

UC Berkeley

Technical Completion Reports

Title

Temperature requirements of Pacific coastal fishes

Permalink

<https://escholarship.org/uc/item/7qg862b1>

Authors

Moyle, Peter B
Knight, Ned K

Publication Date

1984-09-01

G

G402
XU2-7

no. 641

TEMPERATURE REQUIREMENTS OF
PACIFIC COASTAL FISHES

Peter B. Moyle

and

Ned K. Knight

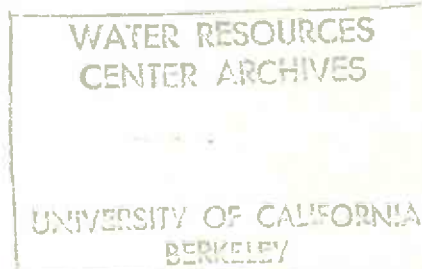
Wildlife and Fisheries Biology
University of California, Davis

CALIFORNIA WATER RESOURCES CENTER
University of California, Davis

U.S. GEOLOGICAL SURVEY

G830-03

WATER RESOURCES CENTER PROJECT
UCAL-WRC-W-641



The research on which this report is based was financed in part by the United States Department of the Interior as authorized by the Water Research and Development Act of 1978 (P.L. 95-467). Contents of this publication do not necessarily reflect the views and policies of the United States Department of the Interior, nor does mention of trade names or commercial products constitute their endorsement by the U.S. Government.

TECHNICAL COMPLETION REPORT

September 1984

ABSTRACT

This project was designed to determine the temperature requirements of native California stream fishes. The importance of temperature in regulating the abundance and distribution of fishes has been well-documented, although primarily for species from the eastern United States and Canada. Three sets of experiments were used to define the thermal niches of these fishes - acute temperature preferences, routine metabolic rates, and critical thermal maxima. Acclimation temperatures were standardized at 10, 15, 20, 25, and 30°C. The acute final temperature preferences for hardhead (Mylopharodon conocephalus), Sacramento squawfish (Ptychocheilus grandis), hitch (Lavinia exilicauda), and California roach (Lavinia symmetricus) were 28.35, 26.04, 30.67, and 24.72°C, respectively. Partial data for Sacramento blackfish (Orthodon microlepidotus), Sacramento perch (Archoplites interruptus), tule perch (Hysteroecarpus traski), and Sacramento sucker (Catostomus occidentalis) are also presented. Plots of standard deviations of preferred temperatures at each acclimation temperature provided an estimate of the relative activity of each species, both intraspecifically and interspecifically. Routine metabolic rates were highest and most variable for squawfish, and most gradual (with increasing temperatures) for hardhead. Critical thermal maxima (CTM) generally increased with increasing acclimation temperatures for each species. All the values were quite close (within 4°C at each test temperature), ranging from 28.29°C for squawfish at 10°C to 38.14°C for hitch at 30°C.

The laboratory results generally agree with field observations of macrohabitats of the species tested. For example, California roach had the lowest of the four preferences, and are found at slightly higher elevations where the temperatures can be cooler than for the other species. Squawfish showed generally high activity levels in the temperature preference trough and high metabolic rates, corresponding to their roving and piscivorous feeding habits. High preferences and low metabolic rates were determined for hitch, corresponding to their occurrences in lower elevation, warmer waters with little or no velocity.

This project is important to provide background information for management agencies. Other studies have shown that preferred temperatures are optimal for growth, which also implies feeding and, indirectly, for reproduction as well. Man-made alterations, such as diversion dams, channelization, or removal of riparian vegetation can change stream thermal regimes that reduce the efficiencies of these fish activities, or in extreme cases, threaten their survival. Along with temperature changes from these alterations are usually changes in oxygen levels of the water, which may become stressful to the resident species. The critical thermal maxima can be used to detect sublethal doses of pollutants or the presence of disease before mortalities occur.

Management personnel can sample stream sites for fish species and water temperatures, and then with the background information provided in this report, can predict the impact of proposed water projects or determine the effects of existing ones. Recommendations can then be made for modifications in plans or existing structures so that the impacts on native fish populations and communities can be minimized.

INTRODUCTION

Temperature is one of the most important factors determining the abundance and distribution of stream fishes. Each species has fairly narrow ranges of temperature that are optimal for spawning, migration, growth, feeding, and other activities. Above and below the ranges are suboptimal temperatures at which these activities may be possible but at reduced efficiencies. In addition, each species has a broader range of temperatures for survival, with the absolute minima and maxima dependent on the thermal history or acclimation and on the length of exposure to the extreme.

These thermal requirements are species-specific to the point that even a small change in the thermal regime of a stream may not only alter the composition of the fish community but also affect the activities of the resident species. Most water projects on California streams, from major dams and diversions to small hydro projects, have been detrimental to the fish species in one or more of these aspects. There is a need to understand the instream requirements of these fishes such that a water project can be built or modified to minimize the impact on the existing fish populations. Temperature is one of the least studied requirements of California stream fishes, so the thermal niches of these species need to be defined.

OBJECTIVES

The purpose of this project is to define the thermal niches of California stream fishes by determining their preferred temperatures, the temperatures at which they are stressed, and the temperatures at which they start to die after a short exposure. Three procedures, determination of acute temperature preferences, routine metabolic rates, and critical thermal

maxima, all using five different acclimation temperatures, will be followed to meet these objectives. Data are presented for eight species, including hardhead (Mylopharodon conocephalus), Sacramento squawfish (Ptychocheilus grandis), hitch (Lavinia exilicauda), California roach (Lavinia symmetricus), Sacramento blackfish (Orthodon microlepidotus), Sacramento perch (Archoplites interruptus), tule perch (Hysterochampus traski), and Sacramento sucker (Catostomus occidentalis). Continued work on these species, as well as speckled dace (Rhinichthys osculus), riffle sculpin (Cottus gulosus), rainbow trout (Salmo gairdneri), and juvenile chinook salmon (Oncorhynchus tshawytscha) is anticipated. Published studies on the thermal requirements of rainbow trout, as well as other species occurring in California streams, such as smallmouth bass and carp, can be used for comparative purposes. The eventual goal is to define the thermal niches of all stream fishes in California as well as those found in the Sacramento-San Joaquin Delta region.

RELATED RESEARCH

There is an enormous literature on the temperature requirements of fish, thus substantiating the importance of temperature in regulating the distribution and abundance of fishes. There are several review articles on temperature preferences, including the works from two recent symposia (Richard et al. 1977; Reynolds 1979) as well as Magnuson and Beitingger (1978), Stauffer (1980), Mathur et al. (1981), Jobling (1981), and Houston (1982). Several conclusions derived from these reviews are relevant to this project: 1) Fish are very sensitive to temperature and will behaviorally thermoregulate if possible both to seek optimal and avoid stressful temperatures; 2) Each species has specific responses to temperature, including a rather narrow range of preferred temperatures, which are usually

optimal for growth (Jobling 1981; Kellogg and Gift 1983); 3) Acclimation history is an important determinant of the response of a fish to a particular temperature; 4) In streams, fish may be found at suboptimal temperatures in response to such factors as food availability, predators, competitors, disturbance, availability of cover, etc.; 5) Laboratory measures of thermal responses are nevertheless reliable predictors of responses to environmental temperatures and may be used to predict environmental impacts upon populations and communities; 6) The methods and measures used in this project are standard and have produced repeatable results from other investigations.

There is also an enormous literature on fish metabolism, though comparatively few studies have been conducted on relationships between temperature and standard or routine metabolic rates. Reviews by Job (1955), Fry (1957), Beamish (1964), Beamish and Mookherjee (1964), and Jobling (1982) generally reach the following conclusions: 1) Better distinctions need to be made between routine and standard metabolic rates; 2) Within the temperature tolerance limits of a species, metabolic rates generally increase with rises in temperature; 3) The rate of increase can vary from one species to another; 4) The temperature-metabolic rate relationships can be affected by fish size, season, water chemistry, apparatus, and acclimation period; 5) Given these and other variables, caution must be exercised in comparing results from different studies.

There is also a fairly extensive literature on the critical thermal maxima of fishes. Many of these studies are brought together in reviews by Fry (1971), Becker and Genoway (1979), Paladino et al. (1980), and Houston (1982). Several relevant conclusions can be obtained from these reviews: 1) The CTM is a good indicator of the thermal tolerance of a fish; 2) It can

be a measure of a species' ability to acclimate to different temperatures; 3) Usually the CTM increases with an increase in acclimation temperature; 4) It can also be used to determine how well a species can respond to physiological stress in a stream; 5) The CTM test can be a good model system for both laboratory and field studies (Paladino et al. 1980); 6) The procedure used in this project is standard and has been used by other workers.

Most of the temperature response studies have been conducted on fishes native to the eastern United States and Canada. Only recently has much temperature work been done on western fishes. Baltz et al. (1982) found that temperature played an important role in determining the outcome of competition between two riffle-dwelling species. Smith and Li (1983) showed increasing water temperatures altered the feeding habits of juvenile steelhead (Salmo gairdneri gairdneri). Preferences of 16 inshore marine fishes of California were determined in horizontal gradients by Ehrlich et al. (1979). Generally good correlations between preferred temperatures and field temperatures were found for four other inshore California marine species (Shrode et al. 1982). Cech et al. (1979b) examined the effects of temperature changes on oxygen consumption rates in largemouth bass. Metabolic rates of rainbow trout, Sacramento squawfish, Sacramento sucker, hardhead, tule perch, California roach, and riffle sculpin at 10, 20 and 30°C under normoxic and hypoxic conditions were measured by Cech (1983). The USFWS Instream Flow Group recognizes the importance of temperature as a component of their models predicting usable habitat areas under changing flows (Bovee and Milhous 1978), but they realize the paucity of basic information on the temperature requirements of stream fishes.

METHODS

General

Fish were captured either by seine or electroshocking and brought immediately to the laboratory in aerated ice chests. They were held a minimum of 4 days before experiments were begun. Where temperature adjustments were necessary, increases of 1°C/day or decreases of 0.5°C/day were made before using the fish. Water temperatures were maintained using a combination of immersion heaters and cold water, and the photoperiod was controlled at 12 hrs of light. Fish were fed ad libitum every day except 24 hrs before each experiment. No individual was used more than once in the same apparatus, but was used in different sets of experiments. The critical thermal maxima test was always the last trial for an individual fish because it was the most stressful. A minimum of ten fish of each species were acclimated to each of 10, 15, 20, 25, and 30°C. After each trial for every experiment, fish were immediately measured (± 0.5 mm SL) and wet weights (± 0.005 g) were recorded from a Mettler PC2200 electronic balance.

