Use of a Quadrat Rotenone Technique and Bioenergetics Modeling to Evaluate Prey Availability to Stocked Piscivores

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Abstract. — Young-of-year gizzard shad *Dorosoma cepedianum*, the primary prey for piscivores in Ohio impoundments, are difficult to sample by conventional techniques. We developed a technique for sampling littoral zone quadrats with rotenone and compared this method to other gear. To sample, we isolated 0.15-hectare shoreline areas ($N = 28$ quadrats) with a plastic barrier, which confined the rotenone and even small fish, and applied rotenone at concentrations of 2–3 mg/L. To quantify densities of dead fish that sank, about 18% of the bottom within quadrats was covered with netting. These nets eliminated the need for species-specific recovery rates, which typically are highly variable. Tucker trawls and seines provided lower density and size estimates of gizzard shad than did our quadrat method. Despite difficulties associated with the quadrat rotenone technique such as site selection, variability, and personnel requirements, this method provided the best estimate of size structure and density of gizzard shad populations. To determine if prey size or density influenced stocking success of age-0 piscivores, we used our estimates of gizzard shad biomass and growth to calculate total production of prey (71.3 kg/hectare) during its first growing season. Five taxa of piscivorous fish were stocked and their growth and survival were monitored in conjunction with regular estimates of gizzard shad. Total consumption of prey by all predators, calculated from observed growth by bioenergetics models, was 14.5 kg/hectare, or only about 20% of total young-of-year gizzard shad production. Apparently, factors other than summer prey production, such as spatial and temporal overlap of predators and prey, the gizzard shad : predator size ratio at time of stocking, or availability of gizzard shad in winter, limited first-year growth and survival of stocked predators.

Because of inadequate natural reproduction, particularly by esocids and walleyes *Stizostedion vitreum*, many Ohio reservoirs must be stocked to maintain harvestable populations of some piscivores. These reservoirs are productive, and prey (predominantly gizzard shad *Dorosoma cepedianum*) are often abundant (Carline et al. 1984). Survival of stocked predators may be enhanced if numbers stocked and times of introduction are based on prey availability (i.e., size structure and abundance of prey). However, accurate estimates of prey availability are difficult to obtain with conventional sampling techniques due to gear selectivity and habitat constraints. Whereas rotenone appears to be the least-selective fish sampling

method available (Lambou and Stern 1958), its use has been restricted primarily to sampling fish in coves isolated with block nets. Data gathered in this fashion do not represent the reservoir as a whole (Hayne et al. 1967; Aggus et al. 1980). In addition, personnel requirements, about 6–10 people per hectare of cove sampled (Davies and Shelton 1983), rarely can be met to allow adequate sampling. Hence, new techniques are required to estimate prey fish availability, especially in lakes that lack convenient-sized coves.

Sampling quadrats with rotenone avoids many of the problems associated with cove sampling (Timmons et al. 1979; Shireman et al. 1981). Consequently, our first objective was to develop procedures to assess the abundance of prey fishes, mainly young-of-year (age-0) gizzard shad, in the littoral zone of Ohio's small- to moderate-sized impoundments with quadrat rotenone sampling. We determined the optimal design and sample sizes for this design to achieve reasonably precise estimates based on observed variability, and then compared the method with other sampling techniques.

Our second objective was to use age-0 gizzard shad production and size structure estimates gen-

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[3] The unit is jointly sponsored by the U.S. Fish and Wildlife Service, Ohio Department of Natural Resources, The Ohio State University, and the Wildlife Management Institute.

erated from quadrat samples to evaluate the effect of stocked piscivores on prey abundance, and to attempt to refine predator stocking procedures by comparing stocking dates with prey availability. We stocked five taxa of predators (three esocids and two percids) and monitored their growth and survival. With known numbers and sizes of predators stocked, we had the opportunity to monitor interactions between predators and their prey during a well-defined time interval. By comparing total consumption by predators (computed from observed growth with bioenergetics models) to total production of age-0 gizzard shad, we could assess the effect of stocked predators on the prey population. This analysis, and estimates of prey size structure through the growing season, allowed us to identify important factors that should be considered when predator stocking recommendations are developed.

Study Site

Kokosing Lake, in Knox County, central Ohio, was constructed as a flood control impoundment in 1968. With a maximum depth of 4.9 m and an average depth of 2.0 m, its surface area is 65 hectares. It has 7.5 km of shoreline (Youger 1982) and few coves. Mean summer Secchi-disk depth is less than 1 m and few aquatic macrophytes exist. The bottom of the upstream 95% of the lake is composed mostly of fine sediments and flooded timber. The remaining downstream portion has a rocky bottom. It is part of a state wildlife area, and human developments are limited to a small campground and boat landing. Thus, interaction with the public was limited, making this a convenient site for sampling with rotenone.

Rotenone Sampling

Methods

Sampling procedures and prey estimates. — We conducted experimental sampling of the gizzard shad population during 1983 and 1984. Work in 1983 was devoted to refinement of sampling methods; data collected in 1983 were not used in the bulk of the analysis. In 1984, quadrats were sampled with rotenone ($N = 28$ quadrats) every other week from July 10 until September 28, when water temperatures were high enough for rotenone to be effective ($>20°C$: Davies and Shelton 1983). Plastic barriers (2.1 × 122 m, 0.15 mm thick) with floatline and leadline isolated 0.15-hectare quadrats. Two quadrats were isolated the first day of each 5-d sampling period. To set barriers, one end was anchored on shore, and the remaining barrier

was thrown from the bow of a boat to form a rectangle, delineated by posts driven into the substrate at the corners, 27 m offshore and 56 m parallel to shore (Figure 1).

After a diver ensured that the leadline was on the bottom, six (three were used during July 10–19) bottom nets (1.7 × 26 m, 5-mm mesh) were placed at regular intervals within each quadrat, covering about 18% of the quadrat area. We used these nets because low recovery rates of age-0 gizzard shad (they sink shortly after treatment and decompose) and high handling mortality prevent estimates of recovery rate from mark–recapture experiments. Variability in recovery rates indicated that use of published correction factors for incomplete recovery would not be justified (Table 1).

Because setting barriers and bottom nets required all day, we applied the rotenone (synergized liquid rotenone, 2 mg/L) the next day (day 2) by spraying it along the shoreline and into the propeller turbulence of a small outboard motor. After all young-of-year gizzard shad had sunk (within about 1 h), bottom nets were lifted and all fish on these nets were counted. At least 100 gizzard shad were measured (total length, TL, to the nearest millimeter). On day 3, barriers were removed and set (with bottom nets) at two new sites. Rotenone was applied to these sites the next morning (day 4) and fish were handled as described above. On day 5, barriers were removed. Sampling four 0.15-hectare sites required a crew of three for each 5-d operation.

