but was attracted to the anode and captured during electrofishing of the adjacent unit downstream. Of the 56 fish not captured on the first pass, over 20% did not move, 50% moved <4.5 m, and 95% moved <18 m during that pass based on radiotelemetry (Figure 1). Consequently, movement among habitat units by these uncaptured fish was limited; 41% remained within the habitat units of origin, 71% used ≤ 2 habitat units, and 91% used ≤ 3 habitat units. Slightly fewer mobile fish moved upstream ($n = 20$) than downstream ($n = 24$).

Physical and biotic covariates explained little of the variation in probability of fish capture or movement associated with the first electrofishing pass. None of the independent variables were significantly related to the probability of capture during the first electrofishing pass (Table 2). There was a positive

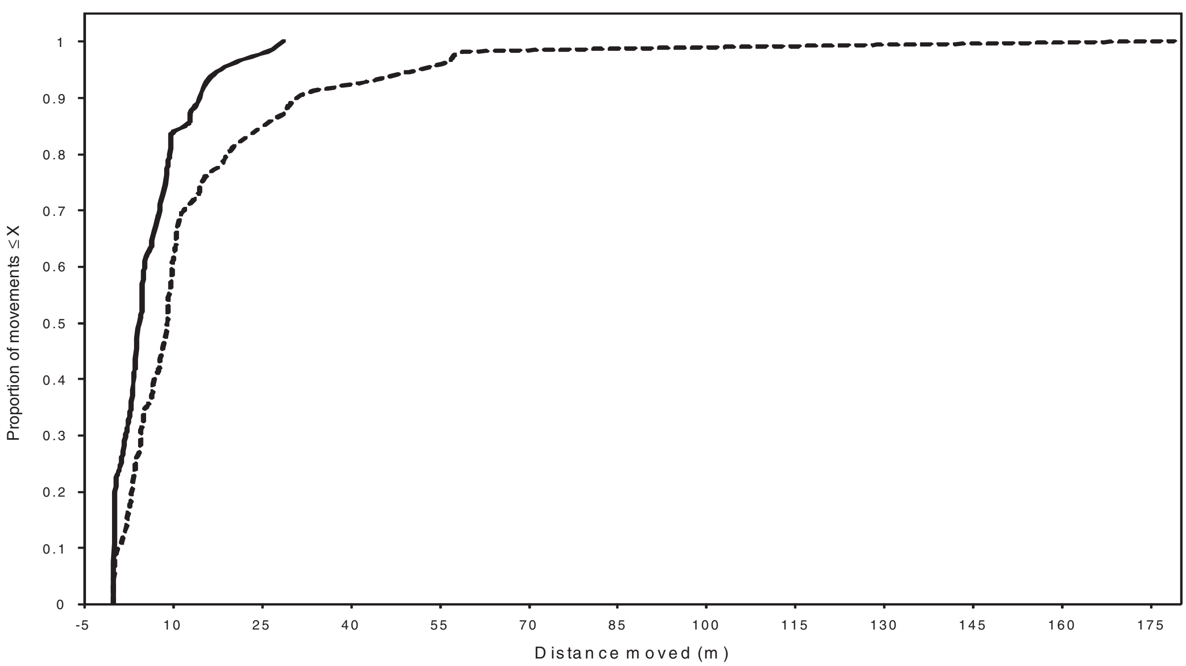

FIGURE 1. Cumulative distributions of movements after the first pass (solid line) and after all passes (dashed line) for fish not captured on the first electrofishing pass.

TABLE 2. Univariate logistic regression model sample sizes and coefficients for the probability of capture (P_C) of fish on the first electrofishing pass, the probability of moving ≥1 m (P_{M1}) if not captured on the first pass, and the probability of moving to a new habitat unit (P_{M2}) if not captured on the first pass. The percentages of substrate >150 mm and of overhead or instream cover were arcsine-transformed.

