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Effect of Electrofishing Sampling Design on Bias of Size-Related Metrics for Blue Catfish in Reservoirs

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Abstract.—We used electrofishing data from Oklahoma and Texas reservoirs to evaluate potential temporal (spring, summer, and fall) and spatial (reservoir section and habitat) biases associated with different sampling strategies for estimating size-related metrics (mean total length, proportional size distribution [PSD], and proportion of stock length fish [PSL]) of blue catfish *Ictalurus furcatus*. Regardless of how many individual fish were sampled, site-specific estimates of mean total length often deviated from the population mean, suggesting that fish within a site were of similar size. Bias across seasons was not consistent for any of the length metrics tested. Only one population had length-related differences between reservoir sections. Blue catfish collected from channel habitats were consistently larger than those collected from point or flat habitats. To identify the number of sites required to reduce deviations in estimates of size-related metrics, we used a Monte Carlo simulation technique to evaluate 3, 5, 10, 20, or 50 randomly selected sites. Regardless of how many individual fish were sampled, when too few sites were sampled, size-related metrics deviated farthest from the population mean. Notably, the population with a truncated length distribution had the least deviation. Simulations indicated that randomly sampling 10–20 sites resulted in estimates with consistent deviations ≤50 mm from the population mean. More effort may be required to routinely estimate PSD and PSL within 10 units. In some situations, biologists may consider stratifying the sample by habitat; however, gains in accuracy and precision may not compensate for increased effort needed to precisely quantify the habitat.

Introduction

Low-frequency electrofishing (LFE) efficiently collects blue catfish *Ictalurus furcatus*, with samples often producing more than 100 fish. Recent studies indicate that individual LFE samples accurately represent size structure of blue catfish within a given sampling location (Buckmeier and Schlechte 2009; Bodine and Shoup 2010). While this could suggest that just a few LFE samples could produce enough fish to provide precise length-frequency data, it is not clear how well single, large samples represent the overall population. Information regarding size-specific distributional patterns of this species is needed to develop sampling strategies that accurately represent total population size structure. For many fishes, variables such as season, reservoir section, habitat, water depth, and time of day affect their distribution (Hubbard and Miranda 1986; Post et al. 1995; Schael et al. 1995). Size-related spatial and temporal migrations, both vertically and horizontally, may also affect the portion of the population that is vulnerable to electrofishing at a given place and time. In addition, similarly sized fish often school together (Krause et al. 1996; Hoare et al. 2000; Barber 2003). Consequently, individual samples likely only represent a portion of the entire size structure and oversampling any one location or habitat type could bias metrics typically used to assess populations. By understanding these issues, sampling designs can be developed to reduce most sources of bias by accounting for nonrandom distributions of fish.

Proportional size distribution (PSD), proportion

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of stock length fish (PSL), and measures of central tendency are commonly used to describe population size structure (Anderson and Neumann 1996; Guy et al. 2007). To accurately represent these size-related metrics, fisheries scientists must collect unbiased, representative samples from the population of interest (Anderson and Neumann 1996); to represent these metrics precisely, adequate numbers (Vokoun et al. 2001; Miranda 2007) must be collected. Recommended sample sizes for these metrics (Anderson and Neumann 1996; Vokoun et al. 2001; Miranda 2007) require a random sample of fish and are only applicable to situations where fish can be treated as the primary sampling unit. However, fish are rarely, if ever, distributed randomly within a population (Lambou 1963; Cyr et al. 1992). In these situations, sampling sites become the primary sampling unit rather than individual fish. As a result, sample designs must account for some minimum number of sites in addition to a minimum number of fish to accurately represent these metrics.

Bodine and Shoup (2010) recommended a stratified sampling design for blue catfish electrofishing that incorporates reservoir section (upper versus lower reservoir); however, their recommendations were primarily based on quantifying catch per unit effort (CPUE). They also found evidence that PSD of preferred-length fish was related to habitat (points, flats, and river channels) but suggested this was unlikely to meaningfully effect catch-per-unit-effort estimates. It could, however, affect size-specific metrics. Sampling strategies designed to accurately estimate size-related metrics may or may not be similar to sampling designs recommended for other types of data collection (e.g., CPUE, presence/absence).

To develop sampling strategies that reduce bias of size-related metrics, we (1) evaluated the size distribution of blue catfish within individual sample sites compared to the overall size distribution of the total population, (2) evaluated if size-related metrics (Mean total length, PSD, and PSL) were biased seasonally (spring, summer, and fall), (3) evaluated if sampling different reservoir sections (upper or lower) and habitats (channels, points, and flats) resulted in spatial size biases, and (4) used simulations to identify sampling strategies (i.e., number of fish and sampling sites) required to obtain a representative sample.

Methods

Data Sources

Data were acquired from two previous studies that evaluated electrofishing for blue catfish. In the first study, data were collected to evaluate capture efficiency and size selectivity (within a given sampling area) in the Trinity River and Lake Livingston, Texas (Buckmeier and Schlechte 2009). The second study evaluated gear selectivity and effects of temperature (e.g., season) and habitat (i.e., points, channels, flats, and reservoir section) on proportional size distribution of preferred-size blue catfish and catch rate of all size-groups of blue catfish in three Oklahoma reservoirs (Bodine and Shoup 2010). This included sampling in a population with a known length structure. Although these studies found that LEF collected a representative sample of catfish at a given sampling location (i.e., it did not have an inherent size bias), they did not address the spatial distribution of different size-groups of fish. So, while LEF is not size-biased, it is still unclear if single samples accurately reflect the size structure of the entire population. This study uses data from these two studies to examine differences in size-related metrics of blue catfish at the site level and identify temporal and spatial biases associated with several size-related metrics for blue catfish populations with differing population characteristics. We then simulated sampling to estimate the number of fish and sampling sites required to estimate mean total length (TL) and indices of stock density for blue catfish at a reasonable level of precision by LEF. Because of a potential for fish less than 250 mm TL to be underrepresented in electrofishing samples (Buckmeier and Schlechte 2009), only fish ≥250 mm TL were included in the analyses.