Suitable sampling sites were limited (areas 0.5–2.0 m deep with few bottom snags and distant from public access); thus, sites were chosen arbitrarily from six possible sites, provided that no site was sampled more than once during each 5-d operation and at least one site of each substrate-location combination (rock–downstream or mud–upstream) was sampled. In other lakes, such fixed-site sampling can provide relatively unbiased estimates of fish population parameters when compared to randomly selected sites (King et al. 1981); however, we could not evaluate bias due to nonrandom sampling in Kokosing Lake.

Growth rates of age-0 gizzard shad were determined from regressions of log_e(wet weight) versus Julian date. We used a length–weight regression developed from gizzard shad collected during July–September to convert measured TL (mm) to wet weight (g):

$$log_e(\text{wet weight}) = 3.3570\ log_e(\text{TL}) - 12.9716;$$
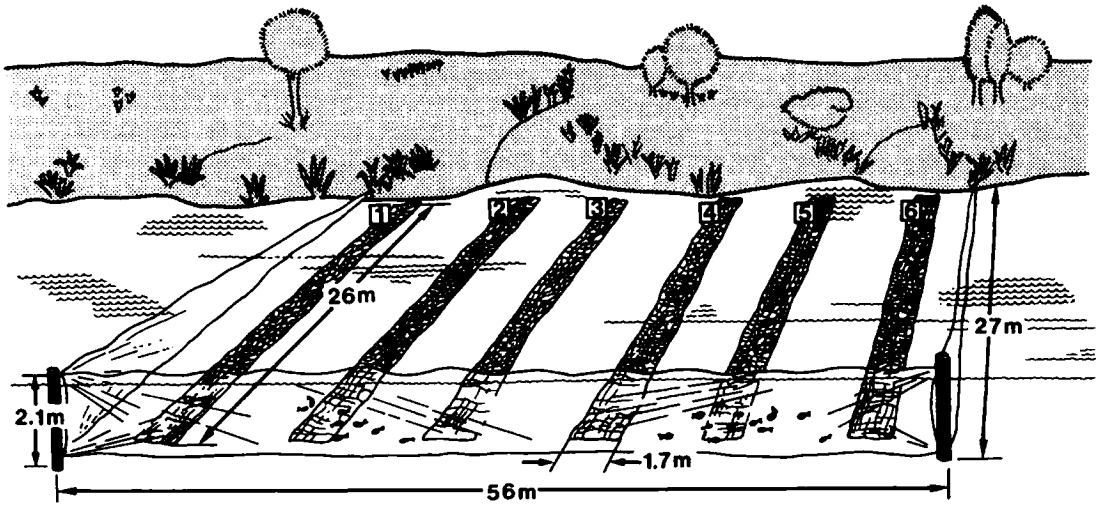$$r^2 = 0.97;\ N = 182;\ P < 0.001.$$

FIGURE 1.—Schematic diagram of a rotenone quadrat used to sample young-of-year gizzard shad in Kokosing Lake, Ohio, during 1984. Positions of the six bottom nets are numbered.

Weight-frequency data for each site and date were multiplied by the estimated number of gizzard shad per square meter to estimate total biomass. We then averaged biomass estimates by date and averaged these means across all dates to generate average July-through-September biomass (kg/hectare). Production (kg/hectare, sensu Ivlev 1961) was calculated as the product of average biomass and instantaneous growth rate (Ricker 1975). A variance of products was used to generate confidence limits for this estimate (Chapman 1978; Newman and Martin 1983). Density and mean length estimates were calculated by averaging the number of fish per square meter and lengths across the six within-quadrat bottom nets.

We then grouped within-quadrat means into four sample periods (at 19-d intervals from July 10 to September 28) to obtain means by period (reported as mean ± 1 SE).

Optimal design and sample size. —Variability estimates for density and mean length were calculated as the variance among the within-quadrat means. These variability estimates were used to calculate coefficients of variation (CV = $100 \cdot SD/$ mean). Analysis of coefficients of variation in conjunction with a power formula (Elliott 1977) was used to determine the number of quadrats necessary to estimate density and size structure within desired limits of accuracy and precision. Cost estimates (in worker-hours) for (1) handling bar-

TABLE 1.—Average recovery rates (percentages of marked fish recovered) from rotenone studies in two Ohio lakes (Kokosing and Caesar Creek) and three published studies. In Kokosing Lake (our study), fin-clipped fish were placed in a holding net within quadrats. Fin-clipped fish were released in coves in Caesar Creek Lake (data obtained from S. Hurley, Ohio Division of Wildlife) and in 20 predator stocking evaluation (PSE) reservoirs (Grinstead et al. 1977). Axon et al. (1980) released dart-tagged fish into coves. Values from Henley (1967) represent percentages of all fish in a cove that were recovered based on scuba observations of fish that remained on the bottom after surface recovery.

	Recovery rate (%) by lake or data source				
Species	Kokosing Lake (7 quadrats)	Caesar Creek Lake (2 coves)	Grinstead et al. (1977) (20 PSE lakes)	Axon et al. (1980) (9 coves)	Henley (1967) (11 coves)
Adult gizzard shad	57	49	75		77
Minnows	67	17	50	67	39
Lepomis spp.	55	58	54	78	96
Crappie			62	77	76
Yellow perch	89		43		
All species sampled	57	54	58	75	74
Range of recovery rates (all species)	29–89	17–100	43–82	43–100	1–96

riers and applying rotenone (c_1) and (2) handling bottom nets (c_2) were used with measures of variability (standard deviation) between quadrats (S_1) and within quadrats (i.e., among bottom nets, S_2) to calculate the optimum number of bottom nets per quadrat (M_{opt}). This was computed from the formula

$$M_{opt} = \frac{S_2(c_1/c_2)^{1/2}}{[S_1^2 - (S_2^2/M)]^{1/2}} ;$$

M is the total possible number of bottom nets per quadrat ($M = 33$ for a 56-m × 27-m quadrat). We assumed that travel costs between sample locations were negligible. Details on these calculations can be found in Cochran (1977).

Comparisons with other gear. — We compared rotenone with a Tucker trawl (with an effective opening of 1 m²) on September 13 and September 25. The trawl was fished during the day, from the stern, 50 cm below the surface. Each haul required about 4 min at 1 m/s, and there were 10 hauls per date. Seine catches (one 12-m bag seine haul at each of five sites on 7 d from August 3 to October 1) were compared to rotenone samples to estimate efficiency. This amount of effort, though small, represents a typical seining scheme to evaluate prey size and abundance used in predator stocking evaluations in Ohio (Stein et al. 1984). Coefficients of variation and personnel requirements reported in four cove rotenone studies in the literature were used to compare with quadrat sampling.