Acute Temperature Preference

A stainless steel trough (3.6 m long x 20 cm wide x 25 cm deep) was used to establish a horizontal temperature gradient (Stauffer et al. 1976) to determine acute temperature preferences of the species. Seventeen YSI thermistor probes were spaced 19 cm apart near the bottom of the trough, and water depth was adjusted to just cover the dorsal fin of each fish. The trough was lit by fluorescent tubes and surrounded by wood to minimize fish disturbance. Observations on fish were made through viewing ports via overhead mirrors. Cold water was input in one end of the trough and warmed

by a series of heat lamps as it flowed to the output standpipe at the other end. Plastic screens were placed at both ends of the trough to prevent fish interference with the input and output. The input water was adjusted to 1-4°C below the the acclimation temperature of the fish, and within 2 hrs total gradients of 12-16°C were achieved. The flow of water was maintained between 200 and 400 ml/min, by measuring the output into a beaker.

One fish at a time was placed in the trough at the point of its acclimation temperature. After a 30-minute adjustment period in the apparatus, readings of the position (nearest probe to the opercular openings, see Crawshaw 1976) and corresponding temperatures were recorded (YSI model 441D tele-thermometer) every 15 seconds for 20 minutes (Shingleton et al. 1981). At the end of a trial, the fish was removed before another one was inserted.

The mean temperature was determined from the resulting 80 observations on each fish. Also, plots were constructed with acclimation temperature as the independent variable and preferred temperature as the dependent variable. After constructing the best-fitting curves through the data (Hall et al. 1979), the point where the acclimation temperature equals the preferred temperature is the final acute temperature preferendum for each species (Fry 1947). In addition, mean standard deviations of the preferred temperatures were plotted for each acclimation temperature, in order to examine relative activities of individual fish in the trough and also to examine differences in activity between species.

Routine Metabolism

Routine metabolic rates were measured on the test fish, owing to the difficulties in maintaining precise conditions for static metabolic rate

measurements (Moyle and Cech 1982). This should not present a problem, however, since routine rates are probably more typical of a resting fish in its dynamic stream environment.

A large insulated wood box (63 cm x 44 cm x 41 cm inside) was constructed as a water bath for six glass respirometer jars, allowing simultaneous measurements on five fish and one control. Three container sizes were used (0.65, 1.74, and 2.90 l), depending on fish size. Rubber stoppers with input and sampling tubes were tightly fitted on each jar. One fish was placed in each jar, a stopper secured in place, and a wooden cover was placed over the box. A small flow of oxygenated water through each jar prevented oxygen depletion during the ensuing 3-hr acclimation period. At the end of this time, the input to each jar was stopped and initial water samples were taken using 12 ml plastic syringes. The oxygen content of the water sample (approx. 8 ml) was measured immediately using a Beckman model 325814 oxygen macro-electrode and read on a Beckman model 160 physiological gas analyzer (± 0.5 mm O_2). Final water samples were taken in the same method. Appropriate time intervals were initially determined to take into account fish size and jar size such that there was sufficient oxygen depletion for the meter to detect yet not so much that hypoxia was induced. Adjustments were made for barometric pressure, time interval, and jar size so that oxygen consumption could be expressed in mg $O_2/g \cdot hr$.

Plots were constructed of mean oxygen consumption at each acclimation temperature for comparative purposes. Also, the effects of temperature on metabolic rates can be seen by examining the Q_{10} , defined as the increase in rate caused by a $10^\circ C$ increase in temperature (Schmidt-Nielsen 1979). This quantity can be calculated using the following formula:

$$Q_{10} = \left(\frac{R_2}{R_1}\right)^{\frac{10}{T_2 - T_1}}$$

where R_1 is the metabolic rate at T_1 (lower temperature) and R_2 is the rate at T_2 .

Critical Thermal Maxima

Critical thermal maxima (CTM) were determined using two 38 l aquaria. Beginning with water corresponding to the respective acclimation temperatures of the test fish, hot water was introduced from a heated water bath so that the aquaria water was warmed at a constant rate of 1°C/min (Hutchison 1961; Cox 1974). The endpoint of each trial, using one fish at a time, was determined by the onset of muscular spasms (Hutchison 1976; Bonin et al. 1981), at which time the water temperature was recorded. After reaching this point, the fish was immediately removed and transferred to water of its acclimation temperature. Only those fish that survived the test were used in the analyses (Paladino et al. 1980).

The mean of the final temperatures is the CTM value for each acclimation temperature. A plot of CTM against acclimation temperature (Gerking et al. 1975) is used as a basis for interspecific comparisons.

RESULTS

Acute Temperature Preference

Trials were completed at all five temperatures for four species - hardhead, squawfish, hitch, and roach. In order to determine the final

temperature preferendum, several curve-fitting attempts were made for the data. Neither quadratic, cubic, nor square root regressions of acclimation temperature on preferred temperature significantly improved the fit of a linear regression for each species (Table 1). Using linear regressions therefore (Fig. 1-4), the final acute temperature preferenda for hardhead, squawfish, hitch, and roach were 28.35, 26.04, 30.67, and 24.72°C, respectively. The greatest intraspecific variability in preferred temperatures was at 15°C for hardhead and roach, 10°C for hitch, and 25°C for squawfish. The least variability was at 30°C for all species. Only two out of 40 (5%) total fish tested at that temperature preferred water warmer than 30°C.

Preferred temperatures at some of the acclimation temperatures were determined for blackfish, Sacramento perch, tule perch, and sucker, thus permitting a few additional comparisons at individual acclimation temperatures (Table 2). At 10°C, tule perch preferred the warmest temperature (17.77°C), whereas roach preferred the coolest water (11.23°C). Sacramento perch and suckers preferred the warmest temperatures (22.38 and 22.35°C, respectively) when acclimated to 15°C, and roach again preferred the coolest water (17.78°C). At 20°C, there was only a 3°C difference in preferred temperatures from the lowest (tule perch - 21.03°C) to the highest (hardhead - 24.00°C).

Considerable interspecific variability in fish activity in the temperature trough was noticed during the 20-minute trial intervals, despite the same 30-minute adjustment period before any observations were recorded. These activities ranged from little movement throughout the period to persistent swimming back and forth from one end of the trough to the other. One method to quantify the magnitude of this activity is to examine the

standard deviations of the preferred temperature of each fish. The more active a fish in the trough, the greater will be its standard deviation. If the standard deviation is taken for each fish of one species, then means of those values at each acclimation temperature will provide an indication of the relative activity of that species in the experimental apparatus. This is shown in Fig. 5 for hardhead, squawfish, hitch, and roach. At 10, 15, and 20°C, squawfish were the most active and roach the least active species. Peak activities were at 15°C for squawfish and 20°C for the others. Relative activities declined from 20 to 30°C in all four species.

Routine Metabolism

Routine metabolic rates were determined for hardhead, squawfish, hitch, roach, and blackfish at all five acclimation temperatures (except hitch at 20°C). These rates increased with increasing temperatures for each species, though some of the differences were not significant. Hardhead had the most gradual increase in metabolic rate from 10 to 30°C with the least intraspecific variability (Fig. 6). Squawfish metabolic rates were higher and increased faster at each temperature (higher Q_{10} s) and also showed greater intraspecific variability than hardhead. Metabolic rates of roach were higher and more variable than hitch at each temperature (Fig. 7). Blackfish showed a steep rise in oxygen consumption from 20 to 25°C ($Q_{10} = 8.88$), but there was no significant change beyond that to 30°C (Fig. 8). Squawfish, hitch, and roach metabolic rates all increased substantially from 25 to 30°C.

Partial results of routine metabolic rates of Sacramento perch, tule perch, and sucker are presented in Table 3 for additional comparisons. At 15°C, tule perch and suckers had the highest rates (0.21 mg/g*hr for both),

whereas Sacramento perch had the lowest (0.076 mg/g*hr). Suckers had the highest mean rate (0.31 mg/g*hr) and blackfish and Sacramento perch had the highest rates (0.12 mg/g*hr for both) at 20°C.

Critical Thermal Maxima

Critical thermal maxima increased with increasing acclimation temperature for squawfish, hitch, roach, blackfish, Sacramento perch, tule perch, and suckers (Fig. 9). The only exceptions were from 10 to 15°C in which the CTMs for squawfish and roach were not significantly changed. The most significant increase was a 7.17°C rise in CTM for squawfish from 15 to 20°C. Tule perch had the lowest CTMs at 20, 25 and 30°C (31.92, 33.41, and 33.88°C, respectively), whereas squawfish had the lowest at 10 and 15°C (28.29 and 28.26°C, respectively). Roach had the highest CTM at 10°C (30.32°C), blackfish were the highest at 15°C (32.53°C), squawfish were the highest at 20 and 25°C (35.43 and 37.15°C, respectively), and hitch had the greatest CTM at 30°C (38.14°C). No data are presently available for hardhead.

The CTM trials had the lowest intraspecific variability of all three experiments performed in this project. As an example, small standard errors at each acclimation temperature can be seen for hitch in Fig. 10. Then relative differences between the three experiments can be examined by comparing coefficients of variation ($CV = s/\bar{X} \times 100\%$) at one temperature. For example, using the results from hitch at 25°C, the CV was 1.91% in the CTM test, 33.9% for the routine metabolic rates, and 8.79% in the temperature preference test.

DISCUSSION AND SIGNIFICANCE

The acute final temperature preferenda for the four cyprinids tested very broadly correspond to their general distributions in the Sacramento-San Joaquin system. The lowest of the group was for the roach, which can be found in slightly higher elevations than squawfish or hardhead, although there is often considerable overlap (Moyle and Nichols 1973). An interesting observation, however, is that although the final preferenda for roach was the lowest of the group, the water in their habitat may exceed 30°C during summer days, apparently restricting adult squawfish and hardhead from those reaches. The preferenda for squawfish and hardhead are intermediate, partly supported by their occurrences most commonly in pool habitats where summer diurnal temperature fluctuations are not as extreme. And lastly, hitch had the highest preferenda, which may be somewhat explained by their occurrences most characteristically in warm, low-elevation lakes, ponds, and slow-moving stretches of streams and rivers (Moyle 1976). The relative activity analysis (using standard deviations) also corresponds to the relative activities of these species in their respective habitats.

The overall high preferenda of the four species all fall within the summer water temperatures of their stream environments. Abundances of juvenile fish, benthic and drifting invertebrates, and aquatic vegetation during that season would contribute to higher growth rates, thus lending support to the contention that preferenda may indeed correspond to optima for fish growth rates (Jobling 1981; Kellogg and Gift 1983).