Probability of capture or movement	*n*	Coefficient	*P*
P_C (1st-pass capture)			
Habitat length (m)	103	–0.078	0.161
Habitat width (m)	103	–0.380	0.104
Maximum depth (cm)	102	–0.012	0.368
% Substrate > 150 mm	103	0.019	0.208
% Cover	103	–0.009	0.616
Fish length (mm)	103	0.012	0.071
P_{M1} (movement ≥1 m)			
Habitat length (m)	56	0.040	0.632
Habitat width (m)	56	–0.696	0.079
Maximum depth (cm)	55	–0.036	0.114
% Substrate > 150 mm	56	0.189	0.007
% Cover	56	0.037	0.259
Fish length (mm)	56	–0.003	0.763
P_{M2} (movement to a new habitat unit)			
Habitat length (m)	56	0.008	0.897
Habitat width (m)	56	–0.249	0.421
Maximum depth (cm)	55	–0.028	0.136
% Substrate > 150 mm	56	0.082	0.006
% Cover	56	0.003	0.883
Fish length (mm)	56	–0.002	0.812

relation between the percentage of cobble and the probability that fish not caught on the first pass would move ≥1 m or to a new habitat unit, but no other independent variables were correlated with either dependent variable (Table 2). Although there was a negative correlation between habitat width and distance moved on the first pass (Table 3), this was influenced by a single observation (the largest movement detected in this study was by a fish occupying the narrowest habitat unit). Exclusion of this datum resulted in the loss of statistical significance ($P = 0.28$). None of the remaining independent variables were correlated with distance moved on the first pass.

After the first electrofishing pass, many radio-tagged fish continued to elude capture and move despite our targeting their positions. Capture efficiency was greater on the first electrofishing pass (46%) than on all subsequent passes (passes 2–6, mean 33%). Linear regressions between the number of passes (for passes 2–6) necessary to capture a fish and the suite of covariates were not significant (Table 3). Of the 56 fish not captured on the first pass, 51 eventually moved. Total distance moved varied substantially (range, 1–179 m), as did the number of habitat units visited (range, 0–20 units), but fish typically moved short distances (median, 9 m; Figure 1) and occupied few habitat units (median, two units). Total distance moved was positively related to the distance moved on the first electrofishing pass and to the arcsine-transformed percentage of cobble, but not to the other variables (Table 3). When the two variables with significant univariate relations with total distance moved were combined in one model, the arcsine-transformed percentage of cobble was no longer significant ($P = 0.19$).

Most radio-tagged fish exhibited similar patterns of habitat and cover use. Of the 103 radio-tagged fish, 100 were initially located in pools, and 81% were in pools when finally captured. Capture locations were in or adjacent to (<0.1 m) concealment cover for most fish (92%). A typical capture sequence for a fish not taken on the first few electrofishing passes was for it to remain stationary within overhead cover during several subsequent capture attempts even though its location had been pinpointed by radiotelemetry. Recovery of such fish for retrieval of the radio tag often required dislodging boulders, probing by hand beneath undercut banks, or the disassembly of accumulations of woody debris, which was sometimes interrupted by the fish escaping to cover elsewhere before final capture, which was occasionally by hand rather than with electrofishing. In a few cases, we suspended retrieval attempts for 1–2 d, yet recapture sometimes required several more electrofishing attempts. We eventually retrieved all transmitters from implanted fish.

TABLE 3. Univariate linear regression model sample sizes and coefficients for the probability of capture of fish on the first electrofishing pass, the probability of moving ≥1 m if not captured on the first pass, and the probability of moving to a new habitat unit if not captured on the first pass. The percentages of substrate >150 mm and of overhead or instream cover were arcsine-transformed. Coefficients of regression are reported only for significant models.