Results and Discussion

Sampling procedures and prey estimates. — Low recovery rates of age-0 gizzard shad and high handling mortality prevent estimation of recovery rates by mark–recapture techniques. Many factors such as handling mortality, substrate type, predation, scavengers, water temperature, and the ability of workers to recognize marks all affect subsequent recovery rate (Lambou and Stern 1958; Henley 1967; Barr and McDonough 1978; Holden 1980); recovery rates are inherently variable and somewhat unreliable.

Thus, age-0 gizzard shad should not be sampled by the traditional rotenone collection method of surface dipnetting because this requires estimates of recovery rate. Use of bottom nets to estimate the number and size structure of fishes within rotenone-treated quadrats eliminates this requirement. This technique also reduces personnel requirements considerably by allowing investigators to collect all data on the day of rotenone application rather than during the 3-d collection period required in most other studies using rotenone.

Catches of age-0 gizzard shad were highly variable among bottom nets within a quadrat (average coefficient of variation, 87%). This was probably due to the species' patchy distribution, even on a scale as small as 0.15 hectares. Patchiness apparently was affected by wind direction, because when the wind was blowing parallel to shore, downwind bottom nets had greater catches. Bottom net position relative to wind direction and number of fish on these nets were significantly correlated (Kendall's tau: $P < 0.05$; $N = 6$).

Young-of-year gizzard shad density ranged from a high of 30.9 ± 13.8 fish/m² during July 10–28 ($N = 5$ quadrats) to a low of 6.1 ± 1.9 fish/m² during August 19–September 8 ($N = 4$ quadrats). Daily variation in catch was high, with an average coefficient of variation among quadrats of 60.2%. Mean age-0 gizzard shad density during the entire period was 12.8 ± 3.8 fish/m², or about 20 times greater than mean density for any other species.

Estimated density was higher when barometric pressure the day before barriers were set was low (linear regression: $P = 0.01$; $N = 13$). However, this variable explained only 43% of day-to-day variability. Barometric pressure, cloud cover, and wind speed (obtained from National Weather Service, Columbus, Ohio) on the day barriers were set did not explain a significant amount of the variability in density or mean length (linear regression: $P > 0.10$; $N = 13$).

The gizzard shad size structure at the most downstream sites (rock substrate) differed from that at all other sites (mud substrate) (Figure 2). Thus, we calculated growth rates, biomass, and production separately for these two regions. Though growth in wet weight did not differ (*F*-test: $P = 0.08$; $N = 5$), the intercept of a regression of $\log_e$(wet weight) versus date calculated for the downstream sites ($r^2 = 0.90$; $N = 5$) was lower (analysis of covariance, ANCOVA: $P < 0.001$) than for the upstream sites ($r^2 = 0.88$; $N = 5$), suggesting that fish in the downstream sites hatched at a later date than those upstream. Growth of age-0 gizzard shad did not differ between 1983 and 1984 (*F*-test: $P > 0.05$; $N \geq 5$); however, intercepts of regression lines differed (ANCOVA: $P < 0.001$), suggesting differences in hatching date of gizzard shad between years. No yearling gizzard shad were captured in 1983 or 1984.

Average July–September biomass was 3.66 ± 1.38 kg/hectare ($N = 7$) at the downstream sites and 9.19 ± 2.41 kg/hectare ($N = 7$) at the upstream sites. Our estimate of total production of age-0 gizzard shad during July 10–September 28,
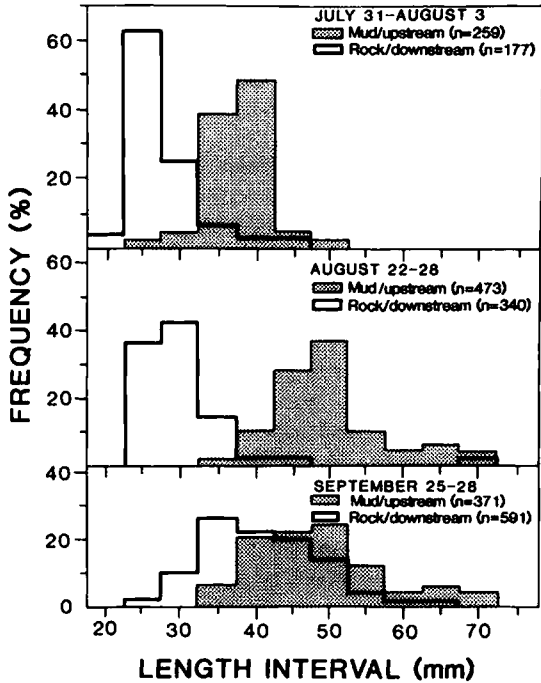
FIGURE 2.—Length-frequency histograms of young-of-year gizzard shad sampled in rotenone quadrats at mud-upstream sites (three sites, unshaded) and rock–downstream sites (two sites, shaded) in Kokosing Lake, Ohio, on three dates during 1984; n = number of fish measured.

TABLE 2.—Cost (c) estimates in worker-hours for quadrat rotenone sampling conducted in Kokosing Lake, Ohio, during 1984.

Activity and time required			
Activity per single quadrat	Worker-hours	Activity per single bottom net	Worker-hours
Measure site, set poles	1.8	Set net	0.4
Set barrier	0.9	Spread net	0.3
Check perimeter (swim)	1.0	Retrieve net	1.0
Apply rotenone (2 mg/L)	0.6	Process fish	1.0
Collect day-2 fish and retrieve barrier	3.3		
Total	7.6		2.7
	(c_1)		(c_2)

calculated as a weighted (by proportion of lake shoreline in each region) average of production in each region, was 71.3 ± 47.7 (SD) kg/hectare.

Optimal design and sample size.—Calculations of power indicate that fewer samples would be needed to estimate size structure than to estimate density of littoral zone gizzard shad. The Tucker trawl was size-selective, though the mean length of age-0 gizzard shad in rotenone quadrats never exceeded 50 mm, which we know to be the upper limit of length of gizzard shad vulnerable to the trawl (S. Hurley, Ohio Division of Wildlife, personal communication). The mean lengths of gizzard shad caught by the trawl in the littoral zone did not differ from those caught in offshore hauls. Thus, quadrat rotenone sampling in the littoral zone provided a good representation of age-0 gizzard shad size structure.