Two factors that may affect the final temperature preferenda need to be considered. The first is the fish size. Juveniles of a species tend to have higher preferenda than adults (McCauley and Huggins 1979; Shrode et al. 1983), corresponding to the general occurrence of juveniles in shallower,

warmer water in streams than adults. With the physical size limitations of the temperature trough used, only adult roach could be tested, a species that seldom exceeds 100 mm in standard length (Moyle 1976). For the other three species, adults could not be used, so the preferenda for hardhead, squawfish, and hitch may be biased slightly upward.

The second factor to consider is the method of graphically determining the final preferenda, or more specifically, the "correct" curve-fitting procedure. Although no significant improvement in the fit of the data was obtained by analyzing higher order or square root models, differences in the final preferenda obtained by these methods should be examined. These were calculated for the data of hardhead and squawfish. For hardhead, the preferenda range was quite small (27.59°C from the square root to 28.35°C for the linear equation). Squawfish differences were low also (25.78°C from the square root to 26.77°C from the quadratic equation). Stauffer (1980) recommended using an expanded quadratic model ($P = a_1A^2 + a_2A + c$, where A = acclimation temperature and P = preferred temperature) and Coutant (in Richards et al. 1977) recommended the "eyeball" method for the best fit, but in this study no significant improvement was obtained over the simpler and readily quantifiable linear regression fit.

No data on preferenda of these species are available for comparisons of techniques or results. A few studies have been done on species that have been introduced to California fresh waters. Final preferenda for goldfish (Carassius auratus) range from 24 to 30°C, depending on season and fish size (Roy and Johansen 1970; Reutter and Herdendorf 1974). The range for carp (Cyprinus carpio) is 27.4 to 32.0°C (Reutter and Herdendorf 1974). The preferenda for green sunfish (Lepomis cyanellus) are 28.2°C for juveniles (Beitinger et al. 1975) and 30.6°C for adults (Cherry et al. 1975), though

the reverse size trend is likely due to different types of apparatus used in the separate studies. Smallmouth bass (Micropterus dolomieu) preferred temperatures of 13 to 31°C, depending on the life stage and season (Barans and Tubb 1973). The preferenda for largemouth bass (M. salmoides) ranges from 26.5 to 32°C (Ferguson 1958; Reutter and Herdendorf 1974; Reynolds and Casterlin 1976; Cherry et al. 1977). All these temperatures correspond to summer stream temperatures in the lower elevation Sacramento-San Joaquin system streams.

Much work has been done on temperature requirements of rainbow trout, a native to higher elevation, cooler streams of northern California. Published final preferenda range from 16.5 to 21.1°C, varying with season, fish size, and method (Horak and Tanner 1964; McCauley and Pond 1971; Spigarelli 1975; McCauley and Huggins 1976; Cherry et al. 1977). Final preferenda for chinook salmon, also native to northern California, for spawning migrations has been reported as 11.7°C by Brett (1952) and 17.3°C by Spigarelli (1975). Future work on this project is intended to target on these two species, for comparative purposes, as well as completion of the partial trials of the other species mentioned earlier.

In the routine metabolism experiment, squawfish had the highest mean rates of oxygen consumption at 10, 25, and 30°C (Fig. 6; Table 3). Coupled with this was high intraspecific variability at each acclimation temperature. This may be due to the observation that squawfish is the only piscivorous species of those tested (Moyle 1976). All the others (except adult Sacramento perch) are either omnivores or herbivores. The higher metabolic rates may be required for the extra energy enabling squawfish to forage for their active prey. Low metabolic rates were measured for hitch, blackfish, and Sacramento perch. These particular species are most commonly found in

warm, slow-moving or stagnant waters. In these habitats, little or no energy needs to be expended on maintaining position, and feeding consists either of filter-feeding (blackfish), picking planktonic crustaceans or insects (hitch), or picking benthic insects (juvenile Sacramento perch). The piscivorous feeding habits of adult Sacramento perch consists primarily of sluggish movement and "inhalation" of nearby prey (Moyle 1976), in contrast to the active roving and foraging activities of squawfish. Fairly high metabolic rates for suckers at 20 and 25°C (Table 3) may be a reflection of their active benthic foraging habits. Intermediate metabolic rates were obtained for hardhead, roach, and tule perch, two omnivores and an insectivore, respectively. Thus the routine metabolic rates measured can be partly explained by the feeding habits and macrohabitats of the particular species.

Routine metabolic rates of hardhead, squawfish, roach, blackfish, tule perch, and suckers at 10, 20, and 30°C were also determined by Cech et al. (1979a) and Cech (1983). Nearly every rate was lower than those determined in this project (Table 4), some significantly. For example, they calculated the rate for squawfish at 20°C to be 0.1088 mg/g*hr, whereas in this study, the rate was 0.2991 mg/g*hr. Yet roach at 20°C consumed 0.2396 mg/g*hr, but here consumed 0.2304 mg/g*hr. However, other than the small roach, most of the test fish used by Cech et al. (1979a) and Cech (1983) were adults that could be accommodated in their larger flow-through respirometers than the static respirometer jars used in this study. When oxygen consumption is analyzed in terms of mg/g*hr or mg/kg*hr, larger fish have lower rates than smaller fish of the same species (Moyle and Cech 1982). Also, the test fish in Cech's trials were acclimated to the experimental chamber for 24 hrs, whereas in this project the fish were subject to a 3-hr adjustment period.

Consequently, Cech's results may be approaching the lower standard metabolic rates rather than the routine metabolic rates obtained in this study. Of importance, however, is that despite absolute differences in metabolic rates between the two studies, there is still agreement in the species order of highest to lowest rate, again generally corresponding to field observations.

Metabolic rates for rainbow trout were also determined by Cech (1983) and found to be the highest of all the species he tested, nicely corresponding to their common occurrences in shallower and swifter water than that normally occupied by squawfish. Metabolic rates of juvenile Tahoe suckers (Catostomus tahoensis) at 8, 13, and 18°C were 0.6247, 0.9400, and 0.1718 mg/g*hr, respectively (Vondracek et al. 1982), considerably below the rates for Sacramento suckers at 15 and 20°C in this study (0.2127 and 0.3089 mg/g*hr, respectively). Hughes et al. 1983 determined the routine metabolic rates of carp to be 0.0311 mg/g*hr at 10°C and 0.0626 mg/g*hr at 20°C. These rates were derived from large test fish (700-1200 g), which may partly explain why they are considerably lower than any other species tested in this study. Metabolic rates of largemouth bass were 0.0677, 0.1029 and 0.1732 mg/g*hr at 20, 25, and 30°C, respectively (Cech et al. 1979b). The rates of these active piscivorous fish are deceptively low, again likely due to the relatively large size of the test specimens (230-470 g).

The critical thermal maxima tests for seven species (Fig. 9) mostly increased with higher acclimation temperatures, as reported by others (Hutchison 1961; Becker and Genoway 1979; Paladino et al. 1980). Of interest in this particular set, however, is the closeness in the CTM values between species. At each acclimation temperature, the range in CTMs is no greater than 4°C from the highest to the lowest value. Although general zones of distribution of these species have been outlined by Moyle and Nichols (1973),

Critical thermal maxima values for goldfish ranged from 28 to 41°C, depending on the acclimation temperature (Fry et al. 1942). Carp had a CTM of 35.7°C when acclimated to 26°C (Weatherley 1970). For largemouth bass, CTMs range from 32 to 37.5°C at acclimations of 20 to 35°C (Hart 1952). Numerous studies have been done on rainbow trout, with CTM values ranging from 21 to 27°C (Craigie 1963; Alabster 1964; Kaya 1978; to name a few). For chinook salmon, reported CTMs range from 19.5 to 24.8°C, again depending on acclimation temperature (Brett 1952; Coutant 1970; Templeton and Coutant 1970).

The critical thermal maxima is a measure of an organisms ability to respond to changes in environmental temperatures (Paladino et al. 1980). It can also be used as an indicator of environmental stress, such as pollutants, turbidity, or disease. Burton et al. (1972) and Cairns et al. (1975) have shown that temperature tolerances (as indicated by the CTM) decline with increasing chemical toxicities. A decrease in the CTM can be an early warning signal for the presence of sublethal doses of pollutants or the presence of disease. This comparative procedure is effective, however, only when background data is available on healthy fish in "clean" water. The preliminary CTM data from this project is the first step in providing the necessary background information. Then if a significant decline in CTM is noticed for one or more species from a certain stream site, then perhaps appropriate management agencies can be alerted so that corrective action can be taken before fish mortalities are seen.

The preferred temperatures are also important because recent evidence points out they are likely the optimal temperatures for growth, feeding, and perhaps reproduction as well. These data would then be useful for predicting the potential impact of a water project on the fish populations in a stream.

Water projects often alter stream temperatures, making them higher or lower than the preferred temperatures of the fish present. The changes may not be extreme enough to affect survival, but reductions in growth rates and/or reproduction may become evident. The more mobile species may move to a location where temperatures are more favorable, resulting in a change in species composition of the fish community. It may thus be possible to manipulate temperatures below dams to favor more desirable fishes.

The routine metabolism set of experiments is also important, to provide background information on the oxygen requirements of the native stream fishes. Man-made changes or severe drought may result in reduced oxygen levels in stream reaches. Species with high activity levels and corresponding high metabolic rates may be affected first under hypoxic conditions. In addition, metabolic requirements are amplified at elevated temperatures, and the oxygen saturation level in water is reduced. Thus the basal oxygen consumption rates of these fishes can be used to predict the effects of dams and other environmental alterations.

PUBLICATIONS

- Knight, N. J. 1984. Microhabitat comparisons between hardhead (Mylopharodon conocephalus) and Sacramento squawfish (Ptychocheilus grandis), and temperature requirements of some native California stream fishes. Ph.D. dissertation. University of California, Davis. In Prep.
- Knight, N. J. and P. B. Moyle. 1985. Temperature requirements of some native stream fishes of California. M.S. In prep.

ACKNOWLEDGEMENTS

The research on which this report is based was financed in part by the United States Department of the Interior, Geological Survey, through the State Water Resources Research Institute, Project No. USGS CT370503, and by the University of California Water Resources Center, Project UCAL-WRC-W-641. Contents of this publication do not necessarily reflect the views and policies of the U.S. Department of the Interior, nor does mention of trade names or commercial products constitute their endorsement or recommendation for use by the U.S. Government.

Bruce Vondracek and Donald M. Baltz were largely responsible for setting up the temperature preference tank and were instrumental in designing the experiments upon which this project is based. Eric Wikramanayake was responsible for running the determinations of critical thermal maxima. Bruce Herbold, Beth Goldowitz, Larry Brown, and, especially, Elaine Knight, assisted the temperature preference trials.