Texas data.—Blue catfish were sampled from a 65–70-ha site at Lake Livingston, Texas, in June, July, and September 2005 (Buckmeier and Schlechte 2009). Fish were collected using a Smith-Root, Inc. (Vancouver, Washington) 7.5 generator-powered pulsator (GPP) set at 15 pulses/s and the 300–500-V DC setting to yield about 1 A (conductivity 437–557 μS/cm). Sampling occurred during daylight hours and fish were measured (total length, to the nearest millimeter). Sites included preferred habitats of blue catfish (i.e., channel and near-channel areas; Graham 1999). Typically, two chase boats assisted with capture of fish. All boats had one driver and one person collecting fish (netter). Each sampling event lasted 5 min and was relatively stationary, with movement limited within the 100 × 100 m cell (similar to Gilliland 1988 and Cunningham 1995).

Oklahoma data.—Kaw, Keystone, and Oologah reservoirs in Oklahoma were sampled seasonally (spring, summer, and fall) for 2 years (Bodine and Shoup 2010). Sampling began in June 2006, with each season spanning three consecutive months (e.g., spring = March–May). Winter was excluded because catch rates of blue catfish declined precipitously when water temperatures were less than 18°C (Grussing et al. 2001; Bodine and Shoup 2010). Each reservoir was stratified by reservoir section (i.e., upper and lower) and contained 12 sampling locations within each section (24 sites/reservoir). Each section was further stratified by habitat type (i.e., channels, points, and flats), and four sites of each type were randomly selected. Ten-minute samples were conducted during daylight hours using a Smith-Root, Inc. 5.0 GPP set at 15 pulses/s using the 100–1,000 V DC setting with percent of range adjusted to yield about 4 A (conductivity 330–1,200 μS/cm). Two chase boats equipped with a driver and two netters were used to collect fish that surfaced away from the electrofishing boat (Boxrucker and Kuklinski 2006). No netters were used on the electrofishing boat.

Data Analysis

Site-specific estimates of mean total length.—We assessed differences in estimated mean total length of blue catfish among sampled sites for seven populations (i.e., three Oklahoma reservoirs in 2 years and one Texas reservoir). We calculated a separate annual estimate of mean total length (all data pooled) for each reservoir because growth, mortality, and recruitment may not have been constant among reservoirs and years. We then calculated residuals of individual sample means (i.e., total population mean – sample mean). To evaluate the variation in estimates of mean total length, we plotted the residuals against the number of fish collected in each sample (representing different-sized samples). In randomly distributed populations, larger samples should more closely resemble the population (Brown and Austen 1996). Therefore, if the size distribution of blue catfish within each site was random, plots of residuals should asymptote near zero as the number of fish sampled at each site increases (Figure 1; expected residuals). Alternatively, consistent deviations of residuals across the range of observed sample sizes could suggest nonrandom size distributions (i.e., that similarly sized fish are found together).

Seasonal bias.—Mean total length, PSD, and PSL (i.e., the number of stock-length fish/the number of recruit-length fish [≥250 mm TL]) were calculated seasonally (spring, summer, and fall) for each reservoir and year to estimate temporal variability. We used a one-way analysis of variance (ANOVA) to test differences in mean total length among seasons for each reservoir and year using the PROC MIXED procedure ($P \leq 0.05$; SAS Institute 2010). We used one-way ANOVAs because the size metric within a reservoir for a given year was the response variable we were interested in, not a pooled response across years or reservoirs. Consistent differences across populations would suggest that seasonal biases should be considered in sample designs.

Estimates of PSD and PSL were calculated annually (all data pooled) and treated as reference population values for comparison. Seasonal PSD and PSL values were compared to annual values and to one another. Differences in estimates of size distribution indices were assessed as important when values differed by more than ±10 units. Radomski et al. (2009) reported that many fisheries biologists require increases in PSD greater than 20 before changing management actions. Miranda (2007) used a criterion of greater than ±5 units for largemouth bass Micropterus salmoides. However, longer length distributions typical of blue catfish require substantial effort to reliably estimate size distribution indices. So, while statistical differences may exist when assessing differences greater than ±5 units, differences may not be biologically significant. Given observed imprecision in these values and wide length distributions associated with these populations, we chose a more conservative approach (±10 units) for evaluating differences for blue catfish. We only analyzed seasonal bias for Oklahoma reservoirs because seasonal data were not collected in Texas.

Spatial bias.—Differences in mean total length, PSD, and PSL were analyzed between reservoir section (i.e., upper and lower) and among habitat (i.e., points, channels, and flats) to determine spatial variability. Mean total length was analyzed by year (seasons pooled) using one-way ANOVA for each variable (section and habitat) on each reservoir. We did not include interaction terms in the model. Although interactions between section and habitat may exist, the focus of this study was to determine if section or habitat were consistently important. If differences were not strong enough to suggest a significant main effect by itself, we do not consider the pattern to be useful in a sampling protocol that would cover a broad range of lakes. We performed all analyses using the PROC MIXED procedure (SAS Institute 2010), and when significant effects were detected