Probability of capture or movement	n	Coefficient	P	r^2
Distance moved on first pass				
Habitat length (m)	56	0.297	0.147	
Habitat width (m)	56	–1.925	0.049	0.07
Maximum depth (cm)	56	0.004	0.944	
% Substrate > 150 mm	56	0.126	0.056	
% Cover	56	0.053	0.481	
Fish length (mm)	56	0.013	0.636	
Number of passes until capture				
Habitat length (m)	49	0.018	0.656	
Habitat width (m)	49	0.131	0.447	
Maximum depth (cm)	48	0.156	0.117	
% Substrate > 150 mm	49	0.003	0.810	
% Cover	49	0.001	0.946	
Fish length (mm)	49	0.004	0.327	
Distance moved on first pass	49	–0.011	0.630	
Total distance moved during capture attempts				
Habitat length (m)	49	0.450	0.267	
Habitat width (m)	49	–0.568	0.750	
Maximum depth (cm)	48	0.075	0.472	
% Substrate > 150 mm	49	0.251	0.025	0.10
% Cover	49	0.145	0.283	
Fish length (mm)	49	0.011	0.819	
Distance moved on first pass	49	1.128	<0.001	0.49

DISCUSSION

Movement by radio-tagged fish in response to electrofishing was common but relatively modest. Overall, 95% of fish not captured on the first electrofishing pass traveled less than six times the average wetted width or three times the average length of a habitat unit. Nevertheless, uncaptured fish continued to move during additional electrofishing efforts directed at their locations, and some of these movements were extensive. This work confirms that movement is a typical response to electrofishing, but provides more precise estimates of fish movements than those previously reported. Most studies have relied on applying section-specific batch marks to fish and noting whether fish marked in one section appeared in adjacent or nearby sections after electrofishing; movement could only be detected if marked fish passed a section boundary and were recaptured (Young and Schmetterling 2004; Peterson et al. 2005).

A number of studies have suggested that habitat characteristics, such as stream width, the abundance of large wood, overhead cover, cobble or larger substrate, or deep water, or biotic characteristics such as fish size, influence the efficiency of electrofishing estimates (Reynolds 1996; Peterson et al. 2004; Rosenberger and Dunham 2005), perhaps in part by affecting the amount that fish move in response to electrofishing. In contrast, we failed to detect any relationships between capture efficiency and variables related to habitat or fish size. Our study segments were typical of small mountain streams in this area, with comparable degrees of habitat complexity throughout each segment and among segments. Moreover, westslope cutthroat trout and brook trout in these streams were relatively small, with few fish exceeding 200 mm. Thus, the limited amount of variation in the independent variables may have contributed to the lack of significant results, although there has been little consensus on the suite of variables that influence capture efficiency in similar montane streams (Peterson et al. 2005; Rosenberger and Dunham 2005).

With respect to movement, the percentage of cobble and larger substrate was related to the probability that fish would move at all or to a new habitat unit. Yet, rather than altering a fish's probability of capture (Peterson et al. 2004, 2005), it appeared that cobble and larger stones may have served as an insecure refuge for fish not caught on the first electrofishing pass, and fish were more likely to abandon these than other cover types. No other independent variables helped to explain whether fish would move. In the small, shallow, but complex streams that we sampled, limited movement may be representative of trout responses to electrofishing regardless of the variation in physical habitat. Additional studies in similar streams may clarify this issue.

Our results demonstrate that sampling trout with electrofishing in reaches of small streams that are not barricaded at both ends, either by natural barriers, human-built structures, or block nets, will provide biased estimates of fish abundance because some proportion of fish will depart the reaches by moving up or downstream. The effects of fish movement on abundance estimates based on electrofishing in open populations can be minimized in two ways: by increasing capture efficiency or by lengthening the sampling reaches. Increased capture efficiency is often recommended to improve precision and reduce bias in abundance estimates (Riley and Fausch 1992). In addition, increasing efficiency also reduces the number of fish remaining in a reach after the initial electrofishing pass. Given that trout in our study streams tended to move after the first exposure to electrofishing, having fewer mobile fish that could leave a sampling reach equates with a less-biased abundance estimate. A number of authors provide direction for increasing electrofishing efficiency in small streams (Bohlin et al. 1989; Temple and Pearsons 2007; Dunham et al. 2009). For example, electrofishing with pulsed DC is generally more effective than unpulsed DC for salmonids in small streams when using electrofishers with limited power sources (Bohlin et al. 1989; Bird and Cowx 1993). Our use of the latter, as in other studies of movement and electrofishing (e.g., Peterson et al. 2005), may have unduly emphasized the importance of movement with respect to abundance estimates.