LITERATURE CITED

- Alabaster, J. S. 1964. The effect of heated effluents on fish. Pages 261-292 in International conference on water pollution research. Pergamon Press, N.Y.
- Baltz, D. M., P. B. Moyle, and N. J. Knight. 1982. Competitive interactions between benthic stream fishes, riffle sculpin, Cottus gulosus, and speckled dace, Rhinichthys osculus. Can. J. Fish. Aquat. Sci. 39:1502-1511.
- Barans, C. A., and R. A. Tubb. 1973. Temperatures selected seasonally by four fishes from western Lake Erie. J. Fish. Res. Board Can. 30:1697-1703.
- Beamish, F. W. H. 1964. Respiration of fishes with special emphasis on standard oxygen consumption. II. Influence of weight and temperature on respiration of several species. Can. J. Zool. 42:177-188.
- Becker, C. D., and R. G. Genoway. 1979. Evaluation of the critical thermal maximum for determining thermal tolerance of freshwater fish. Env. Biol. Fish. 4:245-256.
- Beitinger, T. L., J. J. Magnusson, W. H. Neill, and W. R. Shaffer. 1975. Behavioral thermoregulation and activity patterns in the green sunfish, Lepomis cyanellus. Anim. Behav. 23:203-210.
- Bonin, J. D., R. M. Lee, and J. N. Rinne. 1981. Measuring thermal limits of fish. Trans. Amer. Fish. Soc. 110:662-664.
- Bovee, K. D., and R. T. Milhous. 1978. Hydraulic simulation in instream flow studies: theory and technique. Instream Flow Information Paper 5. FWS/OBS-78/33. 131 pp.
- Brett, J. R. 1952. Temperature tolerance in young Pacific salmon genus Orcorhynchus. J. Fish. Res. Board Can. 21:1183-1226.
- Burton, D. T., E. I. Morgan, and J. Cairns, Jr. 1972. Mortality curves of bluegills (Lepomis macrochirus Rafinesque) simultaneously exposed to temperature and zinc stress. Trans. Amer. Fish. Soc. 101:435-441.
- Cairns, J., Jr., A. G. Heath, and B. C. Parker. 1975. The effects of temperature upon the toxicity of chemicals to aquatic organisms. Hydrobiologia 47:135-171.
- Cech, J. J., Jr. 1983. Metabolism of California stream fishes. Technical completion report. WRC/OWRT Proj. No. W-582/A-082-Cal. 18 p.
- Cech, J. J., Jr., C. G. Campagna, and S. J. Mitchell. 1979a. Respiratory responses of largemouth bass (Micropterus salmoides) to environmental changes in temperature and dissolved oxygen. Trans. Amer. Fish. Soc. 108:166-171.

- Cech, J. J., Jr., S. J. Mitchell, and M. J. Massingill. 1979b. Respiratory adaptations of Sacramento blackfish, Orthodon microlepidotus (Ayres), for hypoxia. *Comp. Biochem. Physiol.* 63A/411-415.
- Cherry, D. S., K. L. Dickson, J. Cairns, Jr., and J. R. Stauffer, Jr. 1977. Preferred, avoided, and lethal temperatures of fish during rising temperature conditions. *J. Fish. Res. Board Can.* 34:239-246.
- Cherry, D. S., K. L. Dickson, and J. Cairns, Jr. 1975. Temperatures selected and avoided by fish at various acclimation temperatures. *J. Fish. Res. Board Can.* 32:485-491.
- Coutant, C. C. 1970. Thermal resistance of adult coho (Oncorhynchus kisutch) and jack chinook salmon (O. tshawytscha), and adult steelhead trout (Salmo gairdneri) from the Columbia River. Battelle Memorial Institute, Richland, Wash. B.N.W.L.-1508. 24 p.
- Cox, D. K. 1974. Effects of three heating rates on the critical thermal maximum of bluegill. Pages 158-163 in J. W. Gibbons and R. R. Sharitz, eds. *Thermal ecology*. Nat. Tech. Informat. Center. CONF-730505. Springfield, Va.
- Craigie, D. E. 1963. An effect of water hardness in the thermal resistance of the rainbow trout, Salmo gairdneri Richardson. *Can. J. Zool.* 41:825-830.
- Crawshaw, L. I. 1976. The effect of rapid temperature change on mean body temperature and gill ventilation in carp. *Amer. J. Physiol.* 231:837-841.
- Ehrlich, K. F., J. M. Hood, G. Muszynski, and G. E. McGowen. 1979. Thermal behavioral responses of selected California littoral fishes. *Fish. Bull.* 76:837-849.
- Ferguson, R. G. 1958. The preferred temperature of fish and their midsummer distribution in temperate lakes and streams. *J. Fish. Res. Board Can.* 15:607-624.
- Fry, F. E. J. 1947. Effects of the environment on animal activity. *Publ. Ont. Fish. Res. Lab* 68. 62 p.
- Fry, F. E. J. 1971. The effects of environmental factors on the physiology of fish. Pages 1-19 in W. S. Hoar and D. J. Randall, eds. *Fish physiology*, vol. 6. Academic Press, New York.
- Fry, F. E. J., J. R. Brett, and G. H. Clawson. 1942. Lethal temperature limits for young goldfish. *Rev. Can. Biol.* 1:50-56.
- Gerking, S. D., T. Ratcliff, and R. G. Otto. 1975. Laboratory and field tests of temperature tolerance on Gambusia affinis, the western mosquitofish. *Veh. Int. Ver. Limnol.* 19:2498-2503.

- McCauley, R. W. and W. L. Pond. 1971. Temperature selection of rainbow trout (Salmo gairdneri) fingerlings in vertical and horizontal gradients. *J. Fish. Res. Board Can.* 28:1801-1804.
- Moyle, P. B. 1976. *Inland Fishes of California*. Univ. Calif. Press, Berkeley. 405 p.
- Moyle, P. B. and J. J. Cech, Jr. 1982. *Fishes: an introduction to ichthyology*. Prentice-Hall, Inc. Englewood Cliffs, New Jersey. 593 p.
- Moyle, P. B. and R. Nichols. 1973. Ecology of some native and introduced fishes of the Sierra-Nevada foothills in central California. *Copeia* 1973:478-490.
- Paladino, F. V., J. R. Spotila, J. P. Schubauer, and K. T. Kowalski. 1980. The critical thermal maximum: a technique used to elucidate physiological stress and adaptation in fishes. *Revue Can. Biol.* 39:115-122.
- Reutter, J. M., and C. E. Herdendorf. 1974. Laboratory estimates of the seasonal final temperature preferenda of some Lake Erie fish. *Proc. Conf. Great Lakes Res.* 17:59-67.
- Reynolds, W. W., ed. 1979. *Thermoregulation in ectotherms*. *Amer. Zool.* 19:191-384.
- Reynolds, W. W., and M. E. Casterlin. 1976. Thermal preferenda and behavioral thermoregulation in three Centrarchid fishes. Pages 185-190 in G. W. Esch and R. W. McFarlane, eds. *Thermal Ecology II*. Nat. Tech Informat. Center. CONF-750425. Springfield, Va.
- Richards, F. P., W. W. Reynolds, and R. W. McCauley. 1977. Temperature preference studies in environmental impact assessments: an overview with procedural recommendations. *J. Fish. Res. Board Can.* 34:728-761.
- Roy, A. W. and P. H. Johansen. 1970. The temperture selection of small hypophysectomized goldfish (Carassius auratus L.). *Can. J. Zool.* 48:323-326.
- Schmidt-Nielsen, K. 1979. *Animal physiology: adaptation and environment*. Cambridge. 560 pp.
- Shingleton, M. V., C. H. Hocutt, and J. R. Stauffer, Jr. 1981. Temperature preference of the New River shiner. *Trans. Amer. Fish. Soc.* 110:660-661.
- Shrode, J. B., L. J. Purcell, and J. S. Stephens, Jr. 1983. Ontogeny of thermal preferences in four species of viviparous fishes (Embiotocidae). *Env. Biol. Fish.* 9:71-76.
- Shrode, J. B., K. E. Zerba, and J. S. Stephens, Jr. 1982. Ecological significance of temperature tolerance and preference of some inshore California fishes. *Trans. Amer. Fish. Soc.* 111:45-51.

- Smith, J. J. and H. W. Lit. 1983. Energetic factors influencing foraging tactics of rainbow trout (Salmo gairdneri). *Env. Biol. Fish.*
- Spigarelli, S. A. 1975. Behavioral responses of Lake Michigan fishes to a nuclear power plant discharge. Pages 479-498 in *Environmental effects of cooling systems at nuclear power stations*. Int. Atomic Energy Agency, Vienna.
- Stauffer, J. R., Jr. 1980. Influence of temperature on fish behavior. Pages 103-142 in C. H. Hocutt, J. R. Stauffer, Jr., J. E. Edinger, L. W. Hall, Jr., and R. P. Morgan, eds., *Power plants, effects on fish and shellfish behavior*. Academic Press, New York.
- Stauffer, J. R., Jr., K. L. Dickson, J. Cairns, Jr., and D. S. Cherry. 1976. The potential and realized influences of temperature on the distribution of fishes in the New River, Glen Lyn, Virginia. *Wildl. Monogr. No. 50*. 40 p.
- Templeton, W. L. and C. C. Coutant. 1970. Studies on the biological effects of thermal discharges from nuclear reactors to the Columbia River at Hanford. IAEA/SM-146/33, BNWL-SA-3465. 35 p.
- Vondracek, B., J. J. Cech, Jr., and D. Longanecker. 1982. Effect of cycling and constant temperatures on the respiratory metabolism of the Tahoe sucker, Catostomus tahoensis (Pisces: Catostomidae). *Comp. Biochem. Physiol.* 73A:11-14.
- Weatherley, A. H. 1970. Effects of superabundant oxygen on thermal tolerance of goldfish. *Biol. Bull.* 139:229-238.

Table 1. Multiple correlation coefficients (R^2) of linear, quadratic, cubic, and square root regressions of acclimation temperature on acute preferred temperature for hardhead, squawfish, hitch, and roach.

Type	Model	Species			
		HH	SQ	HCH	RCH
Linear	$a_1x + b$	0.800	0.828	0.716	0.711
Quadratic	$a_1x^2 + a_2x + b$	0.815	0.872	0.751	0.730
Quadratic	$a_1x^2 + b$	*	*	0.656	0.664
Cubic	$a_1x^3 + a_2x^2 + a_3x + b$	0.815	0.876	0.751	0.734
Square root	$a_1 \sqrt{x}^2 + b$	0.811	0.854	0.736	0.726
Square root	$a_1 \sqrt{x}^1 + a_2x + b$	0.814	0.874	0.749	0.732

* Not computed, based on lower coefficients for HCH and RCH.