Based on an average coefficient of variation of 60.2% for 1984, about 11 sites within Kokosing Lake must be sampled to estimate density to within ±40% of the true mean and about 37 sites to be within ±20%. Average coefficients of variation for length estimates were substantially lower than

for density estimates (4.9 versus 60.2%); therefore, only about two sites need to be sampled to estimate mean length to within ±20% of the true mean. By using cost estimates in worker-hours for quadrat rotenone sampling (Table 2) and average variability in estimated density for quadrats and bottom nets, we determined that the optimum number of bottom nets per quadrat (M_{opt}) is about two. This value holds for average standard deviations of 7.8 among quadrats (S_1) and 8.4 among bottom nets within a quadrat (S_2) as observed in Kokosing Lake, or a similar ratio of among- to within-quadrat variability.

However, before a sampling plan is adopted, the magnitudes of the variabilities within quadrats (among bottom nets) and among quadrats should be determined. If information on small-scale distribution of fish is desired, three bottom nets per quadrat, one placed randomly within each of three strata within quadrats, will give a nearly unbiased estimate of mean length and density (Cochran 1977) and provide information on consistent trends in bottom-net catches due to distribution of fish within the quadrat. Because of practical considerations, the 1.2-m × 56-m bottom nets used in this study would be most useful. Narrower nets cause fish loss during retrieval and wider ones require more workers. Quadrat size seems to be more flexible. However, the quadrat should be large enough that emigration during barrier placement is negligible, a factor that probably varies with the species of interest.

Comparisons with other gear.—The Tucker trawl data underestimated both mean length and density of age-0 gizzard shad; mean lengths of gizzard shad collected in trawls were about 9.3% lower than those from quadrats (Figure 3). These differences might have been greater if gizzard shad in
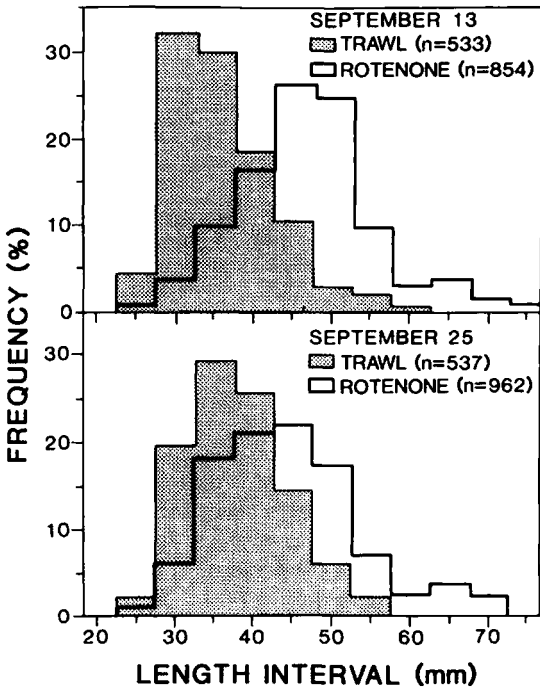
FIGURE 3.—Length-frequency histograms of young-of-year gizzard shad sampled with a Tucker trawl (10 hauls, unshaded) and quadrat rotenone (4 quadrats, shaded) at Kokosing Lake, Ohio, on two dates in September 1984; n = number of fish measured.

the lake had been larger (mean length never exceeded 50 mm), because the Tucker trawl does not catch gizzard shad longer than about 50 mm. Though trawl data yielded density estimates 71 ± 42% (80% confidence limits on differences; $P <$ 0.05) lower than those derived from quadrat samples, only the surface stratum (0.5–1.5 m) was sampled with the trawl, whereas rotenone sampled the entire water column. However, trawl density estimates were 74 ± 42% lower than those obtained with rotenone even in nearshore hauls in a maximum depth of 2 m. If gizzard shad density had been the same from surface to bottom, the trawl would still have underestimated nearshore density had we sampled the entire water column. The Tucker trawl did permit comparisons of gizzard shad density and size in open water and littoral zone. Samples collected in nearshore ($N = 13$) and offshore hauls ($N = 7$) on both sampling dates did not differ in either mean length or surface stratum density (Wilcoxon rank sum: $P > 0.10$).

Gizzard shad densities estimated from seine samples were always lower than those from quad-rat samples (83.0 ± 24.5% mean difference and 95% confidence limits) and differences were greatest later in the year. Gizzard shad in quadrat samples were 10–20% larger than gizzard shad seined from the same site.

Our quadrat method yielded catches that were equally or less variable than cove-sampling catches (Table 3). Furthermore, labor requirements were substantially less for quadrat sampling (44 versus 151–1,848 worker-days: Table 3). This comparison is conservative, given that the hours necessary to plan, prepare for, and administer a cove study (e.g., Hayne et al. 1967; Aggus et al. 1980) were not included in the personnel requirements for sampling coves. Such administrative costs are almost negligible in the quadrat technique.

Bioenergetics Considerations

To determine (1) the effect of stocked piscivores on prey abundance and (2) if prey abundance might limit the growth and abundance of stocked predators, estimates of the amount of prey consumed are required. These estimates can be obtained either from field measurements or by a modeling approach to back-calculate consumption. Though methods are available to estimate food consumption by fishes in the field (e.g., Swenson and Smith 1973; Elliott and Persson 1978; Mann 1978), direct estimates are time-consuming and highly variable due to the complex interaction of environmental factors (Majkowski and Waiwood 1981; Rice and Cochran 1984). Bioenergetics models offer an attractive alternative for estimating food consumption in fishes by providing a theoretical framework relating temperature, consumption, and growth (Kitchell et al. 1977; Allen and Wootton 1982). Because growth integrates feeding rate over time, effects of variations in short-term food availability, temperature, etc., are minimized.

Bioenergetics models use a mass balance equation:

$$dB/Bdt = C - (R + F + U);$$

B = biomass of the predator; C = consumption; R = respiration; F = egestion; and U = excretion. The energy available for growth is assumed to equal the amount of food consumed minus metabolic costs and waste products. Consumption and respiration are temperature- and size-dependent; egestion and excretion are functions of consumption. Given data on temperature and fish size, the energy budget can be solved to determine the amount of food that must have been eaten to produce the observed growth.

TABLE 3.—Sample size (number of coves or quadrats) needed to estimate prey abundance to within ±40% of the true mean (based on average coefficient of variation, CV = 100·SD/mean) for sampling coves and quadrats. Area sampled and personnel requirements to obtain this number of samples are also given.