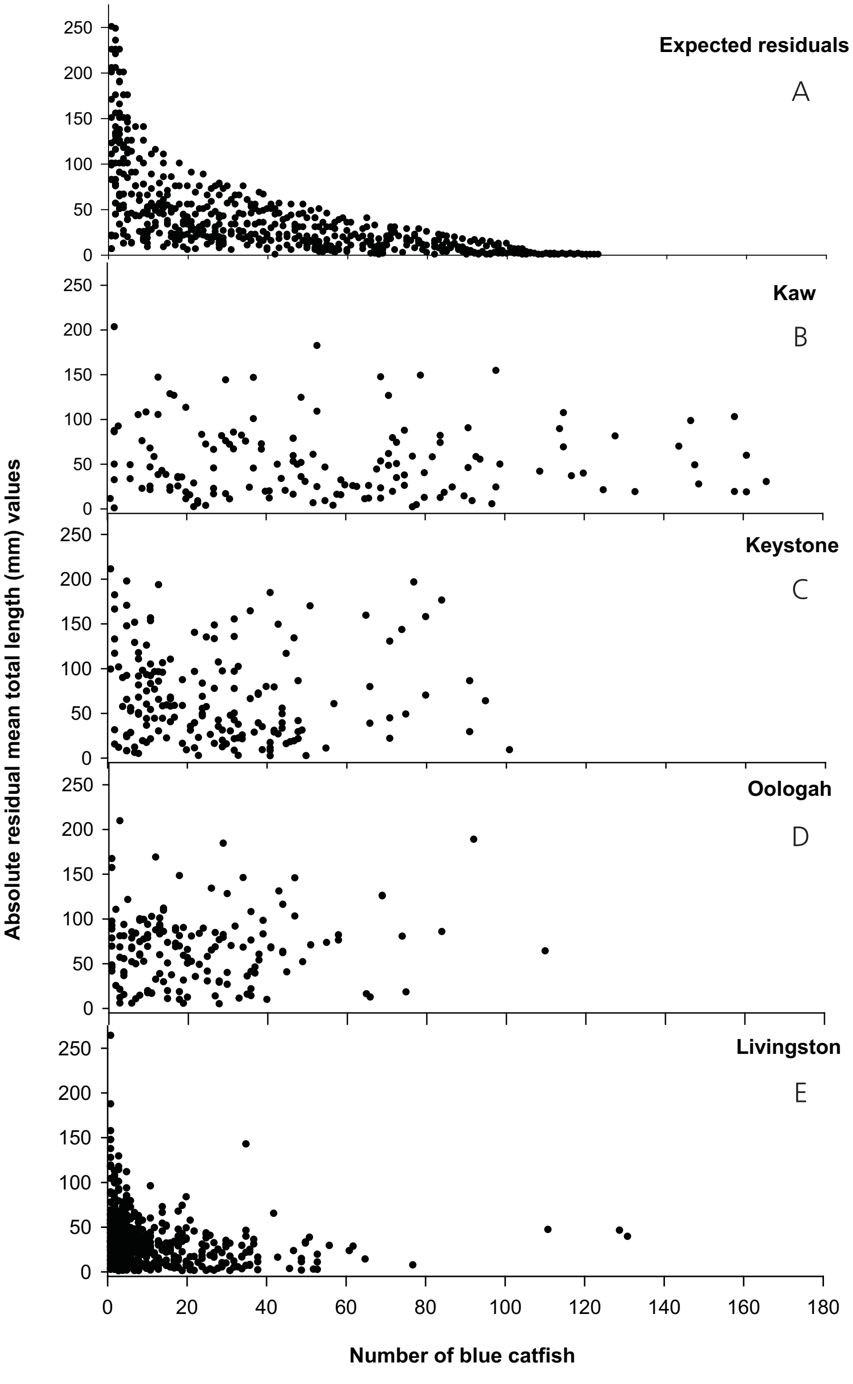

FIGURE 1. Absolute residual values of mean total length (mm) versus the number of fish collected in each sampling site on Oklahoma (Kaw [A], Keystone [B], and Oologah [C]) and Texas (Livingston [D]) reservoirs. Oklahoma reservoirs were sampled from June 2006 through May 2007 and June 2007 through May 2008. Lake Livingston was sampled in June, July, and September, 2005. Zero on the *y*-axis represents the true population mean total length value. Expected residuals are based on a population with a random distribution of all size-classes. Residuals that do not similarly converge on zero for samples with larger numbers of fish suggest nonrandom size distributions (i.e., that similarly sized fish are found together).

($P \leq 0.05$), subsequent pair-wise comparisons of means were made using a Tukey-Kramer test. Differences in PSD and PSL were evaluated using the same criterion as in the seasonal analysis, with annual values being calculated for each reservoir section and habitat type. We examined spatial bias using Oklahoma data because these data were not available for Texas.

Simulated sampling.—We evaluated the deviation in mean total length, PSD, and PSL associated with sampling 3, 5, 10, 20, or 50 sites to estimate effects of using sites as our primary sampling units. These sampling strategies were evaluated using Monte Carlo simulation techniques (PROC SURVEYSELECT; SAS Institute 2010), where we took a simple random sample (with replacement) of individual sample sites and included all fish collected at that site. Sites where fish were not collected were not included in the simulations as they provide no information on the length metrics of interest. We pooled all data across years within each reservoir to increase the number of samples available in the simulated sampling. This created four catfish populations with known size characteristics (Figure 2). We replicated each sampling scenario 5,000 times to estimate variability. We compared the absolute value of each metric to the known value to estimate the magnitude of the deviation for each replicate. We ignored the direction of the deviation because negative and positive deviations are equally important. Further, as a biologist typically collects only one sample per year, not replicate samples, the magnitude of the deviation for any single sample is the important value.

We estimated the level of effort required to reduce the deviation of mean total length to 13, 25, and 50 mm. For PSD, and PSL, we evaluated the level of effort required to reduce the deviation to 10%. We estimated the 80th percentile bounds on the magnitude of the deviation for each metric using PROC QUANTREG (SAS Institute 2010). To illustrate the reduction in deviation associated with these sampling strategies, we plotted the 80th percentiles of the deviation against the number of fish collected in each sample. This is a somewhat risk-averse position, that we consider a reasonable compromise between a highly risk-averse position (95th percentile) and a risk-neutral position (50th percentile). We used the slope to qualitatively indicate consistency in estimating each metric. A positive slope suggests that the sample sites with the most fish deviate farthest from the mean. In contrast, a negative slope suggests that sites with the most fish deviate least from the mean. A line with little or no slope suggests that the deviation is consistent across all sample sizes.

In addition, we simulated a simple random sample (with replacement) of 50, 100, 200, 400, 800, 1,000, or 2,000 individual fish (i.e., ignoring site information), similar to Vokoun et al. (2001) and Miranda (2007). An increase in the deviation associated with sampling individual sites (not individual fish) would suggest that fish within an individual site are more similar than fish within the population as a whole. We hypothesized that as more sites were sampled, the magnitude of the deviation should approach that of the simple random sample of individual fish. We recognize that using individual fish as the primary sampling unit is likely impractical, but we have included it for comparative purposes. Both approaches are asymptotically unbiased.

Results

Site-Specific Estimates of Mean Total Length

We saw no reduction of residuals in estimates of mean total length as the number of fish from a given site increased in the Oklahoma populations examined. The magnitude of residuals from the population mean was consistent throughout the range of sample sizes observed, indicating that sampling sites tend to contain similarly sized fish (Figure 1). For example, in Keystone Reservoir, residuals greater than 150 mm were observed throughout the range of sample sizes observed. However, the magnitude of residuals varied with population length characteristics. Sample residuals from Lake Livingston that showed a truncated length frequency had smaller residual values (<50 mm when samples exceeded 30 fish), suggesting that individual sites more closely represented the total population. However, there was some indication that estimated mean total length was higher at sites with more than 40 fish for this population.