Table 2. Mean (2 S.E.) acute preferred temperatures for hardhead, squawfish, hitch, roach, blackfish, Sacramento perch, tule perch, and suckers at 10, 15, 20, 25, and 30°C. Means are based on ten fish at each temperature except where indicated. Dashes indicate insufficient data.

Species	Acclimation temperature				
	10	15	20	25	30
HH	15.26 (0.96) ^a	19.27 (2.35)	24.00 (1.96)	26.28 (0.98)	28.63 (0.45)
SQ	13.15 (1.42)	19.04 (0.74)	23.67 (0.71)	25.19 (1.87)	27.78 (0.89)
HCH	13.76 (3.26)	19.35 (2.32)	23.94 (1.32)	27.28 (1.52)	28.68 (0.91)
RCH	11.23 (2.69)	17.78 (3.71)	22.18 (1.27)	24.70 (1.48)	28.32 (0.67)
BLK	15.76 (2.14)	18.37 (4.07)	23.04 (3.76) ^b	23.79 (2.72) ^{b,c}	-
SP	12.96 (1.95)	22.38 (1.95)	-	-	-
TP	17.77 (1.31)	18.45 (5.99) ^d	21.03 (1.12)	-	-
SKR	-	22.35 (3.44)	23.24 (3.19)	-	-

^a Based on 15 fish.

^b Fish used after critical thermal maxima were determined.

^c Based on eight fish.

^d Based on three fish.

Table 4. Comparisons in routine metabolic rates ($\text{mg O}_2/\text{g}\cdot\text{hr}$) determined by Cech (1983), Cech et al. (1979a) and the present study for hardhead, squawfish, roach, blackfish, tule perch, and suckers. Dashes indicate no comparative data available.

Species	Study ^a	Acclimation temperature				
		10	15	20	25	30
HH	C1	0.0492	-	0.0819	-	-
	P	0.0770	-	0.1349	-	-
SQ	C1	0.0429	0.1056	0.1088	0.1372	0.2172
	P	0.1065	0.1731	0.2991	0.3934	0.5306
ROH	C1	0.0717	-	0.2396	-	0.3079
	P	0.0993	-	0.2304	-	0.4935
BLK	C2	0.0418	0.0774	0.0985	0.1400	0.1907
	P	0.0686	0.0882	0.1161	0.3460	0.3550
TP	C1	-	-	0.1660	-	-
	P	-	-	0.2549	-	-
SKR	C1	-	-	0.0884	-	-
	P	-	-	0.3089	-	-

^a C1 = Cech (1983); C2 = Cech et al. (1979a); P = present study.

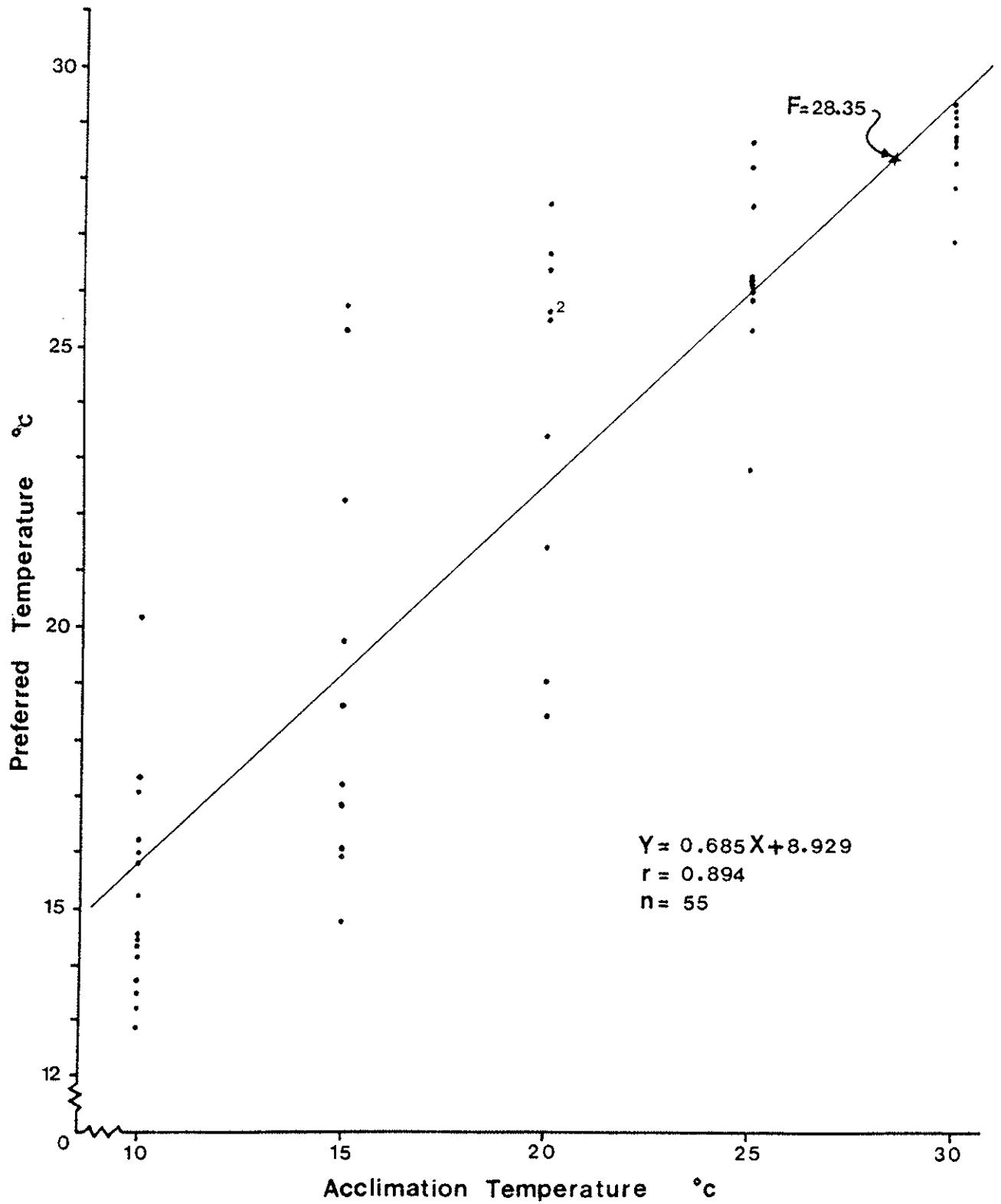


Figure 1. Preferred temperatures of hardhead at five acclimation temperatures. F is the final acute temperature preferendum, based on a linear regression.

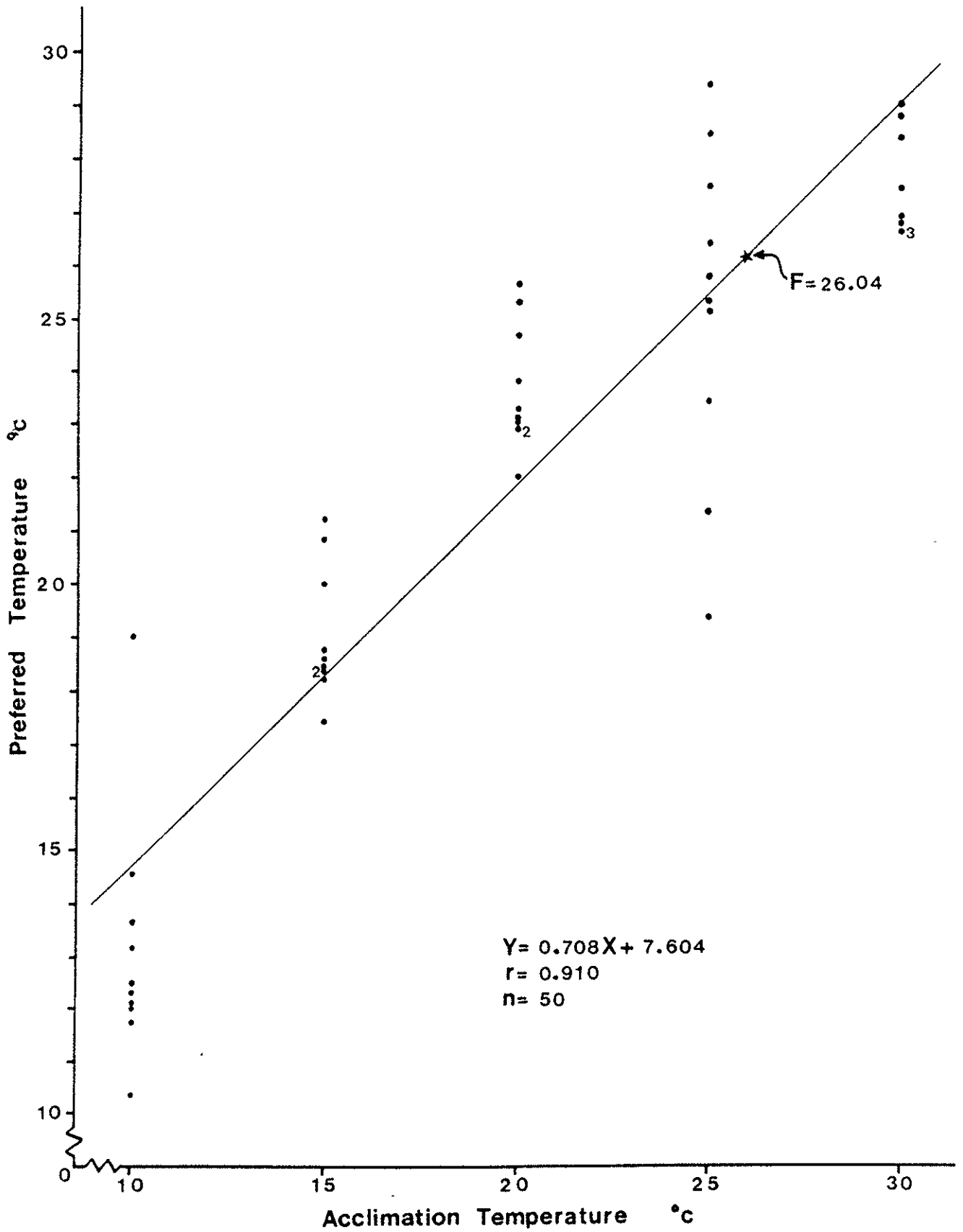


Figure 2. Preferred temperatures of Sacramento squawfish at five acclimation temperatures. F is the final acute temperature preferendum, based on a linear regression.