Minimum reach lengths for electrofishing are often recommended to ensure that a sufficient number of fish are captured to stabilize abundance estimates (White et al. 1982). A similar recommendation can be made for reducing the effects of mobility on abundance estimates (Temple and Pearsons 2007). For example, consider a hypothetical situation in which fish movement rates were comparable to those described in the present study, and in which half the fish present in a 50-m reach were not captured during an initial electrofishing pass. On average, about 6% of the total number of fish originally present would be expected to travel beyond the boundaries of the sampling reach in the absence of barriers to movement. Alternatively, if capture efficiency and movement rates remained constant, but reach length increased to 100 m, about 3% of the fish originally present would have left the reach in response to electrofishing. Relative to the amount of bias in most abundance estimates, particular those based on depletions (Riley and Fausch 1992; Peterson et al. 2004; Rosenberger and Dunham 2005; Sweka et al. 2006), the potential contribution of movement to this error appears relatively small. However, we discourage the extrapolation of these movement rates to other streams or regions because little work has been done to quantify movement patterns elsewhere, although such data could be collected relatively rapidly using the methods we described. Also note that we attempted to recapture fish during short intervals rather than the longer ones (>1 h) often used during depletion estimates. More realistic estimates of fish movement might result from adopting the longer period between recapture attempts.

A more general concern is the relatively low capture efficiency of the radio-tagged fish that we targeted for recapture on the second and later electrofishing passes. It is well known that capture efficiency generally declines after the first electrofishing pass during multiple-pass abundance estimates over short intervals (Cross and Stott 1975; Riley and Fausch 1992; Peterson et al. 2004). An alternative explanation, however, is that vulnerability to electrofishing can vary among individual fish (Bohlin and Sundström 1977; Habera et al. 2010), beyond that associated with length (Anderson 1995). This would lead to violations of the assumptions of equal catchability among passes for removal models and equal catchability among marked and unmarked fish for mark–recapture models. In both cases, overestimates of capture efficiency and underestimates of abundance would result.

Differential vulnerability to capture could also be a problem for tests of electrofishing capture efficiency that rely on recapture rates of marked fish in enclosed stream reaches for which the marked fish were initially captured by electrofishing (Bohlin et al. 1990). In such experiments, more accurate estimates of electrofishing capture efficiency might be obtained by catching the group of fish to be marked by using a different technique, such as netting (Cross and Stott 1975; Peterson and Cederholm 1984), briefly deploying baited minnow traps (Carrier et al. 2009), or angling (the present study). Given the number of fish that were resistant to recapture in our study, more investigation of individual variation in recapture probability seems warranted, particularly with respect to the electrofisher settings and interval between electrofishing runs that may be more typical of those used during abundance estimation.

Movement by fish during sampling efforts and attempts to control their movement will continue to be concerns for biologists that desire precise, unbiased estimates of fish abundance in streams. Although block nets help address the closed population assumption of most removal and mark–recapture abundance estimators, fish occasionally bypass them (Temple and Pearsons 2006; Dauwalter and Fisher 2007). Moreover, the installation and maintenance of block nets require substantial effort that could otherwise be devoted to sampling additional portions of a stream. When estimating abundance, high spatial variation in stream fish abundance (Amiro 1990b) may favor sampling a greater number of reaches with lower accuracy rather than sampling fewer with higher accuracy (Hankin and Reeves 1988; Mitro and Zale 2000; Bateman et al. 2005). Alternatively, biologists focused on detection of trends or estimates of species composition may regard the bias associated with fish movement during sampling—such as with the fish and streams we examined—as relatively unimportant. Given the wide array of objectives of fish sampling, we encourage additional studies of sampling-related movements with other species or fish of different sizes that explore the effects of different electrofishing settings or different sizes and types of streams. Such information will help biologists decide whether to ignore or address fish movement during sampling efforts.