Reference	Sample size	CV (%)	Average area sampled (hectares)	Personnel require-ment to achieve target sample size (worker-days)
Aggus et al. (1980)	15 coves	72	5.0	1,310
Hayne et al. (1967)	57 coves	151	1.4	1,848
Siler (1983)	56 coves	149	1.2	1,526
Aggus et al. (1980)	9 coves	52	0.7	151
Lambou and Stern (1958)	18 coves	80	0.4	163
Present study	11 quadrats	60	0.15	44

The sensitivity of parameters involved in each of the components of the energy budget is known (e.g., Kitchell et al. 1977; Stewart et al. 1983; Bartell et al. 1986); all studies show that predictions of growth are sensitive to errors in estimation of consumption. Bioenergetics models offer more precise predictions of consumption from observed growth, as was done in this study, and less precise predictions of growth from observed feeding rates.

We used bioenergetics models to back-calculate food consumption by resident and stocked piscivores from observed growth. We then compared the total consumption of piscivores to age-0 gizzard shad production, estimated from quadrat rotenone sampling, to determine the influence of predation on prey abundance.

Methods

Young walleyes and "hybrid walleyes" (walleye × sauger *Stizostedion canadense*) were stocked into Kokosing Lake on June 12, 1984 (58 fish/hectare of each, about 63 mm TL). About 18 fish/hectare each of northern pike *Esox luscius*, muskellunge *E. masquinongy*, and tiger muskellunge (their hybrid) were stocked at a length of about 146 mm TL on August 9, 1984. Percids (walleye, hybrid walleye) were sampled at night with pulsed DC electrofishing gear each month during mid-July to mid-November. Esocids were sampled at night by electrofishing and seining (15-m-long, 5-mm-mesh bag seine) at 3-week intervals. All fish were measured (nearest millimeter, TL) and weighed (wet weight to nearest gram), and their stomach contents were identified. Standard and backbone lengths of gizzard shad in stomachs were converted to total lengths (as per Wahl and Nielsen 1985). Catch-per-unit-effort data were used to estimate species-specific instantaneous mortality rates of percids and esocids (Table 4).

The population size structure of resident large-mouth bass *Micropterus salmoides* larger than 50 g was determined from wet weights of fish sampled weekly by electrofishing after dark during August and September; the abundance of this species was estimated by Schnabel mark–recapture techniques. Data on food habits were collected by pumping stomachs of all electrofished largemouth bass larger than 50 g. Biweekly weight-frequency histograms showed four nonoverlapping modes that defined size-classes. Progression of the modes through time was used to determine size-specific growth (ages of fish were not determined). Growth during July was extrapolated from August to September. More than 90% of the largemouth bass (by number) weighed less than 500 g wet weight. Samples of fish larger than this were too small to measure growth, so we modeled consumption of largemouth bass less than 500 g.

We used bioenergetics models for percids (Kitchell et al. 1977) and esocids (Bevelhimer et al. 1985) to estimate prey consumption (grams) by stocked predators from observed growth (grams) and water temperatures. By coupling back-calculated food consumption per individual with percid and esocid mortality rates, we could estimate total population consumption by stocked predators from July 10 to September 28, when prey population production estimates were available. The proportion of this food consumption consisting of age-0 gizzard shad was determined from diet composition data.

We also modeled food consumption by resident largemouth bass because gizzard shad production consumed by these fish would not be available to stocked percids and esocids; a bioenergetics model for largemouth bass (Rice et al. 1983) was used to back-calculate consumption per individual (for each size-class) from estimated growth. We assumed the population size provided by mark–recapture techniques in fall 1984 to be the average population size during July–September and used

TABLE 4.—Predator population data used in bioenergetics modeling to estimate total biomass of gizzard shad consumed by stocked (percids and esocids) and native piscivores (largemouth bass) in Kokosing Lake, Ohio, during June–September 1984. Instantaneous daily growth rate (G) was estimated from a regression of $\log_e$(wet weight, g) on Julian date; instantaneous total mortality rate (Z) was estimated from catch curves (for $\log_e$[catch per unit effort] versus Julian date, r is the correlation coefficient and N is sample size); NA is not available.

Predator	Calendar date stocked (Julian date)	Julian dates of growth stanzas	Growth					Mortality		
			Observed weight		Daily G	P of C_{max}[a]	Initial number/ hectare	Daily Z	Catch curve	
			Initial	Final					r	N
Percids	Jun 12 (163)	191–252	8.0	76.1	0.037	0.89	58.0	0.019	−0.79	5
		252–270	76.1	114.5	0.023	0.40				
Esocids	Aug 9 (221)									
Muskellunge		221–229	11.6	12.9	0.013	0.50	18.0	0.154	−0.99	3
		229–270	12.9	35.1	0.024	0.74		0.015	−0.95	3
Tiger muskellunge		221–229	12.7	12.0	−0.007	0.34	18.0	0.037	−0.69	4
		229–270	12.0	36.7	0.027	0.77				
Northern pike		221–229	12.1	11.5	−0.006	0.34	18.0	0.203	NA	2
		229–270	11.5	50.6	0.036	0.93				
Largemouth bass size class										
I		191–270	115.0	175.0	0.005	0.40	21.2[b]			
II		191–270	187.0	337.0	0.007	049	1.3			
III		191–270	271.0	424.2	0.006	0.45	0.9			
IV		191–270	333.0	478.5	0.004	0.42	1.1			

[a] Proportion (P) of maximum consumption (C_{max}) that was actually consumed.

[b] Average density during the simulation period (mortality rate was not computed).

that value to compute total consumption from consumption per individual.

A recording thermograph placed 1 m below the lake surface provided average daily water temperatures used in the models. We assumed percids thermoregulated behaviorally (as did Kitchell et al. 1977 for Oneida Lake walleyes) at 24°C because midsummer temperature–dissolved oxygen profiles showed that this was the lowest available temperature associated with sufficient dissolved oxygen (>2 mg/L) and percids were usually collected near deep, channel areas. Percids in nearby Pleasant Hill Lake, central Ohio (Johnson et al. 1988), and in Norris Reservoir, Tennessee (Fitz and Holbrook 1978), sought cooler water when surface temperatures exceeded 20–24°C. We assumed that esocids and largemouth bass did not thermoregulate because they were nearly always captured in littoral areas less than 1 m deep.

To use the bioenergetics model, one must specify feeding rate (P) as a proportion of the maximum possible consumption (determined by fish size and temperature). Thus, by manipulating the P value, one changes the growth predicted by the model. For all predators, P was adjusted iteratively to obtain the best fit of simulated growth to observed growth for each species. Because we used observed growth to predict food consumption and wished to obtain the most precise estimate of total food consumed by each predator, we divided the

simulation period into growth stanzas if the observed pattern of growth suggested a change in growth during the simulation period. Two growth stanzas were used in percid and esocid simulations; largemouth bass did not show a noticeable change in growth (Table 4; Figure 4). Percid growth declined in mid-September; this point marked the end of stanza one and the start of stanza two. Esocids did not grow during the first 9 d after stocking (stanza one), then grew at a constant rate thereafter (stanza two).

