REVIEW OF BULL TROUT TEMPERATURE REQUIREMENTS:

A RESPONSE TO THE EPA BULL TROUT TEMPERATURE RULE

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TABLE OF CONTENTS

INTRODUCTION 2

PHYSIOLOGICAL CONSEQUENCES OF TEMPERATURE 4

TEMPERATURE METRICS 7

Definitions 7

Relationships Among Temperature Metrics 9

Temperature Recording Devices 11

Reliability of Temperature Measurements 12

GUIDELINES FOR ESTABLISHING TEMPERATURE CRITERIA 14

BULL TROUT TEMPERATURE REQUIREMENTS 17

Delphi Technique 18

EPA Criteria Protocol 27

TEMPERATURE EFFECTS ON COMPETITIVE INTERACTIONS 29

CONCLUSIONS 32

LITERATURE CITED 33

TABLES 42

FIGURES 55

INTRODUCTION

Several factors can influence the spatial dynamics of salmonids both zoogeographically and locally, with some stresses acting at large ecoregion scales (e.g., effects of aridity) and others at much smaller scales (e.g., thermal gradients formed where groundwater mixes with surface water). Salmonid distribution in North America and worldwide, however, appears to be strongly linked to temperature (Power 1990). In many freshwater environments, it is the combination of high (or low) water temperatures with reduced oxygen that can be lethal to fish or that can impair reproduction (*sensu* Coutant and Benson 1990).

Bull trout *Salvelinus confluentus* appear to be quite sensitive to temperature change (see reviews in Shepard et al. 1984; Goetz 1989; Fraley and Shepard 1989; Rieman and McIntyre 1993; Buchanan and Gregory 1997). Because bull trout frequently live in cold water streams, many biologists have concluded that bull trout are "cold stenotherms." This means that optimal survival and reproduction of bull trout occurs within a narrow range of cold temperatures. However, as we show below, the evidence is mostly correlative, leaving critical thermal thresholds poorly defined.

In an attempt to protect cold-water refugia for bull trout, the U.S. Environmental Protection Agency (EPA) issued a site-specific temperature rule for those waterbody segments in Idaho where bull trout spawn and juvenile bull trout rear (40 CFR 131.E.1.i.d (1997)). "*This Rule establishes a maximum weekly maximum temperature (MWMT) criterion of 10EC for the months of June, July, August and September for the protection of bull trout spawning and juvenile rearing in natal streams, expressed as an average of daily maximum temperatures over a consecutive 7-day period*." The EPA standard is assumed to protect spawning and juvenile rearing bull trout life stages, which are

considered most critical and most at risk from thermal stress. The EPA established the criterion on temperatures "...*judged to be required for maintaining optimal juvenile growth and rearing, and the initiation of adult spawning*." The EPA acknowledges that juvenile bull trout occur in streams with temperatures higher than 10EC, however, the EPA notes that temperatures approaching 15EC reflect suboptimal rearing and growth.

In this report, we examine the temperature requirements of bull trout. In particular, we examine the validity of the EPA rule as it applies to the temperature requirements of juvenile bull trout. We begin by considering the physiological consequences of temperature to fish. This section is intended to give a general background on the effects of temperature on fish energetics and production. Second, we briefly describe temperature metrics, identify relationships among the various metrics reported in the literature, and examine the reliability of temperature measurements. Third, we review the guidelines available for establishing temperature criteria. Here, we also attempt to understand why the EPA elected not to follow protocol and procedures. Fourth, we examine the temperature requirements of bull trout. At this point we have two goals: (1) examine the information cited by EPA and offer additional information that can be used to establish temperature criteria, and (2) explore the use of the EPA Protocol and Procedures for establishing bull trout temperature criteria. Fifth, we discuss the effects of temperature on competitive interactions. We focus on interactions between bull trout and brook trout *S. fontinalis*. Finally, we offer conclusions based on our examination of the data and literature.

PHYSIOLOGICAL CONSEQUENCES OF TEMPERATURE

In this section we provide a general overview of the physiological effects of temperature on fish, offering a general explanation of why temperature is important to fish. In addition, we provide a brief description of how fish cope with extreme temperatures.

Both biotic and abiotic factors affect fish physiology. Temperature is one of the most important. The effects of temperature on biochemical and physiological processes of fish are well known (see Tytler and Calow 1985; Jobling 1994). These processes drive fish to select environmental temperatures at which they can function efficiently (Coutant 1987). Because different physiological processes (e.g., ingestion and metabolism) may have different optimal temperatures, the temperature selected by fish often represents a compromise, or "integrated optimum." Fish appear to select temperatures that maximize the amount of energy available for activity and growth, or metabolic scope (the difference between standard and maximum metabolic rates) (Fry 1971; Hickman and Raleigh 1982; Jobling 1994). Certainly, habitat selection in the wild involves a compromise between temperature requirements and other important factors, such as food availability and avoidance of predators and competitors (Coutant 1987).

Physiological functions that are affected by temperature include growth, food consumption, metabolism, reproduction, activity, and survival. Typically, growth, food consumption, and activity increase with increasing temperature to some critical temperature, after which the rates rapidly decline. The most sensitive physiological function appears to be growth rate, which is an integrator of all physiological responses (Brungs and Jones 1977). The rate of growth at various temperatures is a function of ingestion and metabolism (Jobling 1994). Under conditions of unlimited food, an increase in temperature will result in an increase in food intake, but at high temperature ingestion rates abruptly decline. Metabolic rate, on the other hand, increases with increasing temperature. The temperature at which the

difference between ingestion rate and metabolic rate is maximum is called the *optimum temperature for growth*. For most salmonids, laboratory studies indicate that the optimum temperature for growth occurs between 10E and 17EC (Table 1). These data are then used to estimate temperature criteria (Maximum Weekly Average Temperature; MWAT) for fish in natural water bodies.

Extreme temperatures (both low and high) can lead to death. Proteins, including the enzymes that catalyze critical biochemical reactions, are temperature sensitive. High temperatures can cause structural degradation (denaturation), resulting in partial or complete loss of function. Death can occur quickly or may be delayed. The temperature at which a fish succumbs to thermal stress depends on the temperature to which it was acclimatized[1] and on its developmental stage (e.g, embryo, fry, juvenile, adult). Fish that experience changing environmental temperatures, however, have cellular and subcellular mechanisms for adapting to the new conditions. Many physiological adjustments result from switching on or off genes that are responsible for the manufacture of particular proteins (Jobling 1994). For example, some salmonids (e.g., brown trout *Salmo trutta*, cutthroat trout *Oncorhynchus clarki*, and chinook salmon *O. tshawytscha*) under heat stress initiate the synthesis of *heat shock proteins* (HSPs) (Fader et al. 1994). These reconfigure proteins that become denatured at higher temperatures, thereby allowing them to function biochemically. In addition, fish may produce alternate enzymes or *isozymes* to catalyze the same reaction more efficiently at different temperatures (Jobling 1994).

High water temperatures can increase the susceptibility of fish to disease. Holt et al. (1975) investigated the effect of water temperature on mortality from experimental infection by *Flexibacter columnaris* and on mean time to death in juvenile steelhead trout *O.*

[1]Acclimatization refers to adjustments made under natural environmental conditions, including seasonal changes in temperature, photoperiod, and associated hormones.

mykiss, coho salmon *O. kisutch*, and chinook salmon. With all three species, they found an inverse linear relationship between water temperature and the $\log_{10}$ of the mean number of days from exposure to death. In other words, as the temperature increased above 12.2EC, the disease process progressively accelerated, resulting in a minimum time to death at 20.5 or 23.3EC and a maximum at 12.2EC. Hillman (1991) opined that temperature may have modified interactions between chinook salmon and redside shiners *Richardsonius balteatus* in laboratory channels by increasing their susceptibility to disease. He found that most migrants and a small fraction of resident chinook with shiners in warm water (18-21EC) were infected with *F. columnaris*; the disease infected more sympatric shiners in cold water (12-15EC) than shiners alone or shiners with chinook in warm water. In a similar study, Reeves et al. (1987) reported that most steelhead that migrated from lab channels were infected with *F. columnaris* in warm water (19-22EC), and more than half of the migrant redside shiners were infected in cold water (12-15EC). Preliminary lab studies at Montana State University suggest that juvenile bull trout held at constant temperatures greater than 16EC for extended periods (60 days) show signs of disease (T. McMahon, personal communication). Later we examine the possible effects of temperature on bull trout and brook trout interactions.

In summary, temperature is important to fish because it affects their biochemical and physiological processes, which affect growth, behavior, reproduction, distribution, and ultimately survival. Growth rate appears to be the most sensitive physiological function and is an integrator of all physiological responses. If given a choice, fish will select temperatures near their optimal growth temperature(s). Because physiological optima are affected by and interact with acclimation[2] temperatures, temperature optima often are a “zone of efficient operation,” rather than a single temperature value (Crawshaw 1977).

[2]Acclimation refers to the process of physiological adjustment, typically to a single parameter such as temperature, under artificial conditions.

Thus, fish tend to have a range of optimal temperatures rather than a single optimum (Table 1). This is one reason why no single temperature requirement can be applied uniformly to large regional areas (Brungs and Jones 1977). Because bull trout occur over a large regional area consisting of a wide variety of geo-climatic regimes, elevations, and latitudes, a single temperature criterion for bull trout in Idaho is inconsistent with our understanding of fish physiology.

TEMPERATURE METRICS

Water temperatures can be measured in many different ways. In addition, temperature data are compiled, analyzed, and reported differently by different researchers. Researchers and managers are often tempted to use these data in incorrect ways. Indeed, many causal-relationships have been advanced from temperature data that were not collected for that purpose. Our intent in this section is to define the most commonly-used temperature metrics, examine relationships among the various temperature metrics, describe how temperatures are often recorded, and explore the reliability of temperature measurements.

Definitions

Below we define the most commonly used temperature metrics. Metrics that describe average temperature conditions may be based on two or more instantaneous measurements. Clearly, the greater the number of instantaneous measurements, the more valid the mean or average measurement.

> **Instantaneous or Snap-Shot Temperatures**--These are water temperatures recorded at a specific point in time.

Daily Average Temperature--This is the mean water temperature for a given 24-hour period.

Daily Maximum Temperature--This is the highest water temperature recorded during a given 24-hour period.

Daily Minimum Temperature--This is the lowest water temperature recorded during a given 24-hour period.

Maximum Daily Average Temperature (MDAT)--This is the warmest daily average water temperature recorded during a given year or survey period.

Maximum Daily Maximum Temperature (MDMT)--This is the warmest daily maximum water temperature recorded during a given year or survey period.

Maximum Weekly Average Temperature (MWAT)--This is the mean of daily average water temperatures measured over the warmest consecutive seven-day period (typically during a given year).

Maximum Weekly Maximum Temperature (MWMT)--This is the mean of daily maximum water temperatures measured over the warmest consecutive seven-day period (typically during a given year).

Monthly Mean Temperature--This is the average water temperature recorded during a given month.

Annual Temperature Unit--Sum of daily temperature units for a given year. One daily temperature unit is equal to one degree above freezing for a 24-hour period.

As an example, we provide thermographs from Smithie Fork, a tributary of the Little Lost River, in Figures 1 and 2. Gamett (1998) indicates that Smithie Fork is the most productive bull trout stream in the Little Lost River Basin. Figure 1 shows the raw temperature data (10 readings per day) for the period June through October, 1997. Figure 2 shows daily maxima and daily means for the same site during the same period. We used these data to calculate MDMT, MWMT, MDAT, MWAT, and monthly means. These data show that the MDMT of 15.5EC occurred on 21 July, while the MDAT of 11.4EC occurred on 23 July. The MWMT of 14.6EC occurred during the week of 26 August, while the MWAT of 10.8EC occurred one month earlier.

Relationships Among Temperature Metrics

We examined the relationships among various temperature metrics by compiling 225 temperature records from 73 streams in Montana and Idaho. Data were collected by Plum Creek Timber Company, Potlatch Corporation, and the Idaho Division of Environmental Quality. Approximately 70 of the 225 records were at sites that supported bull trout. Onset temperature loggers recorded water temperatures at fixed intervals (30 to 144-minute intervals) during the summers of 1994 to 1997. For each site, we calculated the maximum daily maximum temperature, maximum daily average temperature, MWMT, MWAT, mean July temperature, and mean August temperature. For each metric, we calculated the mean, standard deviation, maximum, and minimum values. We then used scatter plots and a Pearson correlation matrix to assess relationships among temperature metrics. Finally, we used simple linear regression to describe the relationships among the temperature metrics. It is not necessarily our intention to use regression to establish cause-and-effect relationships, but rather to describe linear relationships between related variables.

Daily maximum temperatures were on average 1E to 5EC warmer and more variable than other temperature metrics (Table 2). Mean July and August temperatures were consistently colder and less variable than mean values of the other metrics. The average difference between maximum daily maximum and maximum daily average temperature was about 3EC. Similarly, the mean difference between MWMT and MWAT was about 3EC. On average, there was only about a 1EC difference between maximum daily maximum temperature and MWMT, while there was less than a 1EC difference between maximum daily average temperature and MWAT.

Not surprising, we found significant relationships among all combinations of temperature metrics. Pearson correlation coefficients consistently exceeded 0.89 for all possible combinations of temperature metrics (Table 3). In addition, all relationships were linear. Simple linear regression models explained 80 to 99% of the variation between independent and dependent temperature metrics (Table 4; Figures 3-7). For example, the linear model, MWMT = 1.15(MWAT) + 0.41, explained 90% of the variation between MWMT and MWAT (Figure 7). These models indicate that a 10EC MWMT corresponds to a 10.6EC maximum daily maximum, 9.3EC maximum daily average, 8.0EC mean July temperature, 7.9EC mean August temperature, and 8.7EC MWAT.

These relationships comport with those in the literature. For example, the ODEQ (1995) notes that in Oregon streams, maximum water temperatures are typically recorded in July or August when incoming solar radiation levels are high, air temperatures are high, days are long, and stream flows are low. The ODEQ notes that MWMT will nearly always be slightly lower than the single warmest daily maximum temperature. They report, as an example, that the MWMT is 1.5EC lower than the daily maximum temperature for the warmest single day on the Grande Ronde River. This is close to the 0.8EC mean difference we found between these two metrics in 73 streams in Montana and Idaho (Table 2).

Temperature Recording Devices

Water temperatures in bull trout streams have been measured with a number of different recording devices. For example, Heimer (1965), Pratt (1984), and Bonneau and Scarnecchia (1996) used hand-held thermometers to record water temperatures in bull trout streams. Graham et al. (1980), Fraley et al. (1981), Adams (1994), and Saffel and Scarnecchia (1995) used maximum-minimum thermometers to measure water temperatures, while Graham et al. (1980), Fraley et al. (1981), Martin et al. (1992), Ziller (1992), Riehle (1993), Adams (1994), Saffel and Scarnecchia (1995), Weaver and White (1985), Thurow and Schill (1996), Parkinson and Haas (1996), and Swanberg (1996) used electronic thermographs to monitor temperatures in bull trout streams. Electronic thermographs consisted of Omnidata recorders (Riehle 1993; Adams 1994), Ryan Tempmentors (Ziller 1992; Riehle 1993; Adams 1994; Saffel and Scarnecchia 1995), Onset loggers (Adams 1994; Parkinson and Haas 1996; Swanberg 1996), and Foxboro loggers (Weaver and White 1985).

Researchers often use hand-held temperature recorders to measure water temperatures during fish or stream habitat surveys. For example, it appears that Pratt (1984) and Thurow (1987) recorded instantaneous water temperatures with hand-held recorders during their fish surveys. Because the accuracy of snorkel counts can be influenced by water temperature (Hillman et al. 1992), observers frequently record instantaneous water temperatures with hand-held recorders before conducting snorkel surveys. As indicated by the name, maximum-minimum thermometers record the highest and lowest water temperatures during a given period. The length of the sample period varies with the frequency with which an observer reads the thermometers. For example, Saffel and Scarnecchia (1995) read their maximum-minimum thermometers every two weeks, while it appears that Adams (1994) read hers daily.

Electronic thermographs can be programmed to record temperatures at various intervals throughout a survey period. Adams (1994) programmed her thermographs to record temperatures every 48 or 60 minutes. Thermographs used by Swanberg (1996), Thurow and Schill (1996), and Parkinson and Haas (1996) recorded temperatures hourly. Most researchers do not report the frequency with which thermographs record water temperatures. Furthermore, the temperature recorded for some electronic thermographs may be an instantaneous value or the maximum, mean, or minimum over the recording period. For example, StowAway loggers can be programmed to make multiple measurements during an interval. The data can be stored as the minimum, maximum, or mean of the readings. Most researchers do not report how they programmed their loggers.

Reliability of Temperature Measurements

How, where, and when stream temperatures are measured can greatly affect the reliability of the measurements. Klamt (1998) warns that temperature data are of limited use if the sampling objectives, sampling design, and data quality procedures are not stated clearly. He notes that analyzed temperature data are usually presented without the actual raw data and conditions under which they were collected. In these cases, there is no way to determine the utility of the information nor to compare it to other data. Thus, the sampling design determines the limitations of the data set. For example, instantaneous water temperatures measured with hand-held recorders for the purpose of conducting electrofishing or snorkel surveys are not reliable indicators of thermal tolerances of juvenile bull trout. In addition, if the researcher does not report the time when the instantaneous measurements are recorded, then one cannot determine if the measurement represents a minimum, maximum, or mean condition.

Although the EPA offered no protocol in the Rules and Regulations for measuring water temperature, we should guess that electronic thermographs would be appropriate. Regardless, the instrument selected should be reliable (accuracy and precision with which the instrument consistently measures temperature) and valid (degree to which the instrument measures what it is supposed to measure). The error (reliability) associated with electronic thermographs can be quite large. For example, Ozaki (1998) found that during calibration tests, thermographs (HOBOs and Optic StowAways) at any one time differed in temperature by about two degrees. Idaho DEQ found that Optic StowAway loggers differed by as much as 1EC during calibration tests. Ozaki (1998) also noted that there was a significant difference in mean temperatures recorded by data loggers and also in mean temperatures within individual types of loggers. She notes that the error introduced from electronic thermographs needs to be considered when comparing temperature data.

The spatial locations at which temperature monitoring occur can influence the reliability of the data. Often, temperature recording devices are placed near the margins of streams where placement is safer and retrieval more certain, even though stream margins are known to be warmer than the thalweg (Moore 1967; Bilby 1984). McIntosh et al. (1998) used Forward-Looking Infrared (FLIR) to map instantaneous stream temperatures and found that stream temperatures can vary significantly across spatial scales (from microhabitats to longitudinal profiles to watersheds). Patches of warm and cool water were readily delineated and in some cases these were related to known point sources, while at other times point sources were not apparent. Their work indicates that stream temperatures are quite variable even at the microhabitat scale, and, therefore, temperature measurements made with a few randomly placed sensors will likely give very different results. Ozaki (1998) believes that temperature probes placed longitudinally and cross-sectionally are needed to accurately determine water temperatures of streams.

We believe the reliability of temperature measurements should not be dismissed cavalierly when examining the temperature requirements of bull trout. One must carefully consider why, how, and where the data were collected, how the data were analyzed, and what temperature metric is being reported. As we indicated above, temperature metrics are not equivalent (e.g., MWMT…maximum daily maximum), measuring instruments have errors, and stream temperatures are quite variable spatially. These factors should influence the way one uses temperature data.

GUIDELINES FOR ESTABLISHING TEMPERATURE CRITERIA

Before we examine temperature requirements of bull trout, it is important to review methodology that can be used to establish temperature criteria for fish. The EPA (Brungs and Jones 1977) has published guidelines for establishing temperature criteria for freshwater fish. The EPA protocol recommends expression of temperature criteria in two forms: (1) a mean temperature value expressed as maximum weekly average temperature (MWAT) and (2) a short-term exposure to extreme temperature. The former is used to protect functions such as embryogenesis, growth, maturation, and reproduction, while the latter provides protection for all life stages against lethal conditions (usually for a duration of 24 hours). We did not find where Brungs and Jones (1977) discussed the use of a 7-day average maximum temperature (MWMT).

The short-term exposure to extreme temperature criteria is based on the fact that fish can withstand short exposure to temperatures higher than those acceptable for reproduction and growth without significant adverse effects. These exposures should not be too lengthy or frequent. According to Brungs and Jones (1977), the length of time that 50% of a population will survive temperatures above the incipient lethal temperature can be calculated from the following regression:

$$\log \text{time (min)} = a + b\,(\text{temp EC})$$

The constants “a” and “b” are the intercept and slope of the regression. Because this equation is based on 50% survival, Brungs and Jones (1977) recommend a 2.0EC reduction in the upper incipient lethal temperature[3] to assure no deaths.

The mean temperature criterion (MWAT) is designed to protect critical life stage functions. Brungs and Jones (1977) describe procedures for calculating MWAT for growth, reproduction, and winter survival. We limit our discussion to procedures for calculating MWAT for growth. Brungs and Jones (1977) state that, “[t]*o maintain growth of aquatic organisms at rates necessary for sustaining actively growing and reproducing populations, the MWAT in the zone normally inhabited by the species at the season should not exceed the optimum temperature*[4] (OT) *plus one-third of the range between the optimum temperature and the ultimate upper incipient lethal temperature*[5] (UUILT) *of the species*.”

$$\text{MWAT for growth} = \text{OT} + (1/3)\,(\text{UUILT} - \text{OT})$$

This calculation is based on the fact that (1) habitat use by fish is limited within the thermal tolerance range somewhat below the ultimate upper incipient lethal temperature and (2)

[3]Upper incipient lethal temperatures are those temperatures at which 50% of the individuals survive indefinitely after acclimation at some other temperature.

[4]Optimum Temperature (OT) is a physiological optimum and can be based on performance, metabolic rate, temperature preference, growth, natural distribution, or tolerance. However, according to Brungs and Jones (1977), the most sensitive function seems to be growth rate, which appears to be an integrator of all physiological responses of an organism.

[5]Ultimate upper incipient lethal temperature (UUILT) represents the “breaking point” between the highest temperatures to which an animal can be acclimated and the lowest of the extreme upper temperatures that will kill the warm-acclimated organism.

that optimum temperatures, such as those producing fastest growth rates, are not necessary at all times to maintain thriving populations (Brungs and Jones 1977). Thus, a true temperature limit for exposures long enough to reflect metabolic acclimation and optimum ecological performance lies between the physiological optimum and the ultimate upper incipient lethal temperature (Brungs and Jones 1977). Research (reviewed in Brungs and Jones 1977) indicates that an average of the optimum temperature and the temperature of zero net growth would be a useful estimate of a limiting weekly mean temperature for resident fish, provided the peak temperatures do not exceed values recommended for short-term exposure. According to Brungs and Jones (1977), a temperature that is one-third of the range between the optimum temperature and the ultimate incipient lethal temperature yields values that are very close to an average of the optimum temperature and the temperature of zero net growth. The EPA method for calculating MWAT for growth offers a practical approach for obtaining allowable limits, while retaining as its scientific basis the requirements of preserving adequate rates of growth. As Brungs and Jones (1977) state, "[t]*he criteria may seem complex, but they represent an extensively developed framework of knowledge about biological responses*."

The EPA did not follow these guidelines for establishing temperature criteria for bull trout spawning and juvenile rearing habitat in Idaho. Although the EPA originally proposed a standard based on the guidelines described above, the final criterion was modified apparently because of comments from reviewers (40 CFR 131.E.1.i.c (1997)). The final temperature criterion adopted by the EPA was based on MWMT, not MWAT. MWMT is expressed as an average of daily maximum temperatures over a consecutive 7-day period. The EPA selected MWMT over MWAT for several reasons. First, greater diurnal fluctuations around the mean daily temperature can be one effect of intensive watershed management (e.g., loss of riparian vegetation). Second, the available literature is insufficient to derive temperature criteria to be protective of short-term temperature extremes (e.g., daily maxima). Finally, MWMT is consistent with certain other temperature

criteria that have been established or recommended to protect bull trout (ODEQ 1995; USFS INFISH).

Given that the EPA elected not to use the protocol and procedures in Brungs and Jones (1977), it therefore appears to us that the EPA used a subjective "Delphi technique" to establish temperature criteria for bull trout. That is, they reviewed available information (most of which was not collected for the purpose of establishing temperature criteria) and inferred causal-relationships between water temperature and bull trout "health." However, the EPA acknowledges that information on relative health of bull trout populations is lacking. Thus, the EPA established temperature criteria based on temperatures they judged to be optimal for maintaining juvenile growth and rearing, and to initiate adult spawning. In the next section we will review the information that the EPA cited in the CFR and show that alternate conclusions can be drawn from the same information. In addition, we will examine information that the EPA did not have or elected not to use. Finally, using the information available to us, we will calculate temperature criteria with the EPA's temperature criteria guidance (Brungs and Jones 1977).

BULL TROUT TEMPERATURE REQUIREMENTS

In this section we calculate juvenile bull trout temperature criteria using two methods. We refer to the first as the "Delphi Technique." Under this technique we examine pertinent literature available to us for relationships between population "health" and temperature. We focus first on some of the literature cited by the EPA in the CFR and then examine other information that may reveal relationships between bull trout and temperature. Under the second method we use the EPA's temperature criteria guidance (Brungs and Jones 1977) to estimate juvenile bull trout temperature criteria.

Although the EPA temperature criterion of 10EC for the months of June through September is intended to protect both juvenile rearing and spawning conditions, we focus our discussion on juvenile rearing. We agree with the EPA that juvenile bull trout are more sensitive to temperature changes than other life stages. We also believe that water temperature is important in initiating adult spawning. However, given that bull trout spawn in the autumn during the declining thermograph, and they tend to select groundwater upwelling zones, which moderate temperatures (Heimer 1965; McPhail and Murray 1979; Fraley and Shepard 1989; Riehle 1993; WWP 1995), an appropriate temperature criterion for juvenile rearing during summer should also adequately protect autumn spawning conditions. Thus, we question the need for a temperature criterion for spawning.

Delphi Technique

As part of the Delphi method, it is important to consider the purpose of each study and the reliability of the temperature measurements. Although we appear critical of some of the work conducted by researchers, our criticism is not of their work per se, but rather how causal-inferences have been drawn from their work. As we noted above, most of these researchers did not work with the idea of developing temperature criteria for bull trout. Thus, as we will demonstrate, inferences other than those of the EPA can be drawn from the same information.

The EPA (40 CFR 131.E.1 (1997)) indicates that temperatures less than 12EC appear to be most suitable for juvenile bull trout rearing, with optimal growth and rearing ranging from 4E to 10EC. The EPA report notes that 12EC appears to be a maximum temperature where juveniles are found in Idaho streams. These observations are based largely on studies by Shepard et al. (1984), Pratt (1984; 1985), Carl (1985), Thurow (1987), Fraley and Shepard (1989), Dambacher et al. (1992), Adams (1994), Saffel and Scarnecchia (1995), Bonneau and Scarnecchia (1996), and Thurow and Schill (1996). Articles by

Shepard et al. (1984), Carl (1985), Pratt (1985), and Fraley and Shepard (1989) are reviews of other studies and offer no “new” temperature data.

As cited by EPA, Saffel and Scarnecchia (1995) observed that the density of juvenile bull trout was negatively related with the maximum summer temperature (MDMT) in six tributaries of Lake Pend Oreille. Using simple linear regression, Saffel and Scarnecchia (1995) found the negative relationship to be significant (P = 0.01), but temperature explained only 33% of the variation in density. However, the data in Saffel and Scarnecchia (1995) do not lend themselves to analysis with simple linear regression. Indeed, the relationship between temperature and density is not linear and the variance of density is not constant for all temperature values (Figure 8). Saffel and Scarnecchia (1995) acknowledge that their data indicate that a non-linear, dome-shaped curve more accurately explains the relationship between temperature and juvenile density. This means that juvenile densities increase (not decrease) as temperatures increase from 7.8E to 13.9EC. At temperatures greater than 14EC, densities appear to decrease. However, because there are no density data between 14E and 18EC, one cannot determine from these data where the relationship changes from positive to negative. Given a dome-shaped relationship, we are not surprised that there was virtually no difference in bull trout densities between a site with a maximum temperature of 7.8EC (0.23 bull trout/100 m^2) and one with 20.0EC (0.30 bull trout/100 m^2). The highest densities of juveniles (>11 bull trout/100 m^2) occurred in sites with maximum summer temperatures between 11E and 14EC.

Farther south in the Weiser River drainage, Adams (1994) assessed the effects of water temperature on bull trout distribution. She found juvenile bull trout in sites with water temperatures much greater than 10EC. For example, in Anderson Creek in 1992, weekly temperatures during late May through October ranged from 2.5E to 19.5EC. Only bull trout occurred in this area, with densities from 5.7 to 9.5 fish/100 m^2. In upper Sheep Creek

during the same period, Adams (1994) recorded maximum temperatures of 20.5EC on several occasions. Maximum weekly temperature was 17.5EC. Densities of bull trout in this area ranged from 3.9 to 5.1 fish/100 m^2. She reported seeing age-0 bull trout in this area. In 1993 in this same area, Adams (1994) found age-0, juvenile, and adult bull trout in water temperatures of 20.5EC. In Dewey Creek, weekly temperatures ranged from 0.5E to 15.0EC and bull trout numbered 0.01 to 3.4 fish/100 m^2.

The EPA cites Thurow (1987) as having found higher densities of juvenile bull trout in the headwater (colder) stream reaches of the South Fork Salmon River, Idaho. In his appendices, Thurow (1987) documents numbers of bull trout observed (snorkeling) and captured (electrofishing) in sampling sites and instantaneous water temperatures recorded at most sites. Inasmuch as these temperatures were recorded as “snap-shots” during the fish surveys, they probably do not represent the true minimum, mean, or maximum temperatures within the sites. We reproduced his data in our Table 5. His data show that during August 1984 and 1985 surveys in the South Fork Salmon River, bull trout occupied stations with water temperatures that ranged from 8.5E to 15.0EC (80% of the sites with bull trout and temperature measurements had maximum recorded temperatures between 12E and 15EC). In tributaries of the South Fork during July and August 1984 and 1985, bull trout occurred in sites with temperatures that ranged from 8.5E to 19.5EC (60% of the sites with bull trout had maximum recorded temperatures between 12E and 15EC; 11% had maximum recorded temperatures between 16.0E and 19.5EC). The site with the greatest number of bull trout had a maximum recorded water temperature of 19.5EC. These data indicate that bull trout occur in sites with temperatures ranging from at least 8.5E to 19.5EC.

Thurow and Schill (1996) examined the effects of water temperature on the accuracy of snorkel counts in the lower 5 km of Profile Creek, a second-order tributary to the East Fork of the South Fork Salmon River. Their data indicate that roughly 1.9 to 11.6 bull trout/100 m^2 (assuming a mean area per site of 714 m^2) lived in Profile Creek at temperatures of 9E

to 13.5EC (densities include age-0 and 1+ bull trout). They note that, except for site 6, there was no relationship between counts of bull trout and water temperatures. In site 6, however, they found that counts of bull trout increased significantly as temperatures increased from 11E to 13.2EC. Of the sites surveyed, site 6 had the greatest number of bull trout. This observation comports with that of Parkinson and Haas (1996), who found that catch per unit of electrofishing effort for bull trout increased with increasing mean stream temperatures. The data of Thurow (1987), Adams (1994), Saffel and Scarnecchia (1995), and Thurow and Schill (1996) do not support EPA's statement that "...*12EC also appears to be a maximum temperature where juveniles are found*."

Bonneau and Scarnecchia (1996) offer a study on the nighttime distribution of juvenile bull trout in a thermal gradient of a plunge pool in Granite Creek, a tributary of Lake Pend Oreille. For three nights, Bonneau and Scarnecchia (1996) noted the distribution of the same five or six bull trout in a large plunge pool. They found that the bull trout consistently occupied the coldest water available in the pool (8-9EC), even though this temperature category made up only 24% of the pool area. The authors also noted that the distribution of juvenile bull trout was not closely associated with a particular water depth or substrate composition. However, our examination of their data (as reported in their Figures 1, 2, and 3) indicates that bull trout were consistently located on the side of the pool with the largest substrates (cobbles, boulders, and some gravels). Given that juvenile bull trout occupy stations offering visual isolation (large clean substrates or woody debris) (Pratt 1984; Baxter and McPhail 1997), it is not surprising that the authors found bull trout where this form of cover was available. Thus, it is not apparent whether the positions occupied by juvenile bull trout at night were related to temperature, substrate composition, or some other factor or combination of factors. In addition, it appears that this work suffers from pseudoreplication (they observed the same 5 or 6 fish during three nights in the same pool).

The EPA also reviewed studies from areas outside Idaho. For example, EPA notes that Pratt (1984) observed only juvenile bull trout in habitats with temperatures of 5E to 12EC influenced by cold springs (5EC) in the upper Flathead River basin. However, Pratt (1984) indicated that bull trout occurred within sites with temperatures of 5E to 15EC. Only in one study stream did only bull trout occur in habitat units influenced by a cold spring. Furthermore, it appears that Pratt (1984) recorded instantaneous temperatures during the time of snorkel and habitat surveys. Therefore, it is unlikely that the temperature range of 5E to 15EC represents the absolute minimum and maximum temperatures for the survey sites. These data do indicate that juvenile bull trout occur in sites with temperatures of at least 15EC. Although she presented no temperature data, Pratt (1985) indicated that juvenile bull trout live in streams in the Pend Oreille system that have warmer temperatures than those in the upper Flathead system, possibly reflecting geo-climatic differences.

Graham et al. (1980) and Fraley et al. (1981) examined the population dynamics of bull trout and habitat in the North Fork and Middle Fork of the Flathead River. We summarize some of their data in Tables 6 and 7. In the Flathead system, as elsewhere, maximum water temperatures occurred during July or August. During all years of the surveys, streams supporting bull trout had monthly averages of daily maximum temperatures that exceeded 11EC during July and August. Daily maximum temperatures in bull trout streams ranged from 14.4E to 18.9EC. Coal Creek, which had the highest fry density (2.0 fish/100 m^2), had daily maximum temperatures that exceeded 15EC and monthly averages of daily maximum temperatures that exceeded 12.5EC during 1977 through 1979. In 1980, Trail Creek had the highest density of bull trout fry (1.6 fish/100 m^2) and a daily maximum temperature of 16.1EC. Within Coal Creek during 1982 to 1984, Weaver and White (1985) monitored stream temperatures and bull trout numbers in three sites. During all years in all three sites, maximum weekly maximum water temperatures (MWMT) exceeded 12.5EC. The highest MWMT was 16.1EC. Bull trout densities in these sites ranged from 1.3 to 5.9 fish/100 m^2, however, the highest densities occurred in a site with MWMTs that ranged from 12.6-12.8EC.

Martin et al. (1992) examined species interactions in four southeast Washington streams. As part of their study they monitored daily maximum water temperatures and bull trout numbers in several randomly selected sites. In the Tucannon River, daily maximum temperatures approached 19EC. Martin et al. (1992) report that several juvenile bull trout were observed and captured downstream from the temperature station on the Tucannon River. They also report that age-0 bull trout were captured in sites with temperatures of 13.0EC; juveniles were captured in sites with temperatures of 16.0EC. Mean densities of age-0 and juvenile bull trout in the Tucannon River were 3.9 and 1.5 fish/100 m^2, respectively. In Asotin Creek, Martin et al. (1992) found 284 juvenile bull trout (0.4 fish/100 m^2) in water with temperatures of 16.0EC. Daily maximum temperatures in Mill Creek reached 13.0EC and age-0 and juvenile bull trout numbered 6.0 and 7.4 fish/100 m^2, respectively.

Our read of the above studies suggests that juvenile bull trout occur within a relatively wide range of water temperatures, but the optimum temperature for juvenile rearing is still unclear. These studies do indicate that juvenile bull trout occur frequently in Idaho streams with temperatures greater than 10EC. In fact, juvenile bull trout have been observed on several occasions in stream reaches with temperatures approaching 20.5EC (Adams 1994). The work by Saffel and Scarnecchia (1995) seems to indicate that the optimum rearing temperature lies closer to 13EC. The EPA (40 CFR 131.E.1 (1997)) acknowledges that "...*juvenile bull trout can be found in streams with temperatures reported to be higher than 10EC, but that available information suggests that temperatures approaching 15EC reflect suboptimal conditions for juvenile rearing and growth and that optimal conditions are closer to 10EC*." They state further that, "*...there are streams where bull trout are present at higher temperatures than those adopted under this rule but in most cases, information was not available to determine the relative health of these populations*." We searched for information on relationships between water temperatures and bull trout "health." Below we offer our findings.

Plum Creek Timber Company has compiled stream temperature data from 70 sites in 33 streams supporting bull trout on their lands in Montana and Idaho. Onset temperature loggers recorded water temperatures at 30-minute intervals (records the average temperature within the 30-minute interval) during the summers of 1994 to 1997. The maximum daily maximum temperature, maximum daily average temperature, MWMT, MWAT, mean July temperature, and mean August temperature were calculated for each site. For each temperature metric, we calculated the mean, standard deviation, maximum, and minimum values (Table 8). These data indicate that for all metrics, save monthly means, mean temperatures among 33 bull trout streams exceeded 10EC. Furthermore, maximum values exceeded 15EC. The mean MWMT for the 33 bull trout streams was 12.4EC. The maximum MWMT was 18.7EC.

Plum Creek Timber Company also estimated juvenile bull trout densities at or near 42 of the 70 temperature sites. We plotted those data to look for relationships between density and MWAT and MWMT (Figure 9). The scatter plots reveal no obvious positive or negative linear relationships between densities of juvenile bull trout and maximum water temperatures. However, the plots do suggest a dome-shaped relationship. The highest densities occurred at MWMTs between 9E and 16EC (the density of 30.2 fish/100 m^2 was observed in Squeezer Creek, Swan River Basin, at a MWMT of 12.2EC). These observations comport with those of Saffel and Scarnecchia (1995), who found the highest juvenile densities (>11 bull trout/100 m^2) in sites with daily maximum temperatures between 11E and 14EC (roughly equates to a MWMT between 10E and 13EC).

Currently, the EPA and the Forest Service are developing a regional database of temperature records. As part of this record the agencies are compiling data on the presence and absence of juvenile or small bull trout and water temperatures. Although a final report on this work has not been released, preliminary draft results were presented at

the 1998 *Salvelinus confluentus* Curiosity Society meeting. We show some of those results in Figure 10. The histograms in Figure 10 describe the frequency distribution of MWAT, maximum summer temperature, and MWMT for the period July 15 to August 31 in sites with and without juvenile or small bull trout. These data indicate that juvenile or small bull trout occur frequently in sites with MWMTs between 10E and 14EC, but that the highest frequencies occurred at 13E to 14EC (MWMT). Interestingly, juvenile bull trout were observed in at least one site with a MWMT of 25EC (Figure 10). As we discussed earlier, such outliers may reflect an unreliable temperature measurement. The draft information in Figure 10 comports with the work of Saffel and Scarnecchia (1995) and Plum Creek Timber Company.

The Idaho DEQ has compiled temperature and fish information from streams in the Little Lost River Basin, Idaho. Gamett (1998) collected the fish data; the Mackay Ranger District, Challis National Forest, provided the temperature data. We summarize those data in Table 9. Within the Little Lost River Basin, juvenile bull trout occurred within streams that consistently exceeded a MWMT of 10EC (Table 9). In fact, age-0 (YOY) bull trout were observed in sites with MWMTs that ranged from 12.1E to 15.5EC. These data also indicate that the largest number of age (size) classes occurred in sites with MWMTs of 12.1E to 15.1EC. Five age classes were found in Smithie Fork, which had a MWMT of 14.6EC. Importantly, Gamett (1998) notes that Smithie Fork is the most important spawning and rearing stream in the basin. His work shows that bull trout densities ranged from 19.5 to 30.3 bull trout/100 m^2 in Smithie Fork. Gamett (1998) also reports finding bull trout in a site with a daily maximum water temperature of 24EC. These data indicate that the highest densities and largest number of age classes of bull trout in the Little Lost River Basin occur in streams with MWMTs of 12E to 15EC. This is consistent with the work discussed above.

We believe some very useful information on relationships between bull trout “health” and temperature comes from the Methow River basin, Washington. Mullan et al. (1992) collected temperature (and developed temperature models) and fish population data from 23 sites throughout the Methow River basin. Mullan et al. (1992) used a fish toxicant to sample fish populations, which means that their population surveys are probably more reliable than surveys based on electrofishing, snorkeling, and angling. As part of the population surveys, Mullan et al. (1992) recorded lengths, weights, and ages (based on reading scales and otoliths) of trout captured. For each sampling site, Mullan et al. (1992) calculated annual temperature units, maximum monthly mean temperatures, and peak weekly mean temperatures (same as MWAT). Using their data (from Table 2, Appendix I and Table 4, Appendix K in Mullan et al. 1992), we examined the relationships between water temperature and bull trout size (length and weight) for each age class.

The data in Mullan et al. (1992) indicate that for each age class (ages 1 through 5), average bull trout length and weight increase as temperatures increase (Figures 11-15). For example, the largest age-1 bull trout were found in the warmest water sampled (peak weekly mean of 14EC, which is roughly equivalent to a MWMT of 16.5EC). For all five age groups, average size (growth) was greatest at peak weekly mean temperatures greater than 10EC (MWMT of about 12EC). Not only did Mullan et al. (1992) find that bull trout grew slower in the coldest water sampled, but that bull trout in the coldest water also matured at a late age. For example, Mullan et al. (1992) found that maiden spawning occurred at age 9 for fish in the coldest streams.

The information above indicates that juvenile bull trout can be found within a wide range of temperatures during the summer (MWMT of 4E to 25EC, although we question the occurrence of juvenile bull trout at MWMTs greater than 20EC, given the preliminary results of laboratory work at Montana State University (see discussion below)). Our review indicates that juvenile or small bull trout are frequently found in sites with MWMTs of 13E

and 14EC, they are typically more abundant at MWMTs between 12E and 14EC, and they grow faster at these warmer temperatures. Therefore, based on the delphi technique, we believe that the EPA temperature criterion of 10EC MWMT is too conservative. It appears that the optimum temperature for juvenile bull trout rearing during summer is near 12E to 14EC MWMT. However, Brungs and Jones (1977) indicate that optimum temperatures are not necessary at all times to maintain thriving populations. Thus, a standard greater than 12E to 14EC MWMT is appropriate as cooler temperatures will prevail most of the time because of normal seasonal cycles.

EPA Criteria Protocol

We believe we have enough information to apply the methods of Brungs and Jones (1977) to estimate a not-to-exceed MWAT for growth of juvenile bull trout. In this exercise we calculate MWAT for growth using a range of optimum temperatures (OT) for growth and ultimate upper incipient lethal temperatures (UUILT). Based on the results of the Delphi Technique, we believe OT for growth of juvenile bull trout ranges from 12E to 14EC. Ultimate upper incipient lethal temperatures are more difficult to estimate. Preliminary laboratory work at Montana State University suggests that juvenile bull trout can live for extended periods (60 days) at constant temperatures up to 20EC, but not for extended periods at constant temperatures greater than 20EC (T. McMahon, personal communication). Field work also indicates that juvenile bull trout occur at temperatures of 20-20.5EC. Although 20EC clearly does not represent the UUILT, we will use it as a very conservative estimate. We will also use 21E and 22EC to capture a range of possible UUILTs.

Following the EPA protocol, we conservatively estimate that the MWAT for growth of juvenile bull trout ranges from 14.7E to 16.7EC (Table 10). The estimate of 14.7EC assumes a very conservative set of conditions (i.e., OT=12EC and UUILT=20EC). By comparison, the estimates of MWAT in Table 10 are less than those reported for other

salmonids (Table 1). Again, we believe this demonstrates that an MWMT standard for juvenile bull trout of 10EC is too conservative.

One of the reasons the EPA elected not to use MWAT is because there was insufficient information available to derive temperature criteria to be protective of short-term temperature extremes (i.e., protection of juveniles against lethal temperatures during a 24-hour period). According to Brungs and Jones (1977), this criteria should be set 2.0EC below the upper incipient lethal temperature to assure no deaths. However, the EPA had no knowledge of the upper incipient lethal temperature of juvenile bull trout. Given the information described above and the preliminary laboratory results, it is clear that juvenile bull trout can survive temperatures up to at least 20EC. The upper incipient lethal temperature for juvenile bull trout must therefore be greater than 20EC. However, a very conservative short-term, maximum temperature criteria of 20E to 21EC would certainly protect juvenile bull trout from significant adverse effects. That is, based on our understanding of the temperature requirements of juvenile bull trout, short-term (24 hours) maximum temperatures of 20E to 21EC would not significantly reduce the production or "health" of bull trout. Compared with those for other salmonids, these maximum temperatures for survival of short exposure are very conservative (Table 1).

These criteria are based on the optimal temperatures for juvenile bull trout growth during the summer. However, the EPA and ODEQ (1995) have suggested that slight increases in water temperature can lead to competitive interactions with other species (e.g., exotics), perhaps to the detriment of coldwater species, even though temperature criteria would be well within the thermal requirements of the coldwater species. In the next section we examine the effects of temperature on competitive interactions.

TEMPERATURE EFFECTS ON COMPETITIVE INTERACTIONS

Here, we examine temperature effects on interactions between bull trout and introduced (non-native) brook trout. We focus on interactions between bull trout and brook trout because most work shows that bull trout are less likely to coexist compatibly with brook trout than with other salmonids. Indeed, there is little evidence that bull trout compete with other salmonids. For example, Pratt (1984) studied the habitat use and interactions of juvenile cutthroat trout and bull trout in the upper Flathead River basin and found that they used specifically different habitat when together or separate (selective segregation as defined by Nilsson 1967).

Competitive interactions among fluvial salmonids usually translate into attempts by individuals of the same or different species to secure territories for adequate space and, therefore, food or cover or both (Chapman 1966). Some studies have shown that competition among various fish species can be mediated or controlled by water temperature (Baltz et al. 1982; Reeves et al. 1987; Hillman 1991; De Staso and Rahel 1994). For example, De Staso and Rahel (1994) examined the influence of water temperature on interactions between juvenile cutthroat trout and brook trout in a laboratory stream. They note that the two species were nearly equal competitors at 10EC, but brook trout showed a clear competitive dominance over cutthroat trout at 20EC.

This knowledge has been generalized to interactions between bull trout and brook trout. For example, ODEQ (1995) state, "*A factor greatly complicating bull trout temperature requirements, however, is competition with brook trout, an introduced species. This competition occurs today in approximately one-fourth to one-third of the bull trout habitat. Brook trout out-compete bull trout at all but the lowest temperatures.*" As we demonstrate below, there are a number of correlative studies that suggest interactions

occur between brook and bull trout; however, we found no studies that address the influence of water temperatures on these interactions.

Several observations suggest that competition occurs between bull and brook trout. For example, Wallis (1948) noted that the feeding habits of brook trout and bull trout were similar. Both species consumed primarily aquatic insects, although brook trout took a slightly higher percentage of terrestrial insects. Rode (1988) believed that stocking brook trout into McCloud Reservoir in California may have contributed to the demise of bull trout there. In all areas in Montana where bull trout and brook trout occur together, bull trout populations have declined (Goetz 1989). Dambacher et al. (1992) assessed the distribution, abundance, and habitat use of bull trout and brook trout in Sun Creek, Crater Lake National Park. They found that both species used similar habitat types and microhabitats. Both preferred pools over other habitats, but brook trout appeared to dominate pool inlets. Dambacher et al. (1992) concluded that competition and hybridization threaten the bull trout with extinction in Sun Creek. Parkinson and Haas (1996) suggested that temperature segregated bull trout and brook trout in the Mesilinka and Osilinka rivers. These correlative studies do not demonstrate cause-and-effect relationships between bull trout and brook trout.

Recently, Nakano et al. (in press) examined competitive interactions for foraging space among brook trout, native bull trout, and westslope cutthroat trout in Elk Creek, a tributary of the Swan River, Montana. In this study, which was more experimental than correlative, the authors found that the three species together interacted with each other, forming a size-structured, mixed-species dominance hierarchy. When cutthroat were removed, brook trout increased foraging rates and distances and used cover less. Bull trout did not change behavior. When the authors removed brook trout, bull trout increased foraging rates and distances and occupied more exposed positions. Based on these observations, Nakano et al. (in press) suggested that competitive interactions with brook

trout are an important factor in regulating bull trout densities. This study, although more experimental than others, does not establish that interactions are influenced by water temperatures.

Not all studies suggest that bull trout and brook trout interact for food and space. For example, work by Rich (1996) in the Bitterroot basin found little evidence that brook trout were replacing bull trout. He noted that different habitat requirements between the two species appeared to be the most important factor influencing their distributions. Brook trout in the Bitterroot system occupied streams having habitat conditions where bull trout were normally absent. Clancy (1993) also reported differences in the habitats used by brook and bull trout.

With few exceptions, the literature seems to suggest that introduced brook trout interact with native bull trout, although these studies are mostly correlative (i.e., they do not demonstrate cause-and-effect relationships). However, we cannot find where the literature demonstrates that temperature influences the outcome of interactions between the two species. Given that brook trout have a wide optimum temperature range (7.0-20.3EC; Table 1) and they seek groundwater upwelling sites for spawning, it may be that brook trout can displace bull trout even at cold temperatures. The work of Cavallo (1997) demonstrates this point. He found that cold water temperatures in springbrooks in the Middle Fork Flathead River did not prevent brook trout from invading and displacing native salmonids such as cutthroat and bull trout. Cavallo (1997) concludes that cold temperatures alone will not prevent brook trout from invading streams supporting cutthroat and bull trout. Therefore, it seems unreasonable at this time to establish temperature standards for bull trout based on presumed temperature-moderated interactions between brook and bull trout. It seems more prudent to establish temperature criteria based on physiological optima.

CONCLUSIONS

We find that bull trout require colder temperatures for juvenile growth and rearing than other salmonids. However, we disagree with the EPA that a temperature standard of 10EC MWMT is required for maintaining optimal juvenile growth and rearing. Our review does not comport with EPA's statement that optimal juvenile growth and rearing range from 4E to 10EC. Instead, our examination suggests that juvenile bull trout are often found in sites with MWMTs of 12E to 14EC, and that they are generally more abundant and grow faster at these temperatures. In addition, larger numbers of bull trout age classes are found at these temperatures. We believe, therefore, that optimal temperatures for juvenile bull trout growth and rearing range from 12E to 14EC, not 4E to 10EC. Furthermore, using the EPA criteria protocol (methods of Brungs and Jones 1977), we find that MWATs of 14.7E to 16.7EC and short-term (24 hour) maximum temperature criteria of 20E to 21EC should adequately protect juvenile bull trout rearing habitat. These results strongly suggest that the EPA temperature standard of 10EC MWMT for juvenile bull trout rearing is too conservative.

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TABLES

Table 1. Optimal temperature ranges, optimal growth temperatures, maximum weekly average temperatures for growth, and maximum temperatures for survival of short exposures (24 hr) of different salmonids. Data are from Brungs and Jones (1977), Jobling (1994), and Pennell and Barton (1996).

Species	Optimum range (EC)	Optimal growth temp (EC)	Maximum weekly average temp for growth (EC)	Maximum temp for survival of short exposure (EC)
Brook trout	7.0-20.3	13.0-16.1	19.0	24.0
Brown trout	6.0-20.0	10.0-15.5	17.0	24.0
Rainbow trout	10.0-22.0	16.5-17.2	19.0	24.0
Cutthroat trout	12.0-15.0			
Lake trout	6.0-17.0			
Coho salmon	9.0-16.6	14.8	18.0	24.0
Chinook salmon	10.0-18.0	15.5		
Sockeye salmon	10.0-15.0	15.0	18.0	22.0
Pink salmon	9.3-15.5	15.5		
Chum salmon	13.0-14.1	13.0		
Arctic charr	5.0-16.0	14.0		

Table 2. Summary of temperature metrics (EC) compiled from 225 sites in 73 streams in Montana and Idaho (data from Plum Creek Timber Company, Potlatch Corporation, and Idaho DEQ).

Statistic	Maximum daily maximum temp[1]	Maximum weekly maximum temp[2]	Maximum daily average temp[3]	Maximum weekly average temp[4]	Monthly mean temp	
					July	August
Mean	15.26	14.45	12.15	11.47	10.53	10.07
Std dev	3.91	3.75	2.74	2.62	2.49	2.04
Minimum	8.29	7.96	6.89	6.77	6.56	6.43
Maximum	26.90	25.51	22.58	21.92	20.93	17.15
Sample size	225	124	218	124	122	123

[1] MDMT is the maximum daily temperature measured on the hottest day of the year.
[2] MWMT is the average of daily maximum temperatures over the warmest consecutive 7-day period.
[3] MDAT is the maximum average daily temperature measured on the hottest day of the year.
[4] MWAT is the average of daily average temperatures over the warmest consecutive 7-day period.

Table 3. Pearson correlation coefficients between all possible combinations of temperature metrics compiled from 225 sites in 73 streams in Montana and Idaho. Temperature metrics MDMT=maximum daily maximum temperature, MDAT=maximum daily average temperature, MWMT=maximum weekly maximum temperature, MWAT=maximum weekly average temperature, JULY=mean July temperature, and AUG=mean August temperature.

	MDMT	MDAT	MWMT	MWAT	JULY	AUG
MDMT	1.00					
MDAT	0.93	1.00				
MWMT	0.99	0.96	1.00			
MWAT	0.92	0.99	0.95	1.00		
JULY	0.90	0.97	0.93	0.98	1.00	
AUG	0.91	0.98	0.94	0.98	0.96	1.00

Table 4. Summary of simple-linear regression analysis of all possible combinations of temperature metrics (EC) compiled from 225 sites in 73 streams in Montana and Idaho. Temperature metrics MDMT=maximum daily maximum temperature, MDAT=maximum daily average temperature, MWMT=maximum weekly maximum temperature, MWAT=maximum weekly average temperature, JULY=mean July temperature, and AUG=mean August temperature. Results are not necessarily intended to show cause-effect relationships. Data are from Plum Creek Timber Company, Potlatch Corporation, and Idaho DEQ.

Independent variable	Dependent variable	Intercept	Slope			r^2
			Coeff	SE	Prob	
MDMT	MWMT	0.03	0.95	0.007	0.00	0.98
	MDAT	1.15	0.77	0.027	0.00	0.87
	MWAT	1.13	0.72	0.028	0.00	0.84
	JULY	1.03	0.66	0.030	0.00	0.80
	AUG	2.09	0.55	0.023	0.00	0.83
MWMT	MDMT	0.15	1.04	0.008	0.00	0.99
	MDAT	0.95	0.83	0.023	0.00	0.92
	MWAT	0.88	0.78	0.024	0.00	0.90
	JULY	0.78	0.72	0.027	0.00	0.86
	AUG	1.91	0.60	0.020	0.00	0.88
MDAT	MDMT	0.58	1.13	0.040	0.00	0.87
	MWMT	0.10	1.11	0.031	0.00	0.92
	MWAT	0.01	0.94	0.014	0.00	0.97
	JULY	-0.08	0.87	0.021	0.00	0.94
	AUG	1.28	0.72	0.015	0.00	0.95
MWAT	MDMT	0.95	1.17	0.046	0.00	0.84
	MWMT	0.41	1.15	0.035	0.00	0.90
	MDAT	0.30	1.03	0.015	0.00	0.97
	JULY	-0.05	0.92	0.018	0.00	0.96
	AUG	1.33	0.76	0.013	0.00	0.96

Table 4. Concluded.

Independent variable	Dependent variable	Intercept	Slope			r^2
			Coeff	SE	Prob	
JULY	MDMT	1.62	1.21	0.055	0.00	0.80
	MWMT	1.03	1.19	0.045	0.00	0.86
	MDAT	0.84	1.08	0.025	0.00	0.94
	MWAT	0.55	1.04	0.020	0.00	0.96
	AUG	1.72	0.79	0.020	0.00	0.93
AUG	MDMT	-0.68	1.49	0.062	0.00	0.83
	MWMT	-1.19	1.47	0.049	0.00	0.88
	MDAT	-1.09	1.32	0.027	0.00	0.95
	MWAT	-1.27	1.27	0.022	0.00	0.96
	JULY	-1.27	1.17	0.029	0.00	0.93

Table 5. Comparison of water temperatures and numbers of bull trout enumerated with electrofishing and snorkeling in tributaries of the South Fork Salmon River during August and September 1984 and 1985. Temperatures were measured at time of fish census. Data are from Thurow (1987).

Survey stream	Site	Year	No. bull trout	Temp. (EC)
		Electrofishing		
Trapper Creek	L1	1984	1	----
Blackmare Creek	L1	1985	1	10.0
Camp Creek	L1	1985	1	13.0-15.0
Cougar Creek	L2	1985	1	11.5
Sugar Creek	L1	1985	3	----
	U1	1985	11	8.5
	U2	1985	19	----
Trapper Creek	L1	1985	2	9.0
	L2	1985	4	----
	U1	1985	14	10.5
	U2	1985	29	----
		Snorkeling		
Burntlog Creek	Lower	1984	3	11.0-13.5
	Upper	1984	21	11.5-13.5
E. Fk of the S. Fk	Sect. 3 & 8	1984	3	12.0-13.0
Johnson Creek	Lower	1984	2	12.5-15.0
Lake Creek	Lower	1984	15	----
Lick Creek	Lower	1984	1	12.0
Secesh River	Meadow	1984	3	12.0-16.0
	Middle	1984	1	11.5-14.0

Table 5. Concluded.

Survey stream	Site	Year	No. bull trout	Temp. (EC)
		Snorkeling		
Buckhorn Creek	Upper	1985	58	12.0-19.5
E. Fk of the S. Fk	Sect. 2,5,8,9	1985	1	14.0
Elk Creek	Lower	1985	6	11.5
	WF Lower	1985	19	8.5-11.5
Fitsum Creek	NF Upper	1985	18	9.5-14.5
Johnson Creek	Lower	1985	1	12.0-14.5
Lick Creek	Lower	1985	1	12.0-15.0
Profile Creek	Lower	1985	41	11.0-14.0
	Upper	1985	39	11.0-11.5
Quartz Creek	Lower	1985	41	9.0-13.0
Riordan Creek	Lower	1985	1	11.5-15.0
Secesh River	Meadow	1985	2	15.5-18.5
Tamarack Creek	Lower	1985	32	9.0-14.0

Table 6. Monthly averages of daily minimum and maximum temperatures recorded during the warmest month (July or August) during 1977 to 1980 in tributaries of the North Fork of the Flathead River, Montana. Data are from Graham et al. (1980) and Fraley et al. (1981).

Stream	Temp metric	Year of survey			
		1977	1978	1979	1980
Big Creek	Mean min.	8.9	10.6	10.1	8.7
	Mean max.	15.0	13.9	14.4	12.9
	Range	7.2-18.3	7.2-18.3	8.9-16.1	7.2-16.1
Coal Creek	Mean min.	8.9	8.3	8.3	8.1
	Mean max.	15.0	12.8	13.9	12.2
	Range	5.6-17.8	6.1-17.2	7.8-15.6	8.9-13.8
Red Meadow	Mean min.	11.1	----	10.6	10.6
	Mean max.	16.7	----	13.3	12.1
	Range	5.6-18.9	----	10.0-14.4	8.3-15.5
Trail Creek	Mean min.	7.8	7.2	7.2	8.4
	Mean max.	14.4	12.2	13.3	11.5
	Range	6.1-16.7	5.6-15.0	6.1-15.6	7.8-16.1
Whale Creek	Mean min.	8.3	8.9	----	----
	Mean max.	13.3	11.7	----	----
	Range	5.6-16.7	6.7-15.0	----	----

Table 7. Bull trout densities and mean lengths at age in tributaries of the North Fork of the Flathead River, Montana. Data are from Graham et al. (1980) and Fraley et al. (1981).

Stream	Ages	Density (fish/100 m^2)		Mean lengths (mm)	
		1979	1980	1977	1978
Big Creek	0	0.1-1.5	0.7		
	1	0.1-0.6	0.1	72	76
	2	0.4-2.8	0.1	112	
Coal Creek	0	0.4-2.0	----		
	1	0.2-2.2	1.2-1.4	83	88
	2	0.1-2.7	0.4	124	
Red Meadow	0	0.1-1.1	----		
	1	0.5	1.1	80	79
	2	0.1-4.0	0.4-3.4	137	
Trail Creek	0	0.3	1.6		
	1	0.1	0.1	78	85
	2	1.5	0.9	121	
Whale Creek	0	0.1-1.0	----		
	1	0.2	----		
	2	1.0-1.2	----		

Table 8. Summary of temperatures (EC) compiled from 70 sites in 33 streams supporting bull trout in Montana and Idaho (data from Plum Creek Timber Company).

Statistic	Maximum daily maximum temp[1]	Maximum weekly maximum temp[2]	Maximum daily average temp[3]	Maximum weekly average temp[4]	Monthly mean temp	
					July	August
Mean	13.14	12.36	11.05	10.43	9.51	9.33
Std dev	2.71	2.52	2.10	1.99	1.78	1.56
Minimum	8.29	7.96	6.89	6.77	6.56	6.43
Maximum	19.72	18.73	15.82	15.23	14.09	13.19
Sample size	70	70	69	69	68	69

[1] MDMT is the maximum daily temperature measured on the hottest day of the year.
[2] MWMT is the average of daily maximum temperatures over the warmest consecutive 7-day period.
[3] MDAT is the maximum daily average temperature measured on the hottest day of the year.
[4] MWAT is the average of daily average temperatures over the warmest consecutive 7-day period.

Table 9. Presence of bull trout (densities, number of age classes, and presence of juveniles) and temperatures in stream sites in the Little Lost River Basin during 1996 and 1997. Fish data from Gamett 1998; temperature data from Mackay Ranger District, Challis National Forest.

Stream	Bull trout			Temperature metric (EC)			
	Density fish/100 m^2	Age-classes	Juv present	MDMT	MWMT	MWAT	MDAT
Little Lost above Summit Ck		1	No	23.7	21.3	15.6	16.7
Little Lost at Forest boundary	0.2	2	No	24.0	22.1	16.2	16.9
Little Lost at Guard Station	0.2	2	No	18.1	16.8	12.5	13.2
Little Lost at Iron Ck Rd		4/YOY[1]	Yes	16.5[2]	15.1	12.0	12.6
Little Lost below Timber Ck	2.3	3	No	15.1	13.6	10.8	11.5
Little Lost above Moonshine	7.0	3/YOY	Yes	13.4[3]	12.6	10.3	11.0
Little Lost above Smithie Fk	20.4[4]	4/YOY	Yes	12.5	12.1	8.9	9.4
Mill Creek	0.8	2/YOY	Yes	16.5	15.5	11.7	12.2
Smithie Fork	19.5	5/YOY	Yes	15.5	14.6	10.8	11.4
Squaw Creek		2/YOY	Yes	15.5	14.0	11.0	11.4
Timber Creek	6.6	4/YOY	Yes	15.8	14.3	11.1	11.8

[1]This notation indicates that there were 4 age (size) classes of bull trout, including young-of-the-year (YOY).
[2]Temperature data from Sawmill Creek at Bull Creek Road, about 1 km below Iron Creek Road.
[3]Temperature data from 200 m above Timber Creek, about 400 m below Moonshine Creek.
[4]Fish data were collected in 1995, while temperature data were collected in 1997; however, July mean air temperature at Howe in 1995 was 19.4EC, while in 1997 it was 18.8EC. Thus, stream temperatures would probably be similar in both years.

Table 10. Maximum weekly average temperatures (MWAT) for growth of juvenile bull trout estimated from a range of optimal growth temperatures (OT; 12-14EC) and ultimate upper incipient lethal temperatures (UUILT; 20-22EC). Calculation of MWAT follows guidelines in Brungs and Jones (1977).

UUILT (EC)	OT (EC)	MWAT (EC)
20	12	14.7
20	13	15.3
20	14	16.0
21	12	15.0
21	13	15.6
21	14	16.3
22	12	15.3
22	13	16.0
22	14	16.7

FIGURES

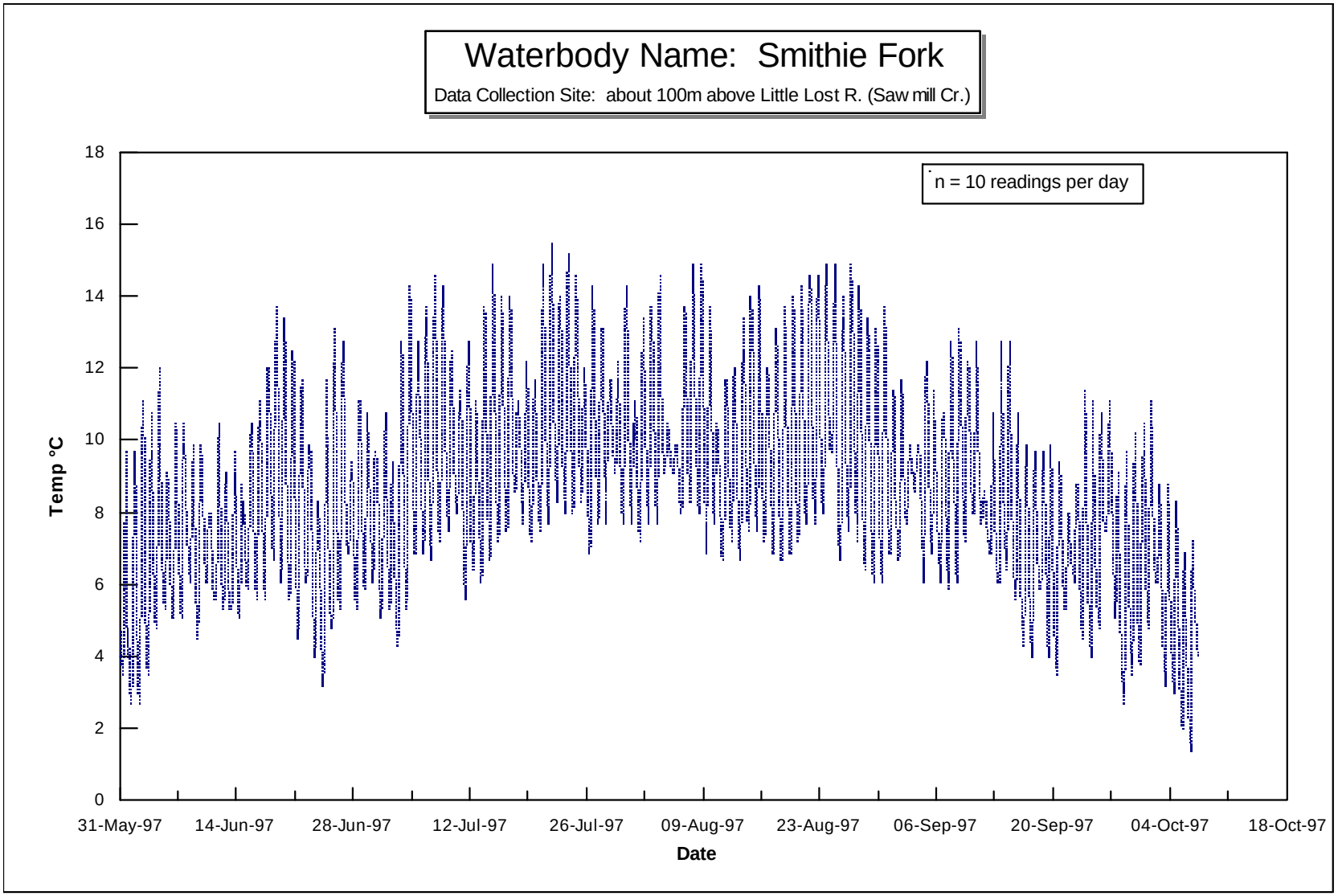


Figure 1. Water temperatures recorded during the period June through October, 1997, on Smithie Fork about 100 m upstream from the Little Lost River, Idaho. Data are from Mackay Ranger District, Challis National Forest.

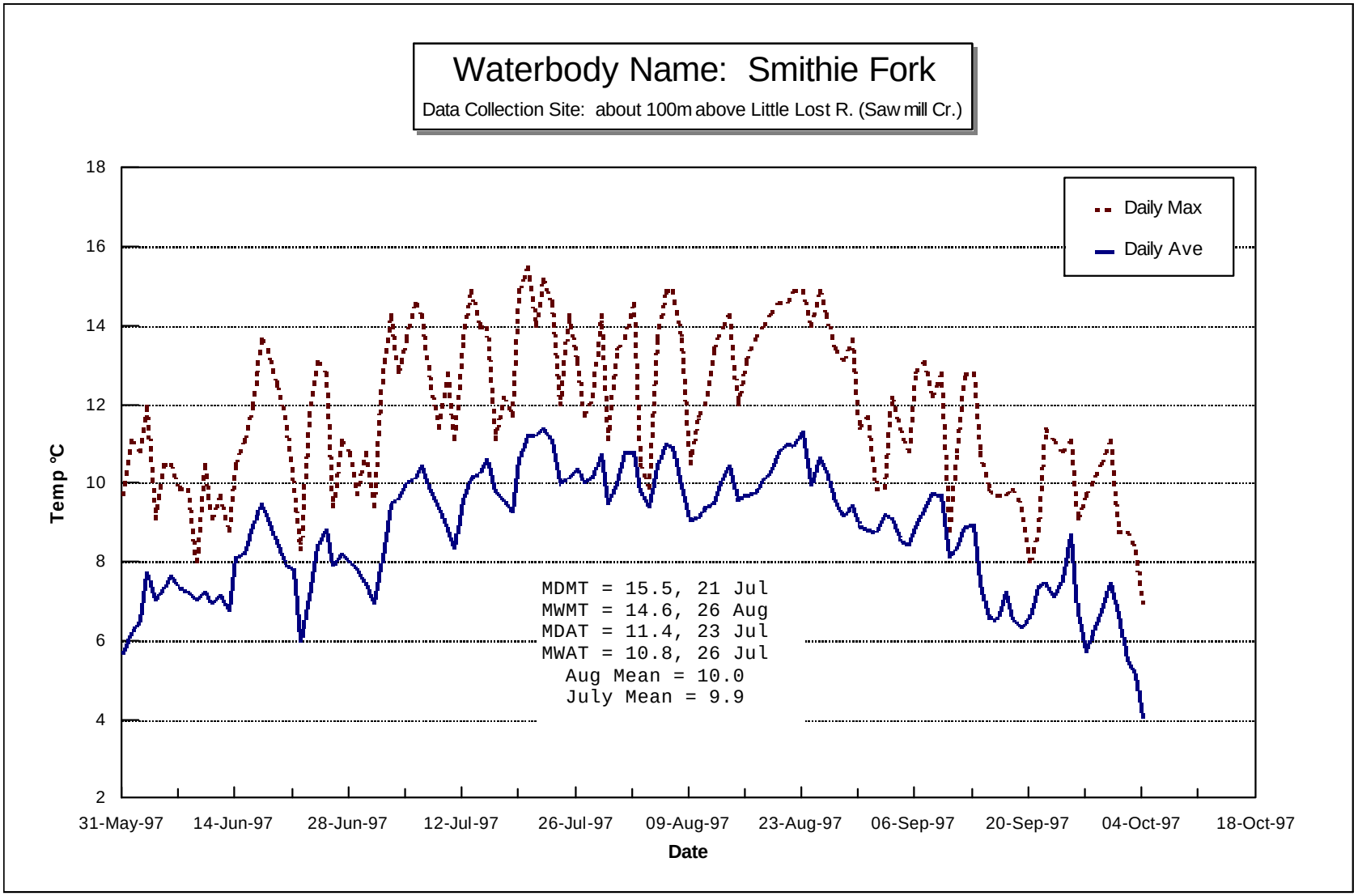


Figure 2. Summary of daily maximum and daily average temperatures collected during the period June through October, 1997, on Smithie Fork about 100 m upstream from the Little Lost River, Idaho. Data are from Mackay Ranger District, Challis National Forest.

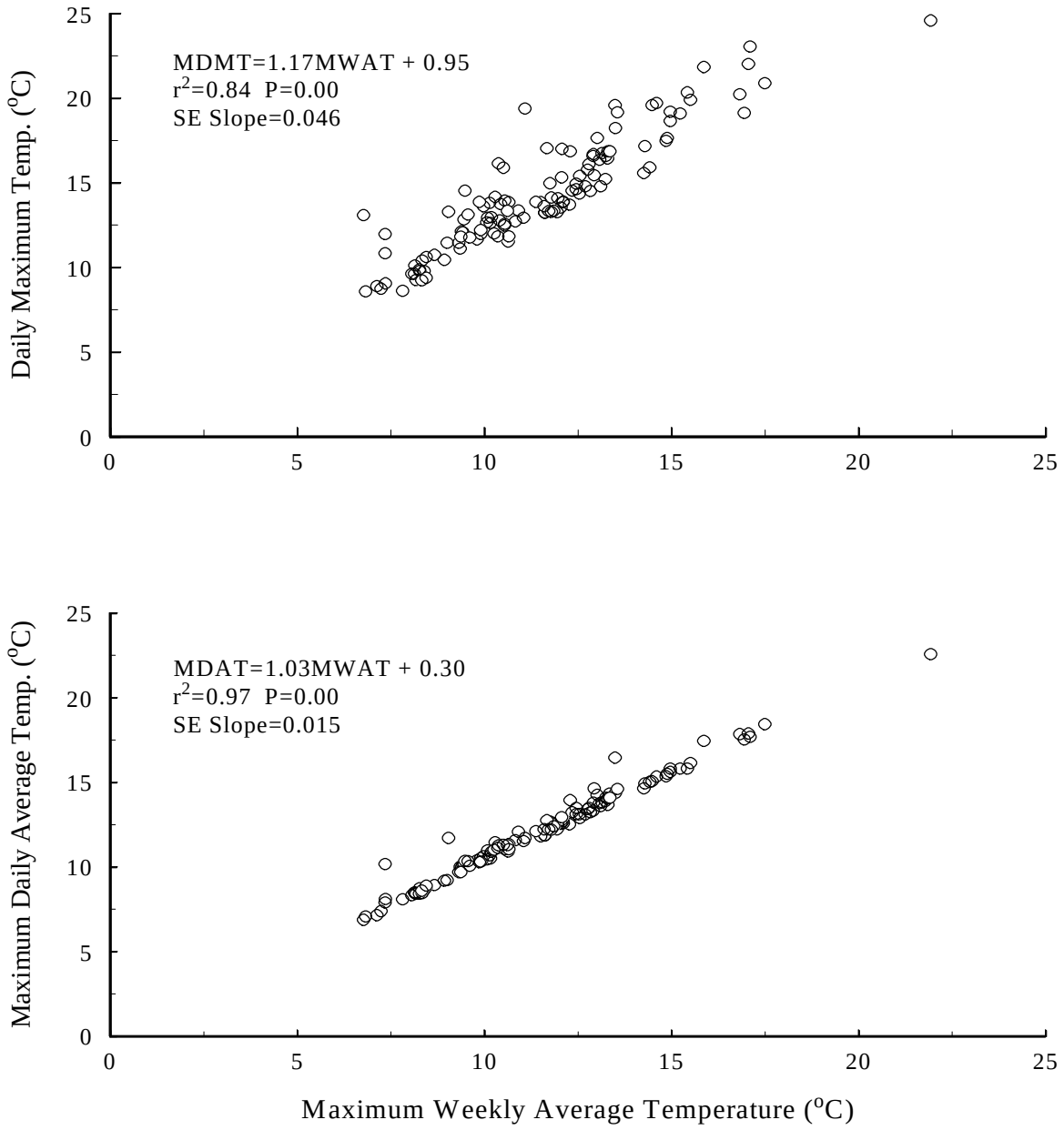


Figure 3. Relationships between maximum weekly average temperatures (MWAT) and maximum daily and average daily temperatures compiled from 225 sites in 73 streams in Montana and Idaho. Simple linear regression results are shown.

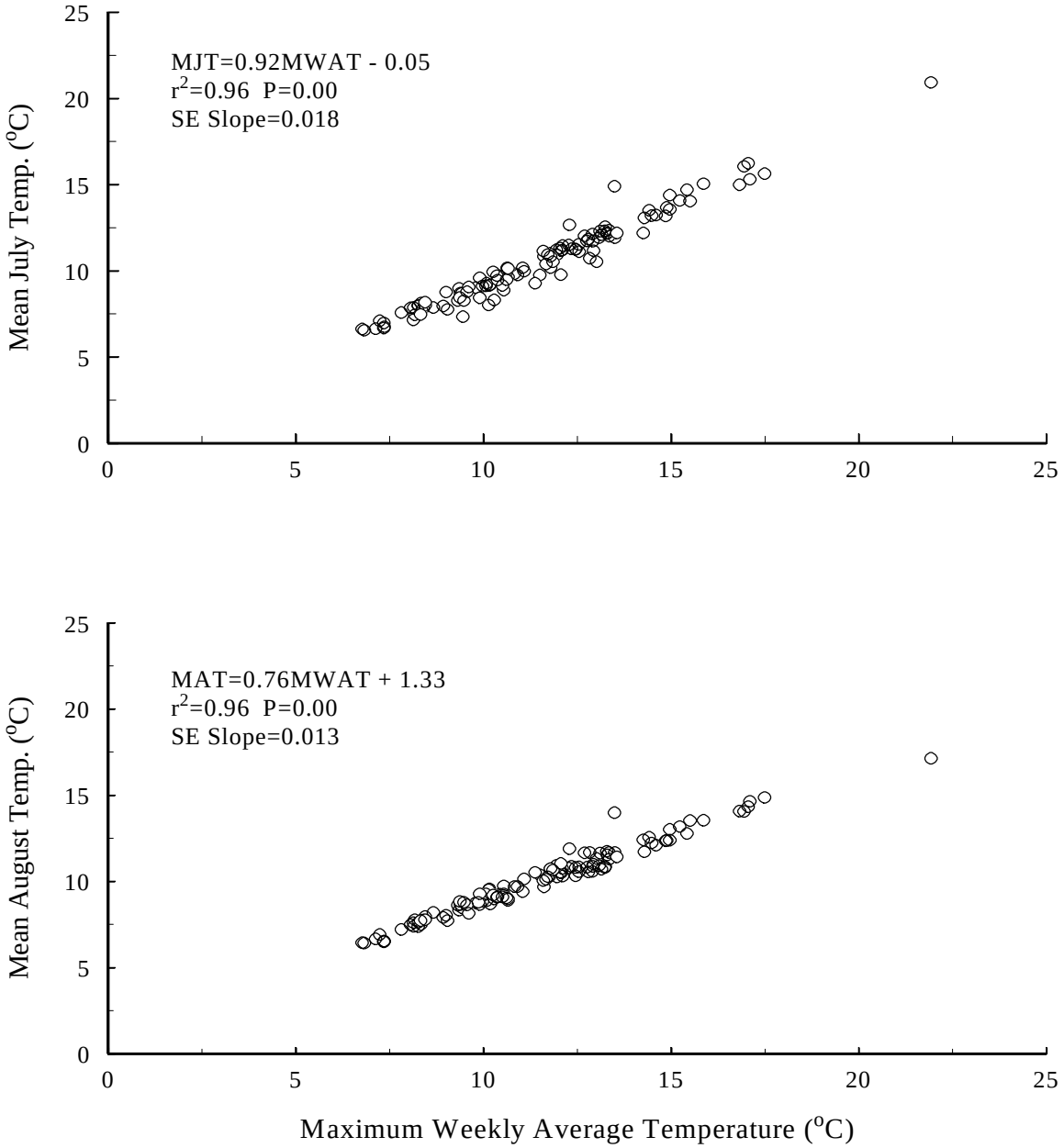


Figure 4. Relationships between maximum weekly average temperatures (MWAT) and the average July and August temperatures compiled from 225 sites in 73 streams in Montana and Idaho. Simple Linerar regression results are shown.

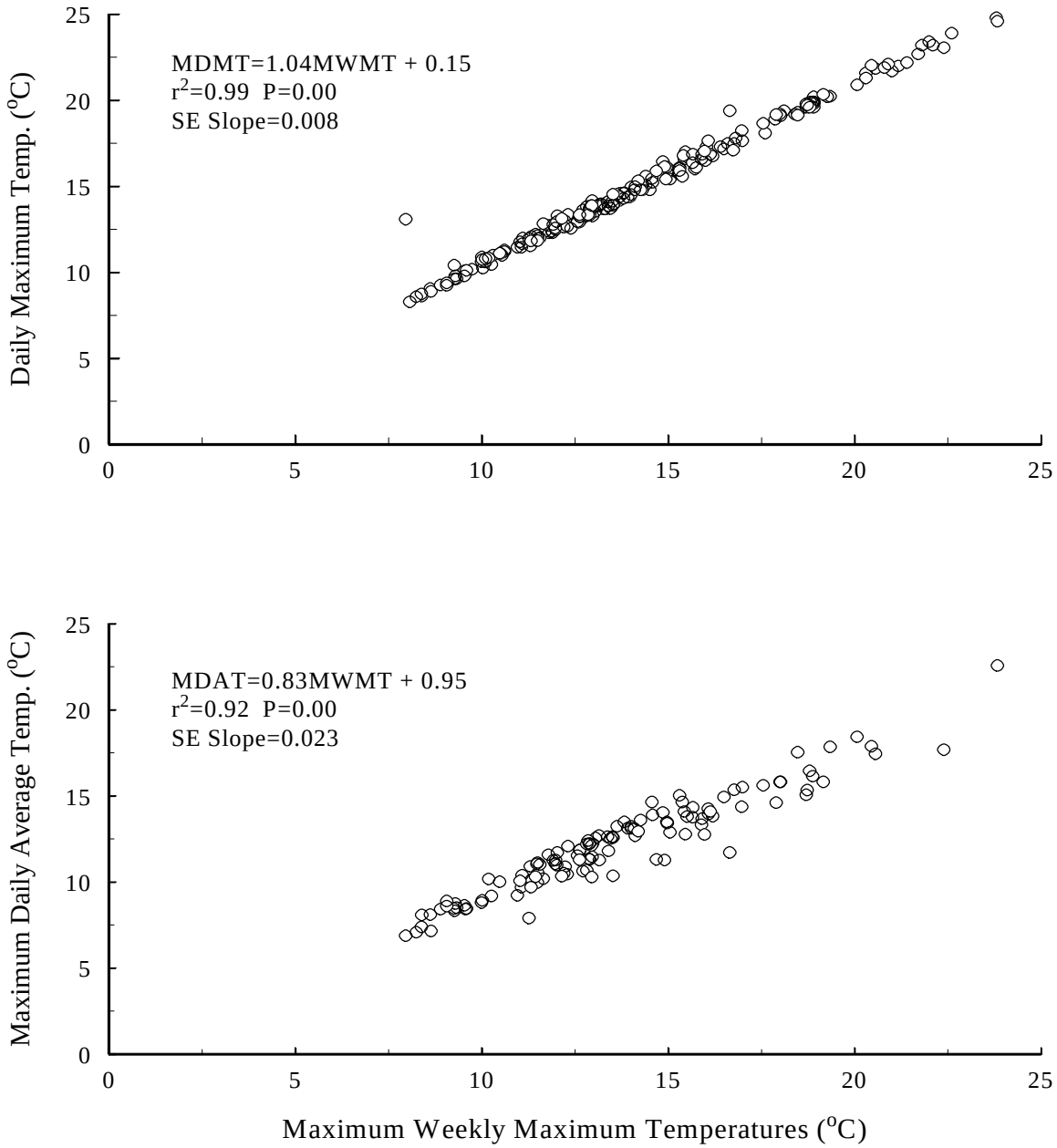


Figure 5. Relationship between maximum weekly temperatures (MWMT) and maximum daily and maximum average daily temperatures compiled from 225 sites in 73 streams in Montana and Idaho. Simple linear regression results are shown.

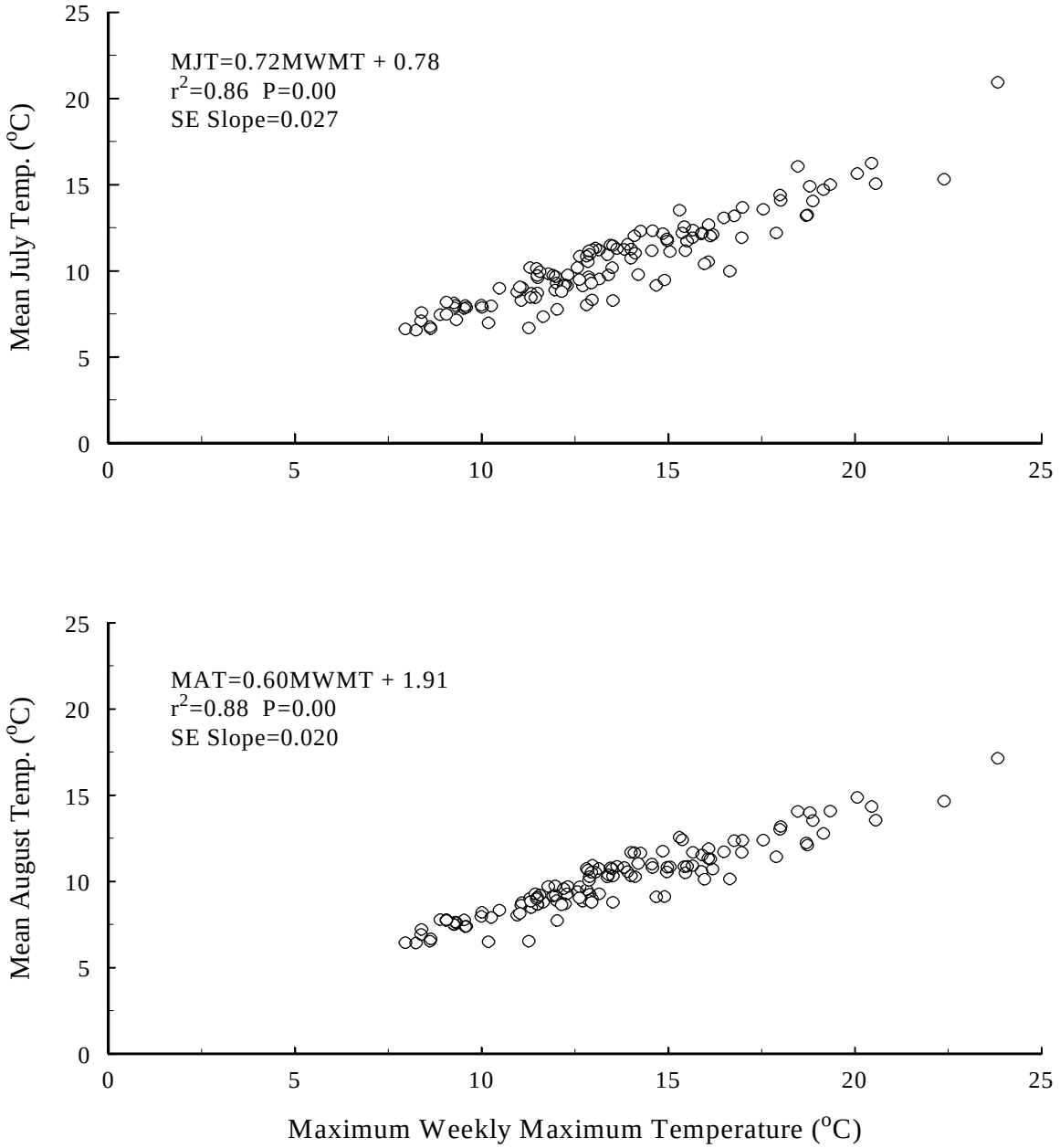
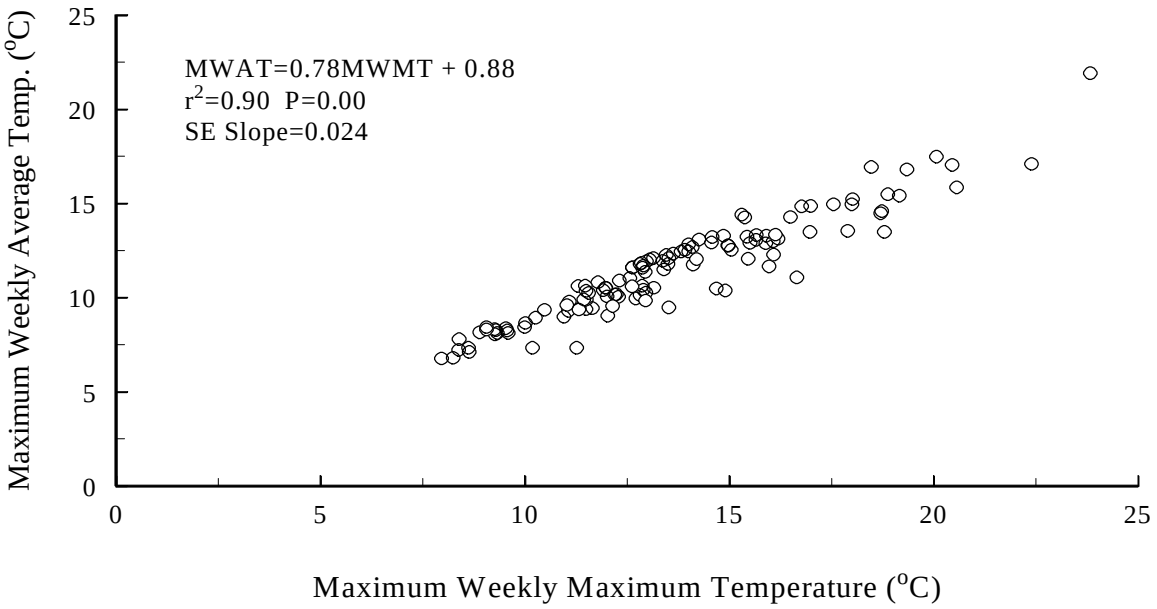


Figure 6. Relationships between weekly maximum temperatures (MWMT) and average July and August temperatures compiled from 225 sites in 73 streams in Montana and Idaho. Simple linear regression results are shown.



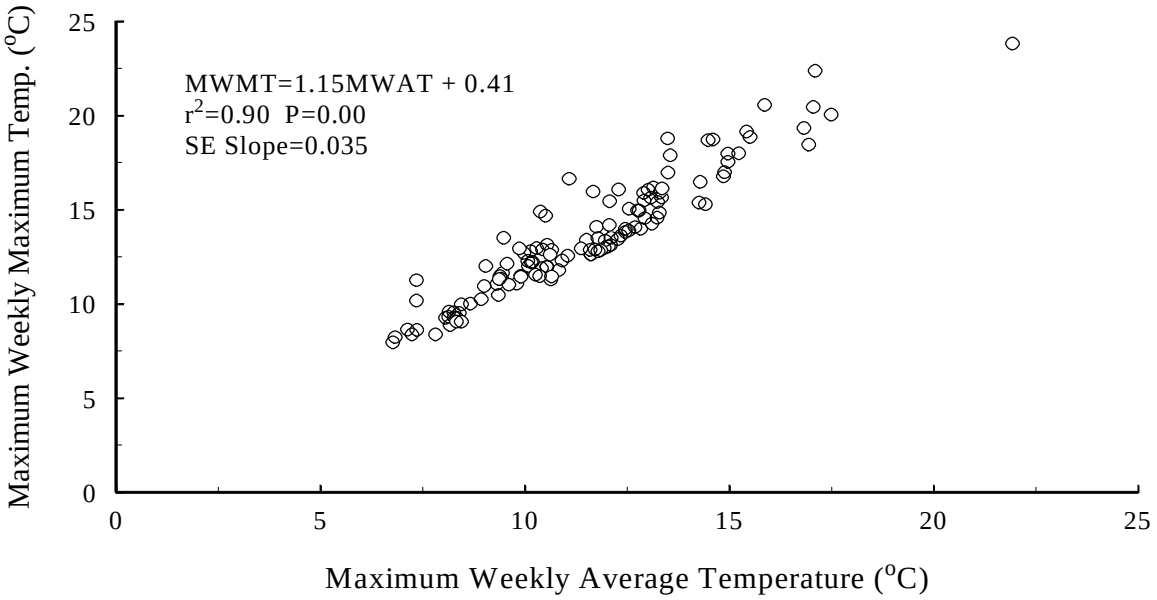


Figure 7. Relationships between maximum weekly maximum temperatures (MWMT) and maximum weekly average temperatures (MWAT). Compiled from 225 sites in 73 streams in Montana and Idaho. Simple linear regression results are shown.

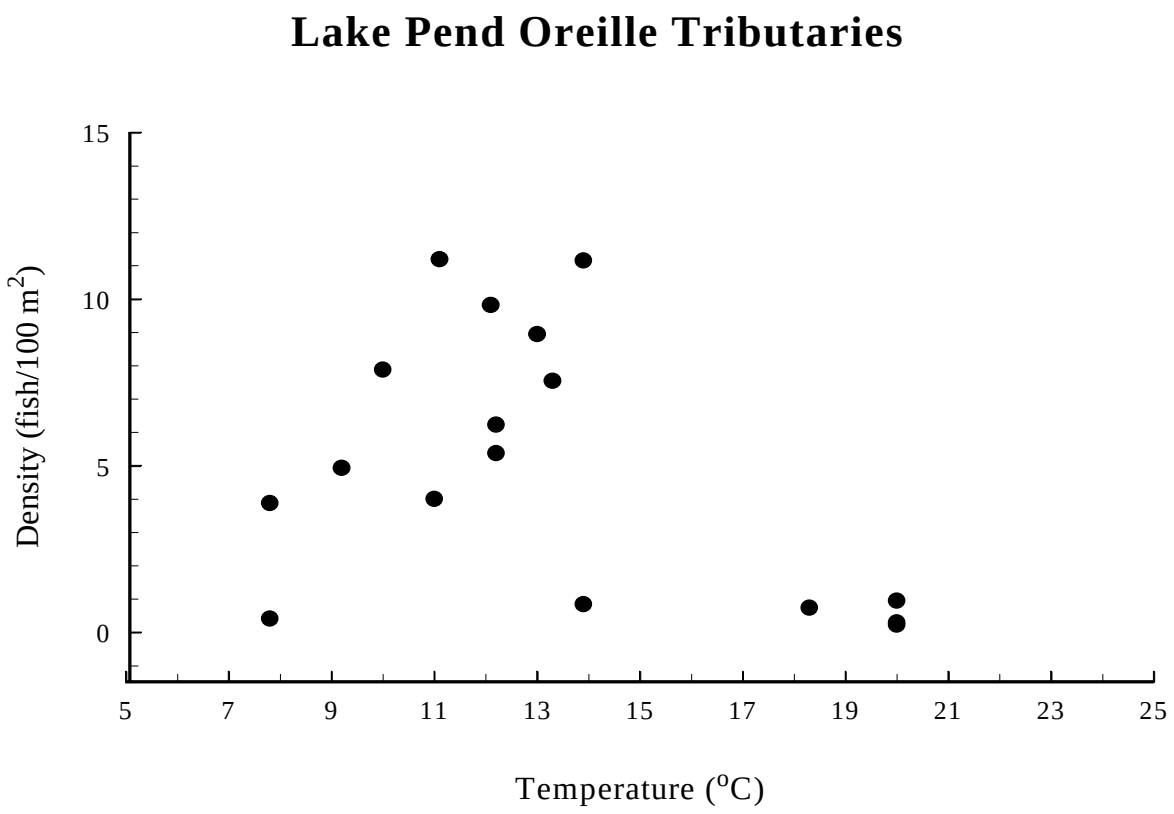


Figure 8. Relationship between juvenile bull trout density and maximum summer temperature (^{o}C) in six tributaries of Lake Pend Oreille (data from Saffel and Scarnecchia 1995).

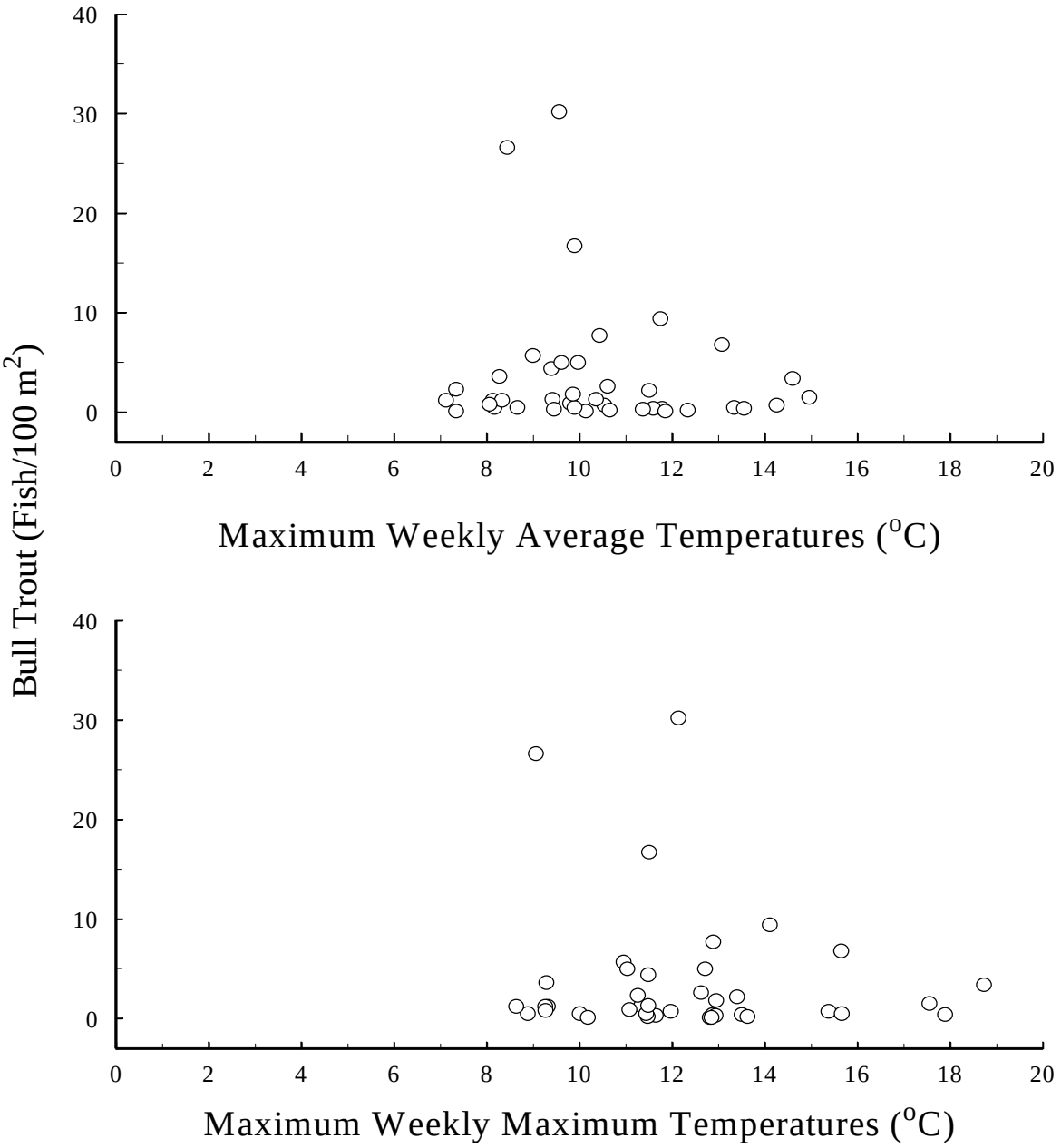


Figure 9. Relationships between juvenile bull trout densities (fish/100 m^2) and maximum weekly average temperature (MWAT) and maximum weekly maximum temperature (MWMT) in 33 streams in Montana and Idaho. Data are from Plum Creek Timber Company.

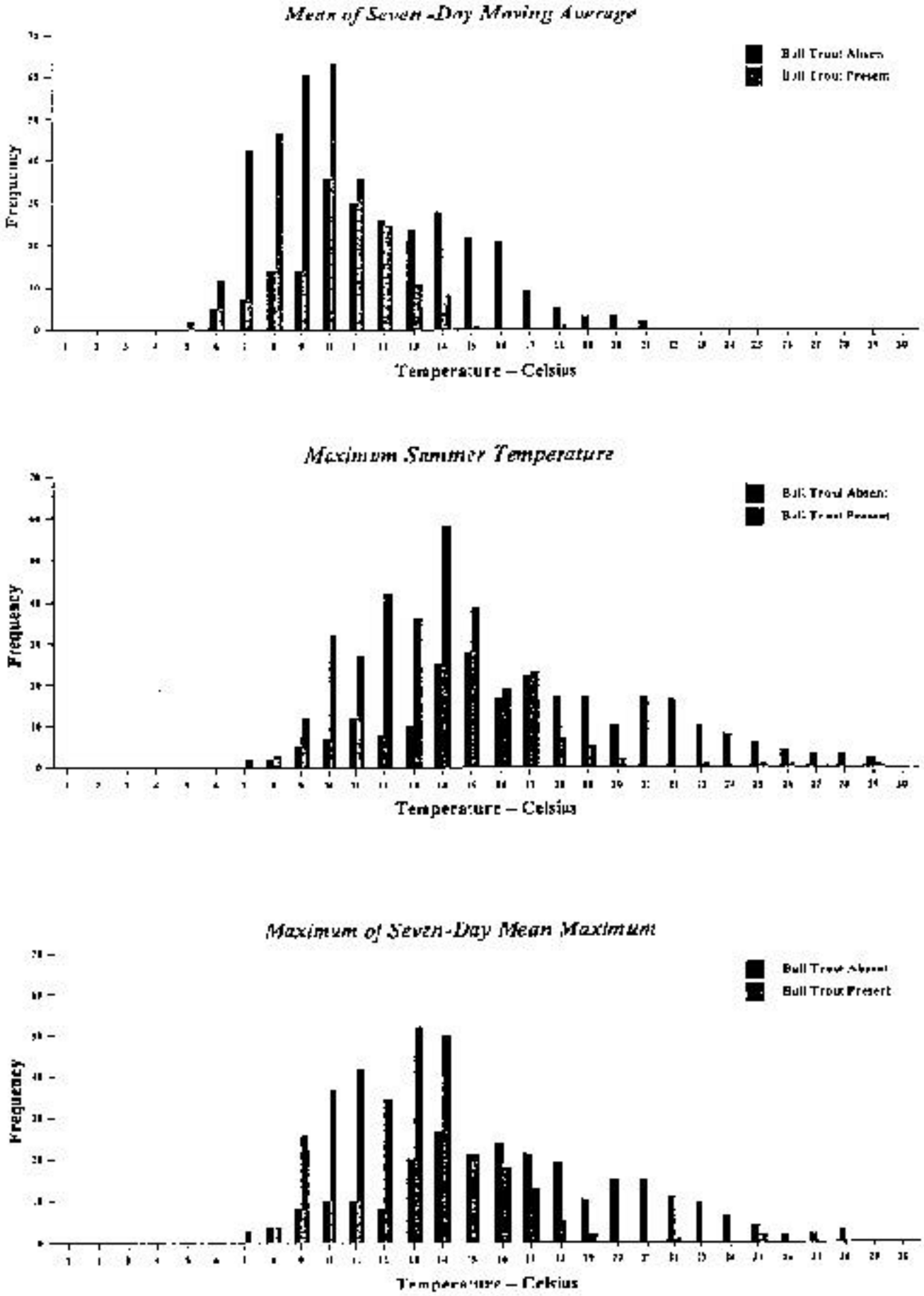


Figure 10. Data presented at the 1998 Salvelinus confluentus Curiosity Society Meeting.