Seasonal Bias

We found no consistent differences among seasons for any of the metrics tested. We detected no bias in mean total length among seasons for either year in any Oklahoma reservoir (Table 1). Similarly, we found no consistent differences between seasonal

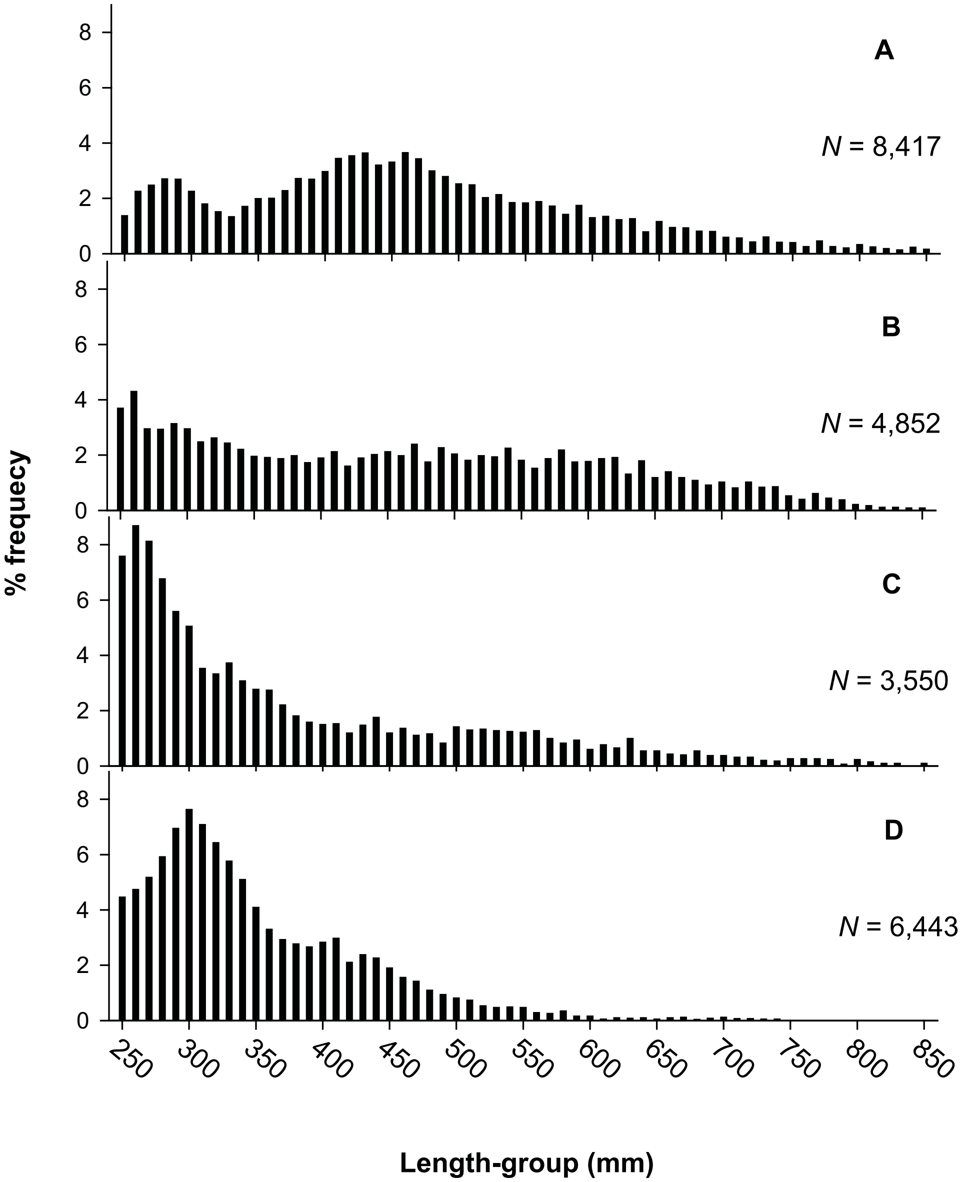

FIGURE 2. Pooled length frequency (total length, 10-mm groups) of blue catfish captured by electrofishing in Oklahoma reservoirs (Kaw [A], Keystone [B], and Oologah [C]) from June 2006 to May 2008 and Lake Livingston (D), Texas, in 2005.

values and annual values of size structure indices, although some values were more variable than expected (Table 2). Seasonal values of PSD differed by more than 10 units from the population PSD on only two occasions (Table 2).

Spatial bias.—Although inconsistent overall, we did observe some notable differences among specific habitat types (i.e., channels, flats, and points) for mean total length and size-structure indices (Tables 1 and 2). We detected significant differences ($P < 0.05$) in mean total length associated with habitat in three populations. In all three cases, the point estimate of the mean total length was highest for channel habitat (Tukey P for all comparisons <0.05; Table 1). The point estimate of PSD was

TABLE 1. Mean total length (mm) of blue catfish collected from different seasons, sections, and habitats on Kaw, Keystone, and Oologah reservoirs, Oklahoma. Samples were obtained using low-frequency electrofishing from June 2006 through May 2007 (2006) and June 2007 through May 2008 (2007). Significant differences ($P < 0.05$) are denoted by an asterisk (*). Sample size or SE is indicated in parentheses below each value. Within a reservoir (row) different letters indicate statistical differences based on a Tukey-Kramer test ($P < 0.05$). TL = total length.

	Population mean	Season				Section			Habitat			
Reservoir	TL	Spring	Summer	Fall	*P*, df	Upper	Lower	*P*, df	Channel	Flat	Point	*P*, df
2006												
Kaw	478	484	473	490	0.55	483	470	0.29	485	468	480	0.56
	(*n* = 5084)	(12.26)	(8.34)	(18.55)	2,80	(8.44)	(9.98)	1,81	(11.12)	(11.47)	(11.13)	2,80
Keystone	463	430	469	478	0.11	463	461	0.89	497 (A)	459 (AB)	435 (B)	0.01*
	(*n* = 2601)	(17.6)	(12.11)	(16.37)	2,92	(11.86)	(12.82)	1,93	(14.79)	(14.08)	(14.15)	2,92
Oologah	392	402	376	433	0.07	413	364	<0.01*	439 (A)	342 (B)	384 (B)	<0.01*
	(*n* = 1642)	(15.17)	(11.56)	(22.87)	2,83	(10.79)	(12.61)	1,93	(11.89)	(13.56)	(13.55)	2,83
2007												
Kaw	443	472	431	444	0.08	443	444	0.94	437	451	442	0.77
	(*n* = 3389)	(14.64)	(9.52)	(31.19)	2,66	(10.54)	(12.24)	1,67	(13.97)	(14.12)	(13.66)	2,66
Keystone	444	456	433	458	0.38	445	445	0.96	455	457	419	0.13
	(*n* = 2241)	(16.85)	(12.16)	(17.54)	2,78	(11.43)	(13.1)	1,79	(15.35)	(14.24)	(13.88)	2,78
Oologah	356	345	362	362	0.65	370	340	0.08	389 (A)	324 (B)	353 (AB)	<0.01*
	(*n* = 1917)	(14.58)	(12.83)	(19.58)	2,69	(11.48)	(12.51)	1,70	(13.34)	(13.71)	(14.92)	2,69