Because energy contents of predator and prey affect the conversion of energy to biomass in these models, we required these data to model predator consumption accurately from growth. We used a Phillipson microbomb calorimeter (methods in Phillipson 1964) to determine the energy content of age-0 gizzard shad (4.184 kJ/g) in Kokosing Lake during June to September. Energy content of percids (4.602 kJ/g; $N = 10$, collected August 9, 1984) was determined with a Parr oxygen bomb calorimeter. Esocid caloric content (3.598 kJ/g) was obtained from Bevelhimer et al. (1985), and an average value for largemouth bass (4.184 kJ/g) was obtained from Rice et al. (1983).

Kitchell et al. (1977) did not have walleye respiration rate data at the time they developed the percid model. Given the sensitivity of bioenergetics models to errors in respiration parameters (Kitchell et al. 1977; Bartell et al. 1986), we used
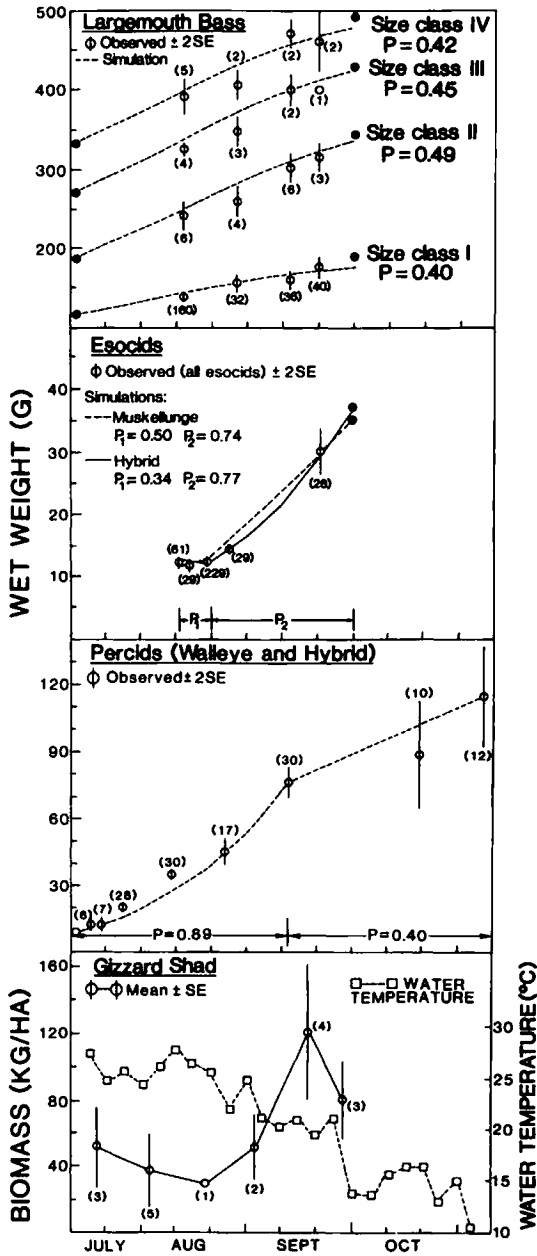
data from Minton and McLean (1982) on the relation between temperature and standard respiration (assumed to be equal to total metabolism in the field) for sauger in our percid model. Growth simulations with our model (with Minton and McLean's field data on water temperature and observed energy ration included) were within 2% of their observed growth estimates.

Results and Discussion

Percids consumed age-0 gizzard shad almost exclusively (>97% of identifiable prey items; $N = 111$ stomachs) during July–September. They chose gizzard shad not significantly different in length from the mean length of age-0 gizzard shad in the lake, as estimated by quadrat rotenone samples. Size of prey chosen was substantially less than maximum prey size observed in walleye stomachs by Knight et al. (1984) and less than the optimal size (33% of body length) predicted by McGee et al. (1979) and Nielsen (1980). Overall, about 75% of the age-0 gizzard shad in the lake were less than 33% of percid length (44% in July, 82% in August, and 98% in September: Table 5). Growth of age-0 walleyes and hybrid walleyes was quite similar to growth of these fishes stocked in nearby Pleasant Hill Reservoir, Ohio, during 1979–1983 (Johnson et al. 1988) and did not differ between the two taxa (F-test: $P = 0.87$; $N = 4$). Both species exhibited two distinct growth stanzas. During July 1–September 10, percids grew rapidly from a wet weight of 4.5 ± 0.3 g (mean $\pm$ SE; $N = 14$) to 76.9 ± 3.4 g ($N = 30$). During September 11–November 5, growth was slower, and the final mean wet weight was 115.0 ± 11.0 g ($N = 12$). Growth differences did not appear to be related to trends in age-0 gizzard shad biomass (Figure 4). Based on bioenergetics modeling, percids consumed about 6.4 kg of prey biomass per hectare.

Stocked esocids also consumed mostly age-0 gizzard shad (>92% of identifiable prey items; $N = 410$ stomachs). Esocids grew slowly or lost weight during the first 9 d after they were stocked (August 8–August 17), but muskellunge grew to a wet weight of 30 ± 1.9 g ($N = 14$), tiger muskellunge to 30.3 ± 2.2 g ($N = 12$), and northern pike

FIGURE 4.—Observed and predicted predator growth (largemouth bass, esocids, percids), based on bioenergetics modeling, biomass of young-of-year gizzard shad (determined from quadrat rotenone sampling), and water temperatures in Kokosing Lake, Ohio, during July to September or October 1984. P is a variable in bioenergetics models that represents the proportion of the maximum consumption possible, for a given temperature and size of fish, that was actually consumed. This value was determined by iteration until model predictions matched observed growth. Esocid and percid growth were separated into two growth stanzas with different P

←
values (P_1 and P_2). Initial and final wet weights for largemouth bass and final wet weights for esocids (closed circles) were projected with the same P value that fit observed growth so that simulations would coincide with the entire period when prey biomass estimates were available.

TABLE 5.—Biomass and density of young-of-year gizzard shad vulnerable to predation by stocked piscivores in Kokosing Lake, Ohio, during July–September 1984 (esocids were not stocked until August). Estimates are based on a maximum prey size of 36% (Carline et al. 1986) and an optimum prey size of 33% (McGee et al. 1979; Nielsen 1980) of mean predator total length (TL) in the middle of each month. Percentages of the young-of-year gizzard shad population that was within a given size range are in parentheses. Prey biomass and density were estimated from quadrat rotenone sampling.