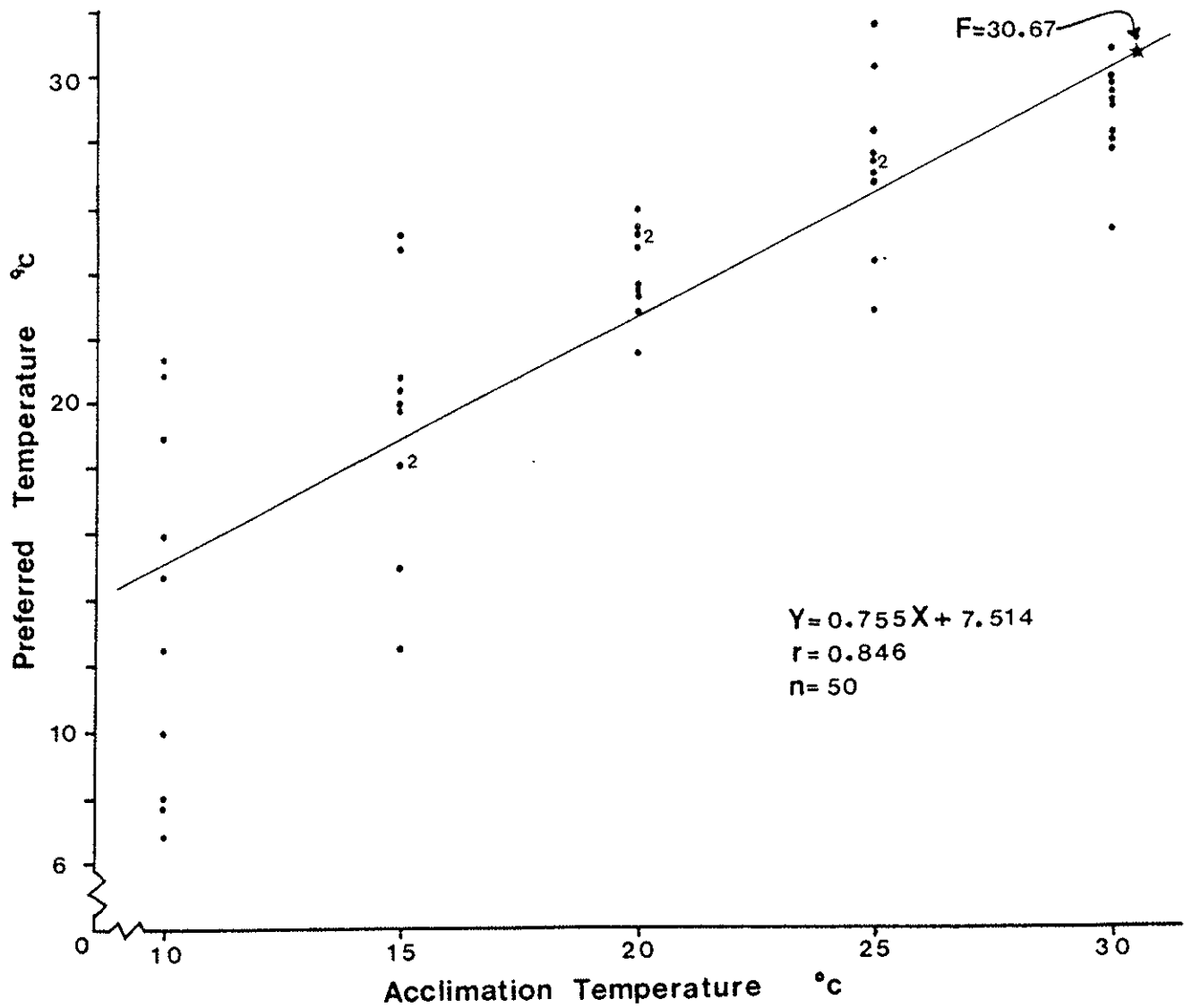


Figure 3. Preferred temperatures of hitch at five acclimation temperatures. F is the final acute temperature preferendum, based on a linear regression.

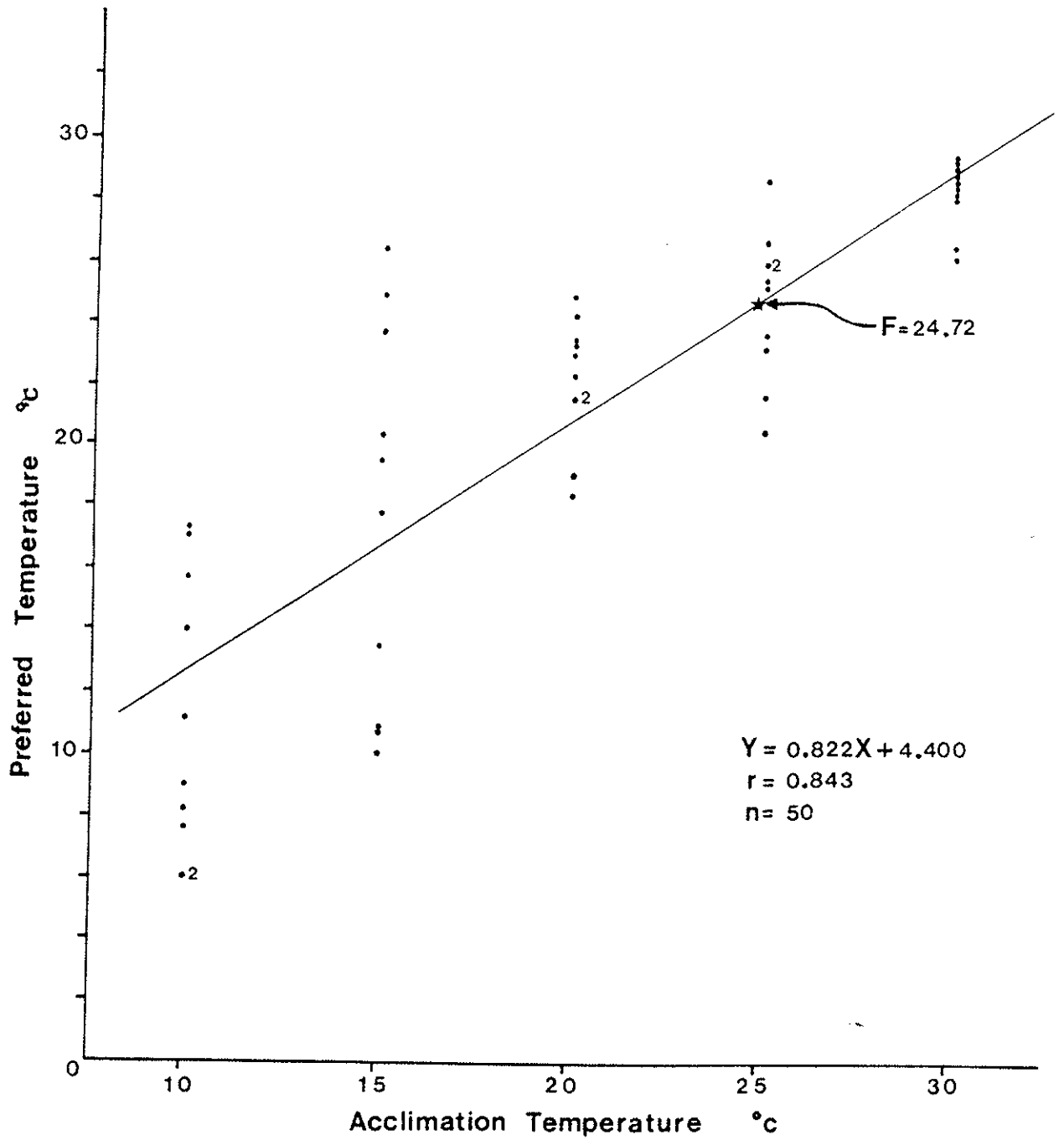


Figure 4. Preferred temperatures of California roach at five acclimation temperatures. F is the final acute temperature preferendum, based on a linear regression.

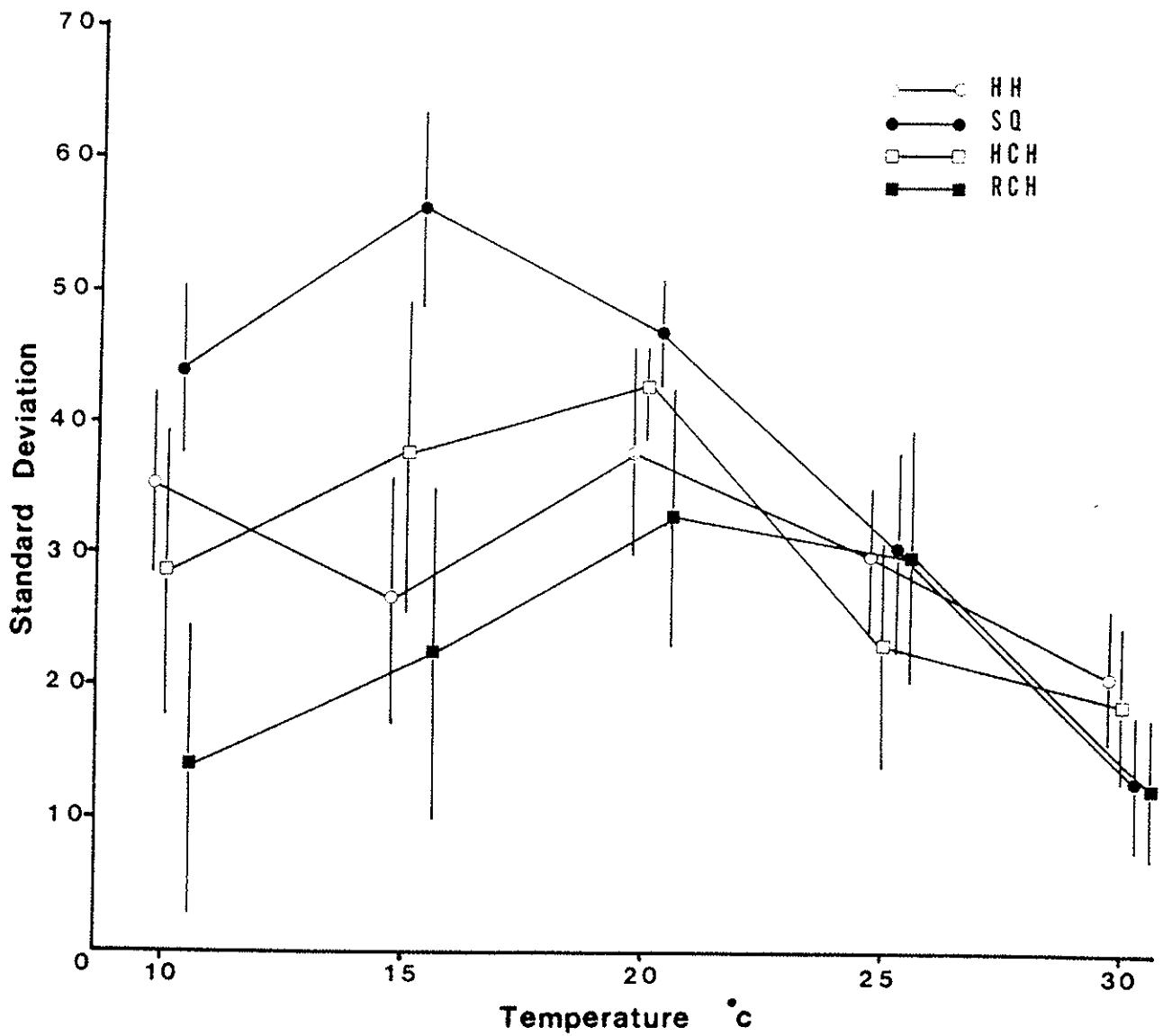


Figure 5. Fish activity in the temperature preference trough, as indicated by standard deviations ($\text{mean} \pm 2 \text{ S.E.}$) of mean preferred temperatures of hardhead (HH), squawfish (SQ), hitch (HCH), and roach (RCH) at five acclimation temperatures. Data are based on ten fish at each temperature.