TABLE 2. Proportional size distribution (PSD) and proportion of stock length blue catfish (PSL) collected from different seasons, sections, and habitats on Kaw, Keystone, and Oologah reservoirs, Oklahoma. Samples were collected using low-frequency electrofishing from June 2006 through May 2007 (2006) and June 2007 through May 2008 (2007). The number of fish used to estimate each metric is denoted in parentheses below the measurement. Differences (>10 units) between variables (season, section, and habitat) and the population value are denoted by an asterisk (*).

	Population	Seasonal PSD			Section PSD			Habitat PSD	
Reservoir	PSD	Spring	Summer	Fall	Upper	Lower	Channel	Flat	Point
2006									
Kaw	39	37	38	50*	41	35	42	38	39
	(5,084)	(1,290)	(3,077)	(717)	(3,580)	(1,504)	(1,712)	(1,437)	(1,935)
Keystone	48	27*	49	55	45	54	71*	35*	32*
	(2,601)	(455)	(1,163)	(983)	(1,845)	(756)	(851)	(890)	(860)
Oologah	31	31	31	33	34	24	42*	7*	30
	(1,642)	(677)	(805)	(160)	(1,205)	(437)	(725)	(353)	(564)
2007									
Kaw	34	37	34	28	34	36	40	38	28
	(3,389)	(1,087)	(1,932)	(370)	(2,360)	(1,029)	(1,106)	(452)	(1,331)
Keystone	47	46	49	45	42	56	54	50	34*
	(2,241)	(602)	(869)	(770)	(1,440)	(801)	(680)	(860)	(701)
Oologah	29	23	37	28	33	21	49*	9*	19
	(1,917)	(989)	(711)	(217)	(1,207)	(711)	(668)	(465)	(784)

	Population	Seasonal PSL			Section PSL			Habitat PSL	
Reservoir	PSL	Spring	Summer	Fall	Upper	Lower	Channel	Flat	Point
2006									
Kaw	95	96	94	96	95	96	95	96	94
	(5,084)	(1,290)	(3,077)	(717)	(3,580)	(1,504)	(1,712)	(1,437)	(1,935)
Keystone	89	83	92	88	90	67*	92	91	83
	(2,601)	(455)	(1,163)	(983)	(1,845)	(756)	(851)	(890)	(860)
Oologah	76	73	77	79	81	61*	83	66	72
	(1,642)	(677)	(805)	(160)	(1,205)	(437)	(725)	(353)	(564)
2007									
Kaw	80	86	73	89	78	83	76	74	85
	(3,389)	(1,087)	(1932)	(370)	(2,360)	(1,029)	(1,106)	(452)	(1,331)
Keystone	77	81	72	78	79	72	77	80	71
	(2,241)	(602)	(869)	(770)	(1440)	(801)	(680)	(860)	(701)
Oologah	53	50	56	56	57	46	62	45	49
	(1,917)	(989)	(711)	(217)	(1,207)	(711)	(668)	(465)	(784)

highest in channel habitats for all six populations (Table 2). In 8 of 12 comparisons between channel habitat and either flat or point habitat, the channel habitat had a higher PSD (i.e., >10 units). We saw rare but no consistent differences between reservoir sections (i.e., upper versus lower) for any of the metrics (Tables 1 and 2).

Simulated Sampling

We found that we needed to sample a minimum of 10 sites (each site with a catch >0) when estimating mean total length and size-structure indices in order to achieve a value that was consistently within an acceptable range of the population mean. The magnitude of deviation was reasonably consistent across all quantities of fish sampled (i.e., a line fit to the estimated 80th percentile of the deviation was roughly horizontal) when ≥10 sites were sampled in the three Oklahoma reservoirs. However, when less than 10 sites were sampled, the magnitude of deviation was considerably higher and displayed strong increasing or decreasing trends (depending on the reservoir), even when a comparable quantity of fish was obtained (Figures 3–5). We found that in all cases at Lake Livingston, the estimated 80th percentile of the deviation appeared to decrease as sample size increased. However, when 10–20 sites were sampled, the deviation was less dependent upon the number of the fish at a site.

Twenty to 50 sampling sites with approximately 200–800 fish were needed to decrease deviations between the estimated mean total length and the true