ACKNOWLEDGMENTS

We thank Robert Clark and Tracy Elam for assistance in the field and data preparation. Funding was provided by the U.S. Bureau of Land Management (BLM) Missoula field office and Northwestern Energy (NWE). We thank Jo Christensen (BLM) and Sam Milodragovich (NWE) for logistical support.

REFERENCES

Adams, N. S., D. W. Rondorf, S. D. Evans, J. E. Kelly, and R. W. Perry. 1998. Effects of surgically and gastrically implanted radio transmitters on swimming performance and predator avoidance of juvenile Chinook salmon (*Oncorhynchus tshawytscha*). Canadian Journal of Fisheries and Aquatic Sciences 55:781–787.

Amiro, P. G. 1990a. Accuracy of removal population estimates of juvenile Atlantic salmon electric fished in wadeable streams. Pages 186–190 *in* I. G. Cowx, editor. Developments in electric fishing. Fishing News Books, Oxford, UK.

Amiro, P. G. 1990b. Variation in juvenile Atlantic salmon population densities between consecutive enclosed sections of streams. Pages 96–101 *in* I. G. Cowx, editor. Developments in electric fishing. Fishing News Books, Oxford, UK.

Anderson, C. S. 1995. Measuring and correcting for size selection in electrofishing mark–recapture experiments. Transactions of the American Fisheries Society 124:663–676.

Bain, M. B., and N. J. Stevenson, editors. 1999. Aquatic habitat assessment: common methods. American Fisheries Society, Bethesda, Maryland.

Barton, B. A., and W. P. Dwyer. 1997. Physiological stress effects of continuous- and pulsed-DC electroshock on juvenile bull trout. Journal of Fish Biology 51:998–1008.

Bateman, D. S., R. E. Gresswell, and C. E. Torgersen. 2005. Evaluating single-pass catch as a tool for identifying spatial pattern in fish distribution. Journal of Freshwater Ecology 20:335–345.

Bird, D. J., and I. G. Cowx. 1993. The selection of suitable pulsed currents for electric fishing in waters. Fisheries Research 18:363–376.

Bohlin, T., S. Hamrin, T. G. Heggberget, G. Rasmussen, and S. J. Saltveit. 1989. Electrofishing: theory and practice with special emphasis on salmonids. Hydrobiologia 173:9–43.

Bohlin, T., T. G. Heggberget, and C. Strange. 1990. Electric fishing for sampling and stock assessment. Pages 112–139 *in* I. G. Cowx and P. Lamarque, editors. Fishing with electricity: applications in freshwater fisheries management. Fishing News Books, Oxford, UK.

Bohlin, T., and B. Sundström. 1977. Influence of unequal catchability on population estimates using the Lincoln index and the removal method applied to electro-fishing. Oikos 28:123–129.

Bridger, C. J., and R. K. Booth. 2003. The effects of biotelemetry transmitter presence and attachment procedures on fish physiology and behavior. Reviews in Fisheries Science 11:13–34.

Carrier, P., J. S. Rosenfeld, and R. M. Johnson. 2009. Dual-gear approach for calibrating electric fishing capture efficiency and abundance estimates. Fisheries Management and Ecology 16:139–146.

Cross, D. G., and B. Stott. 1975. The effect of electric fishing on the subsequent capture of fish. Journal of Fish Biology 7:349–357.

Dauwalter, D. C., and W. L. Fisher. 2007. Electrofishing capture probability of smallmouth bass in streams. North American Journal of Fisheries Management 27:162–171.