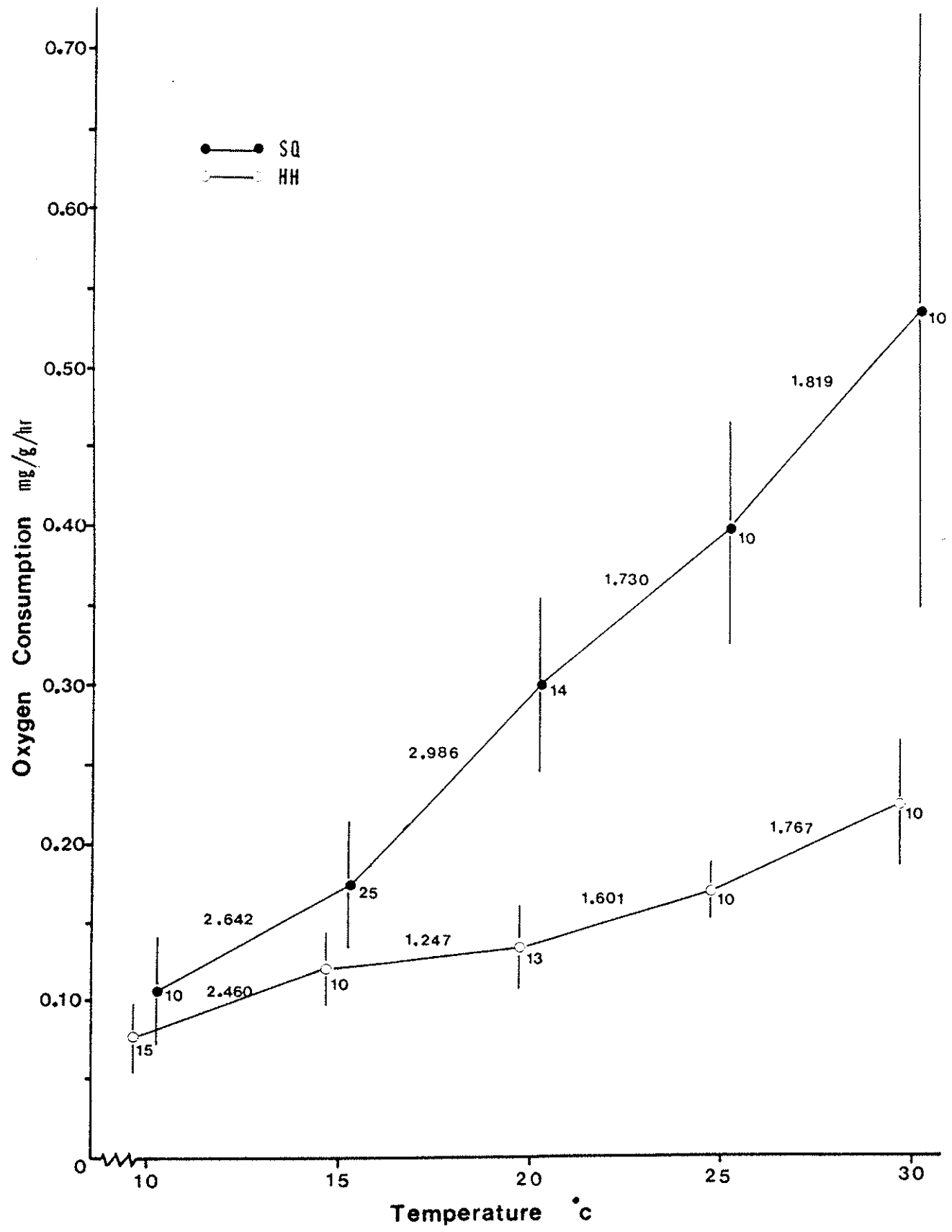


Figure 6. Routine metabolic rates of hardhead and squawfih at five acclimation temperatures. Vertical lines are ± 2 S.E. of the mean. Numbers above lines are Q_{10} 's. Numbers of fish are indicated next to each mean.

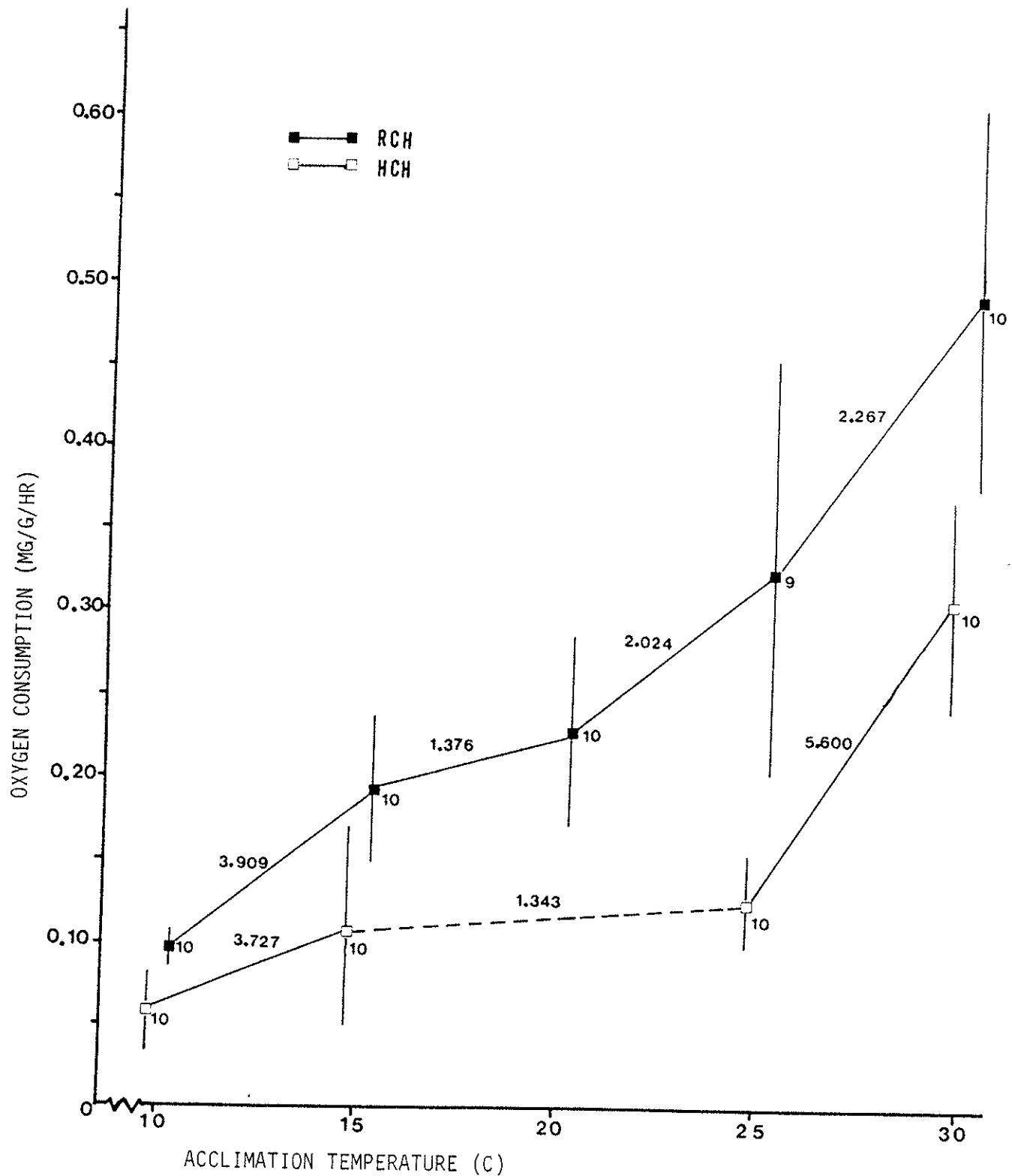


Figure 7. Routine metabolic rates of hitch (HCH) and roach (RCH) at five acclimation temperatures. Vertical lines are ± 2 S.E. of the mean. Numbers above lines are Q_{10} 's ; numbers of fish are indicated next to each mean.