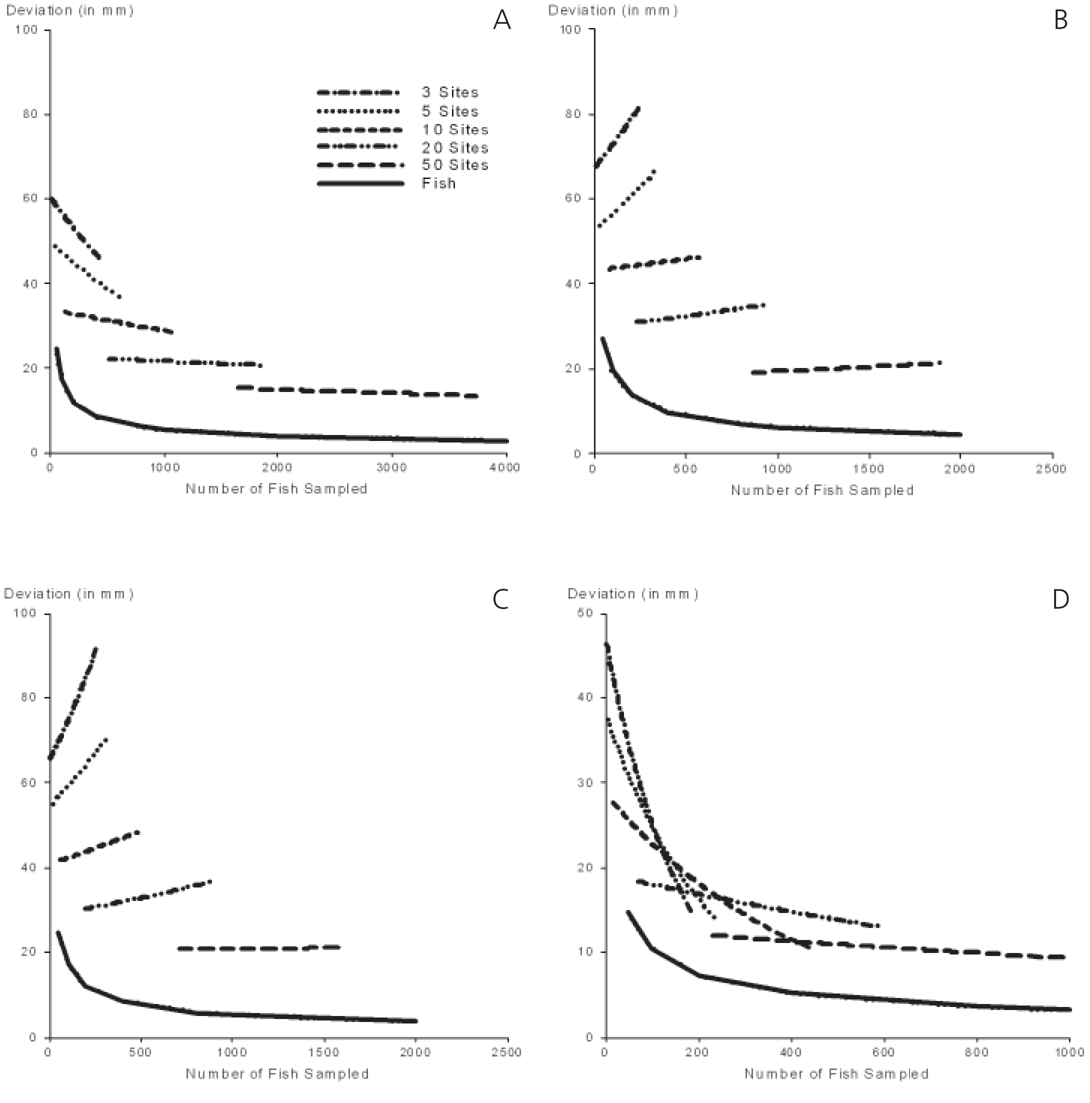

FIGURE 3. Results of simulated sampling to measure deviations (in mm) associated with sampling 3, 5, 10, 20, and 50 sites (Sites) for mean total length in four reservoirs (Kaw [A], Keystone [B], Oologah [C], and Lake Livingston [D]. The solid line indicates deviations associated with assuming individual fish are the primary sampling unit (Fish). The lines represent the estimated 80th percentiles from the simulated results. Notice that the scales at Livingston are appreciably reduced.