Predator and estimate	July	August	September
Percids		165	
Predator TL (mm)	113	59	205
Maximum prey size (mm)	41	3.17 (70.4)	74
Biomass vulnerable (g/m²)	3.03 (44.1)	3.49 (88.4)	16.84 (97.7)
Density vulnerable (fish/m²)	8.07 (68.5)	54.4	14.85 (99.5)
Optimal prey size (mm)	37.3	2.69 (60.0)	67.6
Biomass < optimal size (g/m²)	1.47 (21.0)	3.22 (81.5)	15.97 (92.6)
Density < optimal size (fish/m²)	5.13 (43.6)		14.62 (98.0)
Esocids			
Predator TL (mm)		149	182
Maximum prey size (mm)		54	69
Biomass vulnerable (g/m²)		2.69 (60.0)	16.12 (93.5)
Density vulnerable (fish/m²)		3.22 (81.5)	14.66 (98.2)

to 40.2 ± 8.0 ($N = 2$) (Figure 4). We estimated that all three esocids combined only consumed 0.8 kg/hectare, presumably because of their low initial density and poor survival through summer.

Resident largemouth bass also consumed age-0 gizzard shad (about 85% of identifiable prey items). Average biomass of largemouth bass during summer was low, about 4.5 kg/hectare. Four distinct size-classes were evident from weight frequencies, which had the following average intervals (over-summer average minimum and maximum sizes): I, 0–226 g; II, 256–308 g; III, 353–372 g; IV, 414–438 g. Total consumption by largemouth bass was about 7.3 kg/hectare, about 77% of which was taken by the abundant, smallest size-class.

The high production potential of age-0 gizzard shad, resulting from fast growth (Carline et al. 1984) and large biomass (e.g., Houser and Netsch 1971), make it unlikely that summer production will limit stocked predator growth and survival. Based on bioenergetics modeling, all stocked predators and resident largemouth bass combined consumed 14.5 kg/hectare or only about 20% of total production of age-0 gizzard shad in Kokosing Lake. Another Ohio study (Carline et al. 1984) demonstrated that even a very dense (33.4 kg/hectare) population of adult largemouth bass could consume most of the annual production of a hypothetical gizzard shad population only in those years when age-0 gizzard shad recruitment was poor. Thus, the productivity of age-0 gizzard shad can be high relative to predator consumption. Factors other than gizzard shad production apparently limit success of stocked age-0 predators.

One such factor is time of stocking. From re-lated work with esocids, young predators must be stocked at a time when appropriately sized prey are available (Carline et al. 1986). Keast (1985) also stressed the importance of an appropriate relationship between predator and prey size at time of stocking, and noted that a better understanding of this relationship could make results of predator stockings more predictable. Matching predator size (i.e., diet breadth) with prey size permits predators to feed, grow beyond their window of vulnerability to predation, and gain sufficient energy stores to survive their first winter in the field. Thus, prey size should be evaluated before the date to stock predators can be determined. Considerable differences exist in the mean size of age-0 gizzard shad in midsummer; however, data from Kokosing Lake in 1983 and 1984, as well as from Acton Lake and O'Shaugnessy Reservoir, suggest that gizzard shad growth rates do not differ greatly from year to year or among systems, at least in central Ohio (Figure 5). This indicates that hatching dates are variable and may be more important in determining stocking date than gizzard shad growth.

To evaluate vulnerability of prey to stocked predators, information on prey size, predator size, and predator diet breadth is required. We know that the absolute maximum size of gizzard shad chosen by both percids (Knight et al. 1984) and esocids (Carline et al. 1986) is 45% of predator total length. Carline et al. (1986) suggest using the 95th percentile of prey lengths found in esocid stomachs as the upper limit to diet breadth. If this principle is reasonable for percids as well, then maximum prey size for both walleye and walleye hybrids is 36% of their total lengths. In Kokosing
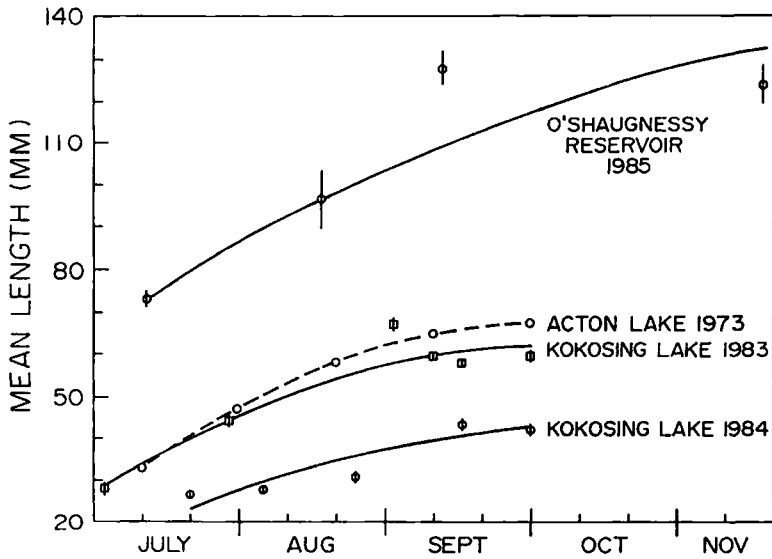
FIGURE 5.—Growth (±2 SE) of young-of-year gizzard shad in three central Ohio lakes. Data for O'Shaugnessy Reservoir were obtained by electrofishing. Acton Lake data are from Pierce (1977). Kokosing Lake data were collected by sampling quadrats with rotenone; all sites in 1983 and downstream sites in 1984 are shown. Number of fish measured was greater than 50 fish on each date for each lake.

Lake, most of the age-0 gizzard shad were small enough to be vulnerable to percid and esocid predation (Table 5; Figure 6); however, similar-sized predators stocked at the same time in O'Shaugnessy Reservoir would have found essentially no age-0 gizzard shad small enough to consume (Figure 6).

Another determinant of stocking success, in terms of survival of predators to age 1, is the availability of appropriately sized prey in winter and in spring before age-0 gizzard shad become available. In Illinois, substantial gizzard shad mortality occurs in late fall and early spring, and reduces the contribution of gizzard shad to largemouth bass diets (Storck 1986). Such mortalities also occur in Ohio (BMJ, personal observation). For other clupeids (alewife *Alosa pseudoharengus*, threadfin shad *Dorosoma petenense*), mortality can be high when water temperatures fall below some critical threshold; small size-classes are most susceptible (Griffith 1978; Adams et al. 1982; Eck and Brown 1985). Temperature-induced mortality of small gizzard and threadfin shad can influence largemouth bass (Adams et al. 1982) and sauger (McGee et al. 1979) populations by reducing food availability and consumption rate, particularly for small predators. Hence, summer prey production alone may not directly determine the number of predators that can be supported by the prey population. By stocking when appropriately

sized prey are available, both oversummer growth and overwinter prey availability (because of greater diet breadth) should be maximized.