Fig 8

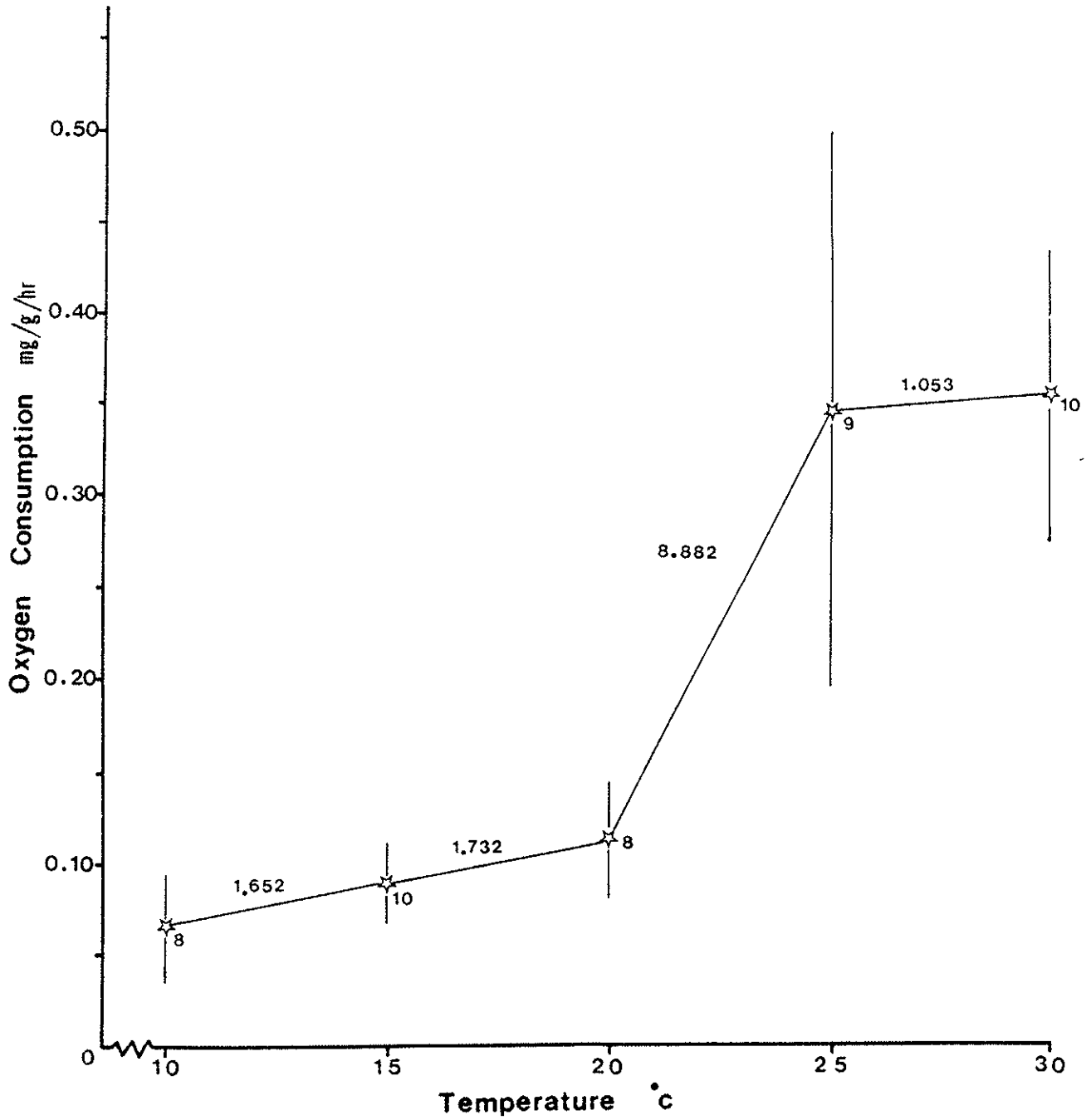


Figure 8. Routine metabolic rates of Sacramento blackfish at five acclimation temperatures. Vertical lines are ± 2 S.E. of the mean. Numbers above line are Q_{10} 's. Numbers next to each mean are sample sizes.

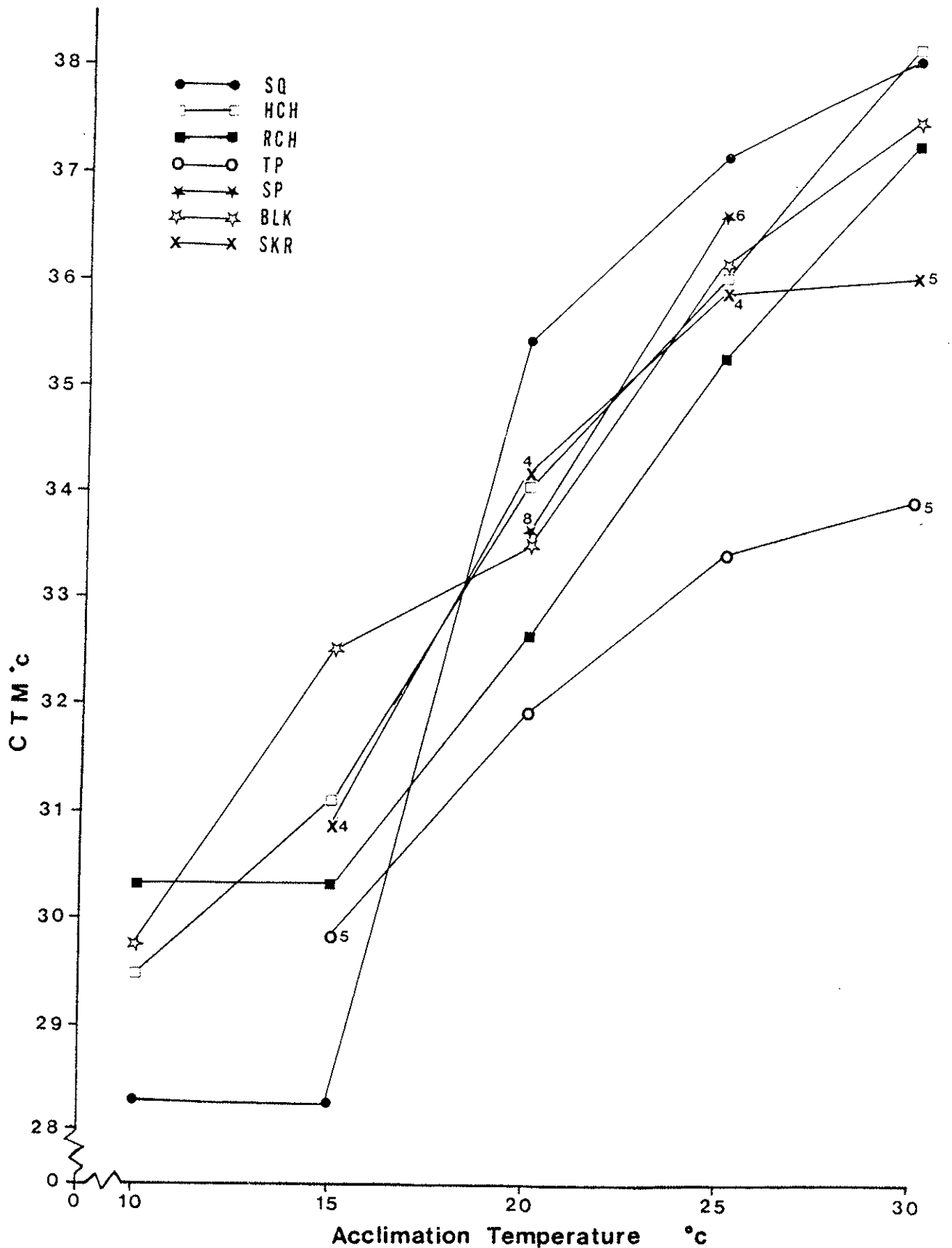


Figure 9. Critical thermal maxima for squawfish (SQ); hitch (HCH), roach (RCH), blackfish (BLK), Sacramento perch (SP), tule perch (TP), and Sacramento sucker (SKR) at five acclimation temperatures. Means are based on 10 fish, except where indicated.

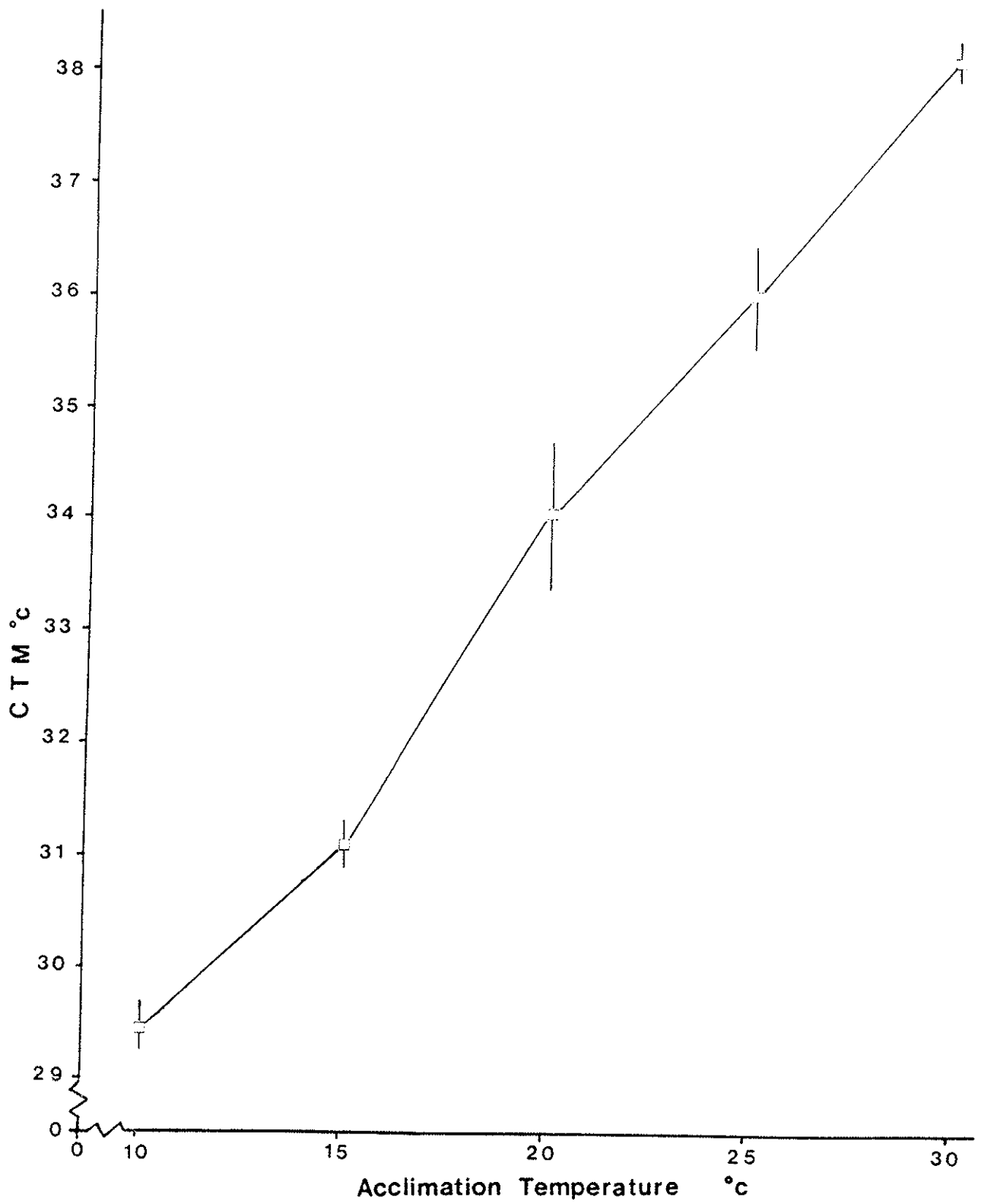


Figure 10. Critical thermal maxima (± 2 S.E.) of hitch at five acclimation temperatures. Means are based on 10 fish at each temperature.