Dolan, C. R., and L. E. Miranda. 2003. Immobilization thresholds of electrofishing relative to fish size. Transactions of the American Fisheries Society 132:969–976.

Dunham, J. B., A. E. Rosenberger, R. F. Thurow, C. A. Dolloff, and P. J. Howell. 2009. Coldwater fish in wadeable streams. Pages 119–138 *in* S. A. Bonar, W. A. Hubert, and D. W. Willis, editors. Standard methods for sampling North American freshwater fishes. American Fisheries Society, Bethesda, Maryland.

Dunham, K. A., J. Stone, and J. R. Moring. 2002. Does electric fishing influence movements of fishes in streams? Experiments with brook trout, *Salvelinus fontinalis*. Fisheries Management and Ecology 9:249–251.

Grabowski, T. B., T. D. Ferguson, J. T. Peterson, and C. A. Jennings. 2009. Capture probability and behavioral response of the robust redhorse, a cryptic riverine fish, to electrofishing. North American Journal of Fisheries Management 29:721–729.

Habera, J. W., M. A. Kulp, S. E. Moore, and T. B. Henry. 2010. Three-pass depletion sampling accuracy of two electric fields for estimating trout abundance in a low-conductivity stream with limited habitat complexity. North American Journal of Fisheries Management 30:757–766.

Hall, J. E., J. Chamberlin, A. N. Kagley, C. Greene, and K. L. Fresh. 2009. Effects of gastric and surgical insertions of dummy ultrasonic transmitters on juvenile Chinook salmon in seawater. Transactions of the American Fisheries Society 138:52–57.

Hankin, D. G., and G. H. Reeves. 1988. Estimating total fish abundance and total habitat area in small streams based on visual estimation methods. Canadian Journal of Fisheries and Aquatic Sciences 45:834–844.

Heggenes, J., Å. Brabrand, and S. J. Saltveit. 1990. Comparison of three methods for studies of stream habitat use by young brown trout and Atlantic salmon. Transactions of the American Fisheries Society 119:101–111.

Keefer, M. L., C. A. Peery, R. R. Ringe, and T. C. Bjornn. 2004. Regurgitation rates of intragastric radio transmitters by adult Chinook salmon and steelhead during upstream migration in the Columbia and Snake rivers. North American Journal of Fisheries Management 24:47–54.

Klein-Breteler, J. G. P., A. J. P. Raat, and M. P. Grimm. 1990. Efficiency and selectivity in fishing with electricity. Pages 219–228 *in* I. G. Cowx, editor. Developments in electric fishing. Fishing News Books, Oxford, UK.

Martinelli, T. L., H. C. Hansel, and R. S. Shively. 1998. Growth and physiological responses to surgical and gastric radio transmitter implantation techniques in subyearling Chinook salmon (*Oncorhynchus tshawytscha*). Hydrobiologia 371/372:79–87.

Mesa, M. G., and C. B. Schreck. 1989. Electrofishing mark–recapture and depletion methodologies evoke behavioral and physiological changes in cutthroat trout. Transactions of the American Fisheries Society 118:644–658.

Mitro, M. G., and A. V. Zale. 2000. Predicting fish abundance using single-pass removal sampling. Canadian Journal of Fisheries and Aquatic Sciences 57:951–961.

Nordwall, F. 1999. Movements of brown trout in a small stream: effects of electrofishing and consequences for population estimates. North American Journal of Fisheries Management 19:462–469.

Persat, H. 1991. The efficiency of electric fishing in fish population studies: an experiment on grayling (*Thymallus thymallus*). Internationale Vereinigung für Theoretische und Angewandte Limnologie Verhandlungen 24: 2432–2436.

Peterson, J. T., N. P. Banish, and R. F. Thurow. 2005. Are block nets necessary? Movement of stream-dwelling salmonids in response to three common survey methods. North American Journal of Fisheries Management 25: 732–743.