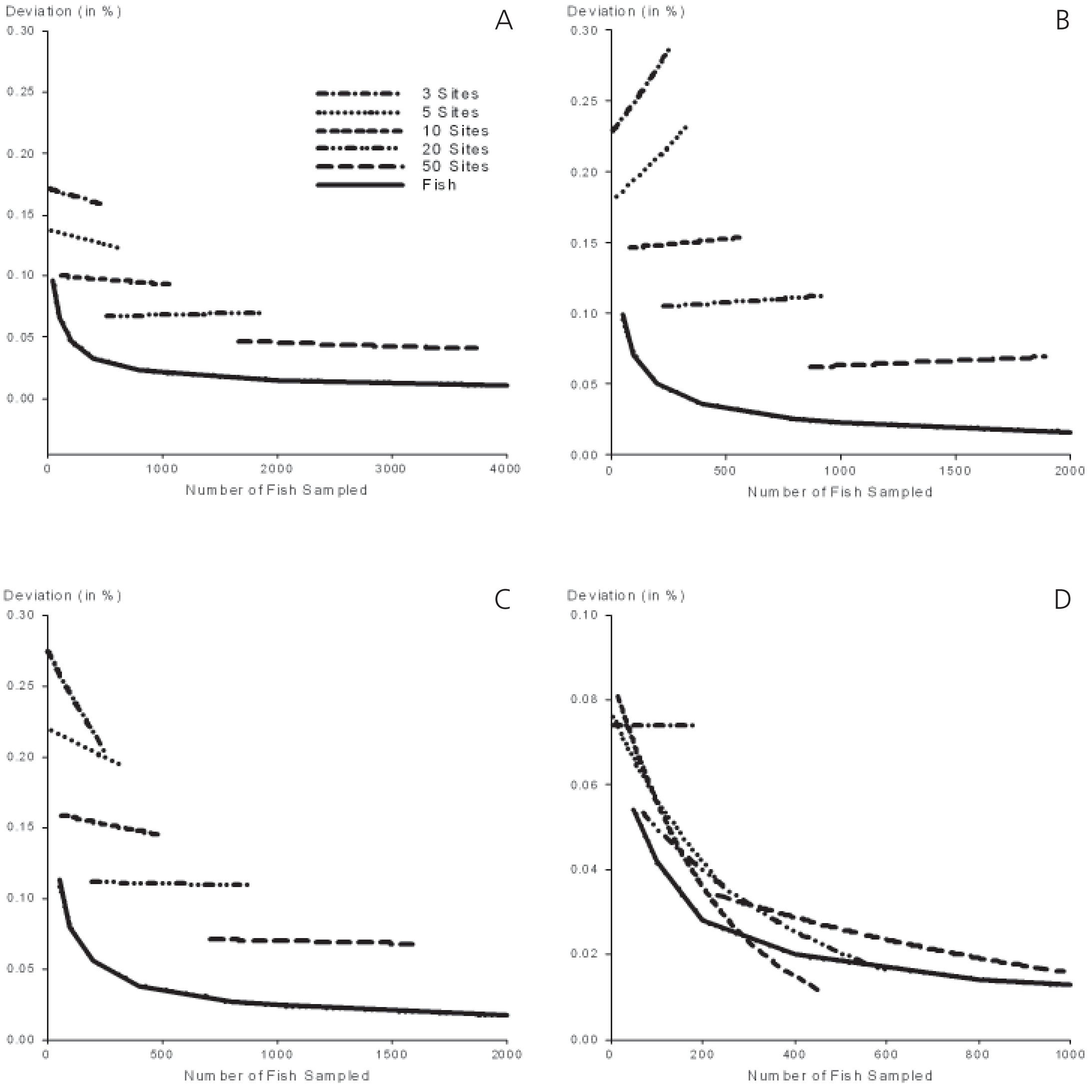

FIGURE 4. Results of simulated sampling to measure deviations (in percent) associated with sampling 3, 5, 10, 20, and 50 sites (Sites) for proportional size distribution in four reservoirs (Kaw [A], Keystone [B], Oologah [C], and Lake Livingston [D]. The solid line indicates deviations associated with assuming individual fish are the primary sampling unit (Fish). The lines represent the estimated 80th percentiles from the simulated results. Notice that the scales at Lake Livingston are appreciably reduced.

mean to less than 25 mm on Oklahoma reservoirs (depending on the reservoir, Figure 3). However, at Lake Livingston, using as few as three sample sites resulted in deviation estimates less than 50 mm, and we routinely observed deviations less than 25 mm. When 50 sites were sampled, deviations were reduced to less than 13 mm, with as few as 400 fish (Figure 3). Additionally, all numbers of sites in Livingston reached deviation less than 10% for PSD, and 20–50 sites were needed to attain a 10% deviation in PSL (Figures 4 and 5).

Discussion

We frequently observed a nonrandom distribution of blue catfish in the reservoirs examined. Regardless of the number of fish captured, mean total length at a given site often deviated from the population mean,

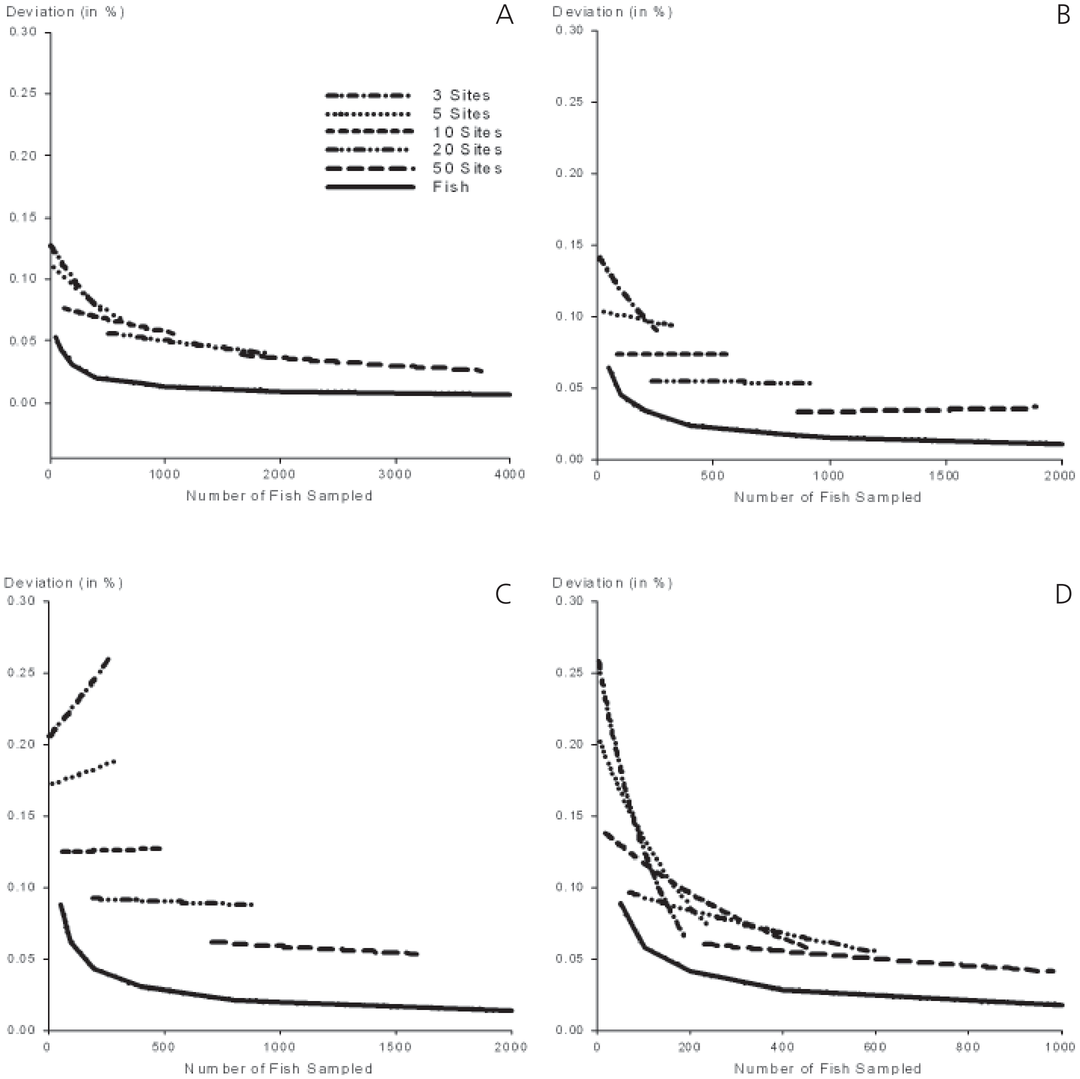

FIGURE 5. Results of simulated sampling to measure deviations (in percent) associated with sampling at 3, 5, 10, 20, and 50 sites (Sites) for PSL in four reservoirs (Kaw [A], Keystone [B], Oologah [C], and Lake Livingston [D]. The solid line indicates deviations associated with assuming individual fish are the primary sampling unit (Fish). The lines represent the estimated 80th percentiles from the simulated results. Notice that the scales at Lake Livingston are appreciably reduced.

suggesting that blue catfish within a site were often similar in size. This size segregation was occasionally related to variables such as habitat and reservoir section. Sampling strategies that account for these underlying spatial biases (e.g., stratified by habitat and reservoir section), in addition to sampling a minimum number of fish, will result in estimates of mean total length, PSD, and PSL that are consistently closer to the actual population mean. Our results suggest if fish are collected from a minimum of 10 randomly selected sites throughout the reservoir, estimates of mean total length, PSD, and PSL should have a consistent deviation. As more sites are sampled, the magnitude of the deviation can be further reduced but with diminishing returns after about 20 sites have been sampled.