Regardless of season, even if appropriately sized prey exist, they must overlap spatially with predators at a time when predators can feed. Patchy distributions of age-0 gizzard shad may affect predator growth despite high average prey density. Further research is needed to establish the importance of patchy shad distribution on predator encounter rates (particularly for sit-and-wait predators), food consumption, activity, and growth. Further, first-year growth and survival are just two of several factors that may influence long-term stocking success in terms of recruitment to a fishery. Because factors such as survival and growth of age-1+ piscivores and predation inertia (see Stewart et al. 1981) were not evaluated, we were not able to address the issue of predator carrying capacity for a specific reservoir. However, our approach allowed us to assess the system's potential to support a known density of stocked age-0 predators and suggested that age-0 gizzard shad production could support considerably higher stocking densities during summer.

Conclusions

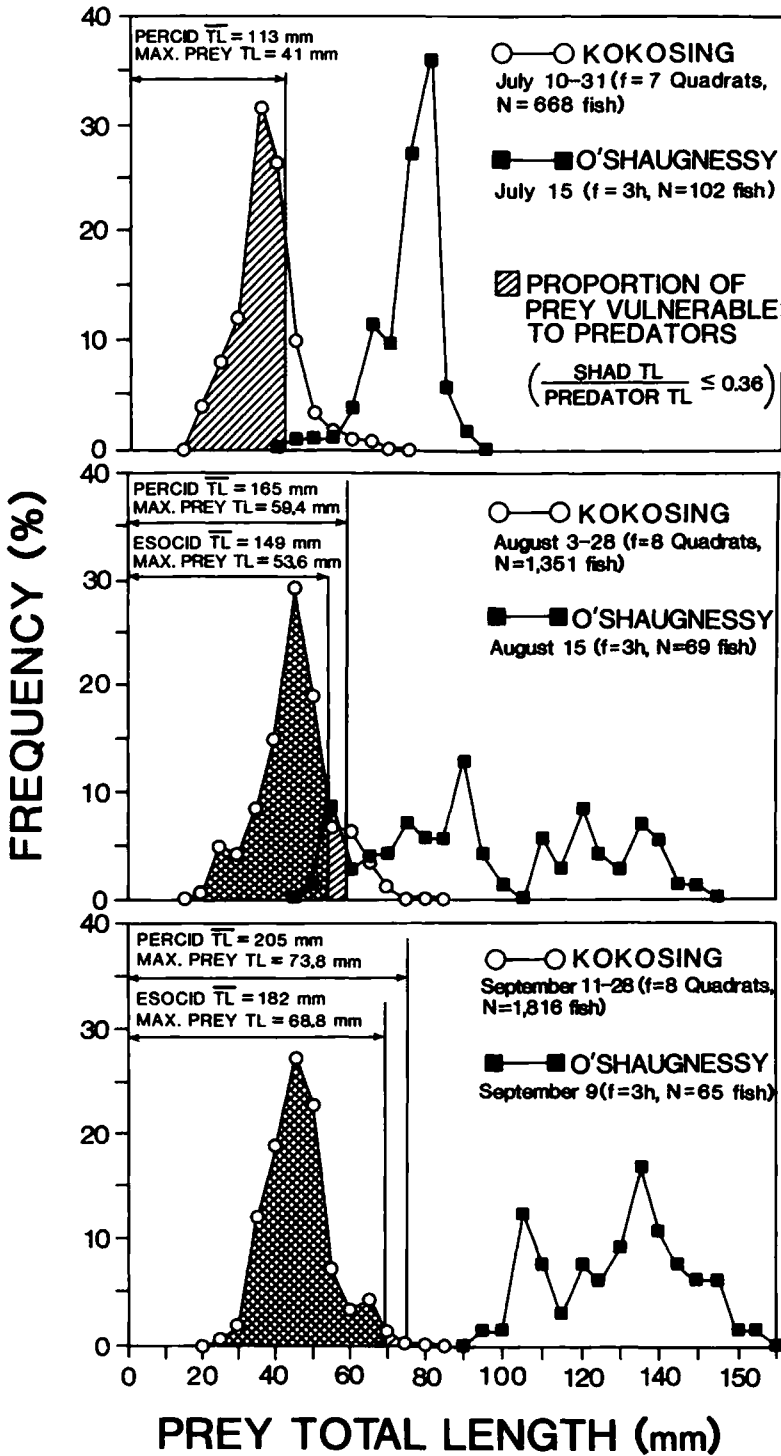Because of problems associated with sampling (Hayne et al. 1967; Aggus et al. 1980; Davies and

FIGURE 6.—Length-frequency histograms for young-of-year gizzard shad from Kokosing Lake, Ohio, during July–September 1984, and from O'Shaugnessy Reservoir, Ohio, during July–September 1985 (f is effort; N is the number of gizzard shad measured; $\overline{TL}$ is mean total length), showing proportions of prey (young-of-year gizzard shad) vulnerable to predation by stocked piscivores (shaded). In Kokosing Lake, fish were sampled in rotenone quadrats; in O'Shaugnessy Reservoir, fish were sampled by electrofishing.

Shelton 1983), cove rotenone does not appear to be a useful sampling tool for prey fishes in Ohio reservoirs. The quadrat sampling technique developed in this study avoids many of the problems associated with cove rotenone sampling. It can be used in small impoundments that have few coves. The small area sampled and relatively low variability among replicate samples reduces personnel requirements. Thus, more samples can be obtained over a wide range of habitats, increasing the statistical precision of estimates.

Patchy distribution of age-0 gizzard shad contributes to high catch variability among sites with any sampling gear. Gizzard shad are patchily distributed even within quadrats, as evidenced by high variability in bottom net catches. Daily coefficients of variation were substantially lower for mean length estimates than for density estimates. Thus, estimates of size structure were more precise than estimates of density.

Given the historic difficulty of monitoring short-term changes in predator populations, detecting short-term changes in prey fish abundance may not be necessary. The high day-to-day variability in age-0 gizzard shad catches with rotenone (due to patchy distribution of the fish) and personnel requirements that are substantial even for this technique probably preclude use of quadrat rotenoning to estimate age-0 gizzard shad density precisely over short intervals. To decide on the appropriate time and size to stock age-0 predators, knowledge of size structure of the prey population may be more important than knowledge of its density, especially in systems dominated by the highly productive gizzard shad. Given its lack of size selectivity, quadrat rotenone sampling provides unbiased estimates of the size structure of age-0 gizzard shad populations and thus may be a useful tool for assessing available prey and for guiding predator stocking policy.

Acknowledgments

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