Peterson, J. T., R. F. Thurow, and J. W. Guzevich. 2004. An evaluation of multipass electrofishing for estimating the abundance of stream-dwelling salmonids. Transactions of the American Fisheries Society 133: 462–475.

Peterson, N. P., and C. J. Cederholm. 1984. A comparison of the removal and mark–recapture methods of population estimation for juvenile coho salmon in a small stream. North American Journal of Fisheries Management 4:99–102.

Pine, W. E., K. H. Pollock, J. E. Hightower, T. J. Kwak, and J. A. Rice. 2003. A review of tagging methods for estimating fish population size and components of mortality. Fisheries 28(10):10–23.

Price, A. L., and J. T. Peterson. 2010. Estimation and modeling of electrofishing capture efficiency for fishes in wadeable warmwater streams. North American Journal of Fisheries Management 30:481–498.

R Development Core Team. 2010. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna. Available: www.R-project.org. (January 2011).

Reynolds, J. B. 1996. Electrofishing. Pages 221–253 *in* B. R. Murphy and D. W. Willis, editors. Fisheries techniques, 2nd edition. American Fisheries Society, Bethesda, Maryland.

Ricker, W. E. 1975. Computation and interpretation of biological statistics of fish populations. Fisheries Research Board of Canada Bulletin 191.

Riley, S. C., and K. D. Fausch. 1992. Underestimation of trout population size by maximum-likelihood removal estimates in small streams. North American Journal of Fisheries Management 12:768–776.

Rivinoja, P., K. Leonardsson, and H. Lundqvist. 2006. Migration success and migration time of gastrically radio-tagged v. PIT-tagged adult Atlantic salmon. Journal of Fish Biology 69:304–311.

Rosenberger, A. E., and J. B. Dunham. 2005. Validation of abundance estimates from mark–recapture and removal techniques for rainbow trout captured by electrofishing in small streams. North American Journal of Fisheries Management 25:1395–1410.

Schmetterling, D. A. 2001. Seasonal movements of fluvial westslope cutthroat trout in the Blackfoot River drainage, Montana. North American Journal of Fisheries Management 21:507–520.

Snyder, D. E. 2003. Electrofishing and its harmful effects on fish. Information and Technology Report USGS/BRD/ITR-2003-0002, U.S. Government Printing Office, Denver.

Sweka, J. A., C. M. Legault, K. F. Beland, J. Trial, and M. J. Millard. 2006. Evaluation of removal sampling for basinwide assessment of Atlantic salmon. North American Journal of Fisheries Management 26:995–1002.

Temple, G. M., and T. N. Pearsons. 2006. Evaluation of the recovery period in mark–recapture population estimates of rainbow trout in small streams. North American Journal of Fisheries Management 26:941–948.

Temple, G. M., and T. N. Pearsons. 2007. Electrofishing: backpack and drift boat. Pages 95–132 *in* D. H. Johnson, B. M. Shrier, J. S. O'Neal, J. A. Knutzen, X. Augerot, T. A. O'Neil, and T. N. Pearsons. Salmonid field protocols handbook: techniques for assessing status and trends in salmon and trout populations. American Fisheries Society, Bethesda, Maryland.

White, G. C., D. R. Anderson, K. P. Burnham, and D. L. Otis. 1982. Capture recapture and removal methods for sampling closed populations. Los Alamos National Laboratory, LA-8787-NERP, Los Alamos, New Mexico.

Young, M. K., and D. A. Schmetterling. 2004. Electrofishing and salmonid movement: reciprocal effects in two small montane streams. Journal of Fish Biology 64:750–761.

Zalewski, M., and I. G. Cowx. 1990. Factors affecting the efficiency of electric fishing. Pages 89–111 *in* I. G. Cowx and P. Lamarque, editors. Fishing with electricity: applications in freshwater fisheries management. Fishing News Books, Oxford, UK.