To precisely assess length-based metrics when fish populations are nonrandomly distributed, biologists need to collect some minimum number of fish and take them from a minimum number of sites. Vokoun et al. (2001) and Miranda (2007) have previously discussed sample sizes needed for various species and metrics. Miranda (2007) recommended collection of 75–140 independently collected fish for PSD and 75–160 fish for mean total length. However, these recommended sample sizes are only applicable to populations where fish are randomly distributed. In these situations, fish are considered independent and can be treated as the primary sampling unit. Our results show that blue catfish often segregate by size and can rarely be considered independent. In all four populations, the simulation that properly accounted for how the fish were actually collected displayed higher deviations than did the one that assumed fish were the primary sampling units. Therefore, when fish are not randomly distributed, biologists will likely need to collect more fish than recommended by Miranda (2007) to precisely assess length-based metrics. The notable exception to this was the estimate of PSD at Lake Livingston. There, the deviation from the site-based sampling protocol approached or was less than that of the fish-based sampling protocol for large numbers of fish taken from 10 and 20 sites (Figure 4). This is likely an artifact of having only a few sites with more than 60 fish, and that these sites have smaller residuals than would be anticipated. It is difficult to visualize a mechanism that could create large schools of catfish for which length-based metrics would be consistently less variable than a random sample of fish.

We found no evidence of seasonal biases when estimating size-related metrics of blue catfish. Estimates of mean total length were similar, and the few differences observed in PSD and PSL were not consistent among years and reservoirs, suggesting that these metrics could be calculated in any of the seasons examined. While we did not identify seasonal differences in the values of these size-related metrics, previous studies have found seasonal differences in capture efficiency (Buckmeier and Schlechte 2009) and CPUE (Bodine and Shoup 2010). As a result, we recommend that sampling be temporally consistent when comparing catch between years. However, selection of which season to sample can vary depending on sampling schedule and study objectives.

Spatial biases were most common among habitat types examined in our study. Estimates of mean total length and PSD were often highest in samples from channel habitats. Bodine and Shoup (2010) reported that CPUE of blue catfish ≥762 mm was highest in channel habitats; however, they observed no differences in CPUE of fish less than 762 mm among habitats. Although we did not evaluate habitat selection, our results suggest that channel habitats may be a preferred habitat of larger blue catfish. Many other aquatic species display spatial segregation (Pace et al. 1991; Cyr et al. 1992) associated with available resources such as temperature and habitat (Schael et al. 1995). Klaassen and Marzolf (1971) reported that large channel catfish *Ictalurus punctatus* selected different habitats than smaller fish. Schael et al. (1995) reported that threadfin shad *Dorosoma petenense* displayed patchy distributions. When this segregation exaggerates size or age differences in the population, even collections with a large number of individual fish can result in severely biased estimates. Hubbard and Miranda (1986) reported that subjectively chosen reservoir habitats thought to contain higher abundances of largemouth bass may also contain a greater proportion of larger fish resulting in positively biased estimates of size-related metrics.

Spatial biases in size-related metrics necessitate sampling strategies to reduce the influence of these biases. We recommend that biologists use either simple random or stratified random sampling for blue catfish in reservoirs, where the primary sampling units are sample sites. Sometimes fish size differed by habitat type; stratification by habitat type could yield greater precision and, thus, should be taken into consideration. However, before a stratified design is used, strata must be defined and quantified. The effort to quantify strata, temporal consistency of strata, and consequences of errors in the classification should be considered. It may be useful to stratify by reservoir section as catch rates can be much higher in the upper section of a reservoir (Bodine and Shoup 2010). Habitat types described in this study were general, and further delineation (e.g., depth or substrate) may be necessary to yield more consistent results.

For the blue catfish populations examined, we found that simple random sampling of 10–20 sites (with catch >0) was the smallest sampling effort that produced consistent results and adequately reduced deviations for the length metrics examined. When fewer than 10 sites were sampled, deviations were greater than 30 mm and inconsistent. This suggests that estimates are unreliable and may be highly influenced by an individual sample site. When more than 20 sites were sampled, magnitude of deviation was reduced to 30 mm or less and became more consistent. Sampling of 50 sites produced estimates closer to the population mean, and, typically, estimates continued to improve (deviations were 15–25 mm), but the added effort required to collect these samples may not be justified for the modest improvements it provided. We suggest that a simple random design is efficient for estimating size-related metrics in reservoirs with high densities of blue catfish. Such an approach does not require prior knowledge of spatial biases and should produce accurate and precise estimates of size-related metrics as long as enough fish are collected from a sufficient number of sites. In situations where resources are limited (e.g., limited effort/budget), fewer sites can be sampled; however, a reduction in precision may result. Understanding these trade-offs will allow biologists to compare the additional costs of sampling more sites with the relative gains in reliability.

Our data also suggests that the shape of the length-frequency distribution can also influence effort needed to estimate length-related metrics. Residuals of sample mean total length often deviated more than 150 mm for our Oklahoma populations, where we routinely observed fish above 550 mm. However, at Lake Livingston, we rarely observed fish above 550 mm and we observed smaller residuals. We also observed that PSD and PSL indices were quite variable. Miranda (2007) suggested using deviations of 10 units (±5 units) to assess equivalence of size distribution indices for largemouth bass, white crappie *Pomoxis annularis*, and bluegill *Lepomis macrochirus*. Our simulations suggested that it will take substantial effort to be able to estimate indices for blue catfish within ±5 units, and the data suggest that ±10 units may be sufficient. These results tend to support Vokoun et al. (2001), who reported that larger, longer-bodied fish cannot be sampled as accurately as smaller fish without increasing effort. More sites will be required to characterize populations with wide and multimodal length distributions.

Sampling blue catfish can be costly and labor-intensive. We found that when at least 10 randomly chosen sites were sampled, we could routinely estimate mean total length within 50 mm of the population mean. We found it could take up to 50 sites to routinely estimate PSD and PSL within ±10 units; such effort is often feasible for high density populations because fish are collected at most sites. However, riverine habitats and reservoirs with low population densities may require more effort (more random sites) or an alternative sampling design. Further investigation in these water bodies is warranted. Also, future efforts should aim to improve sampling and capture efficiency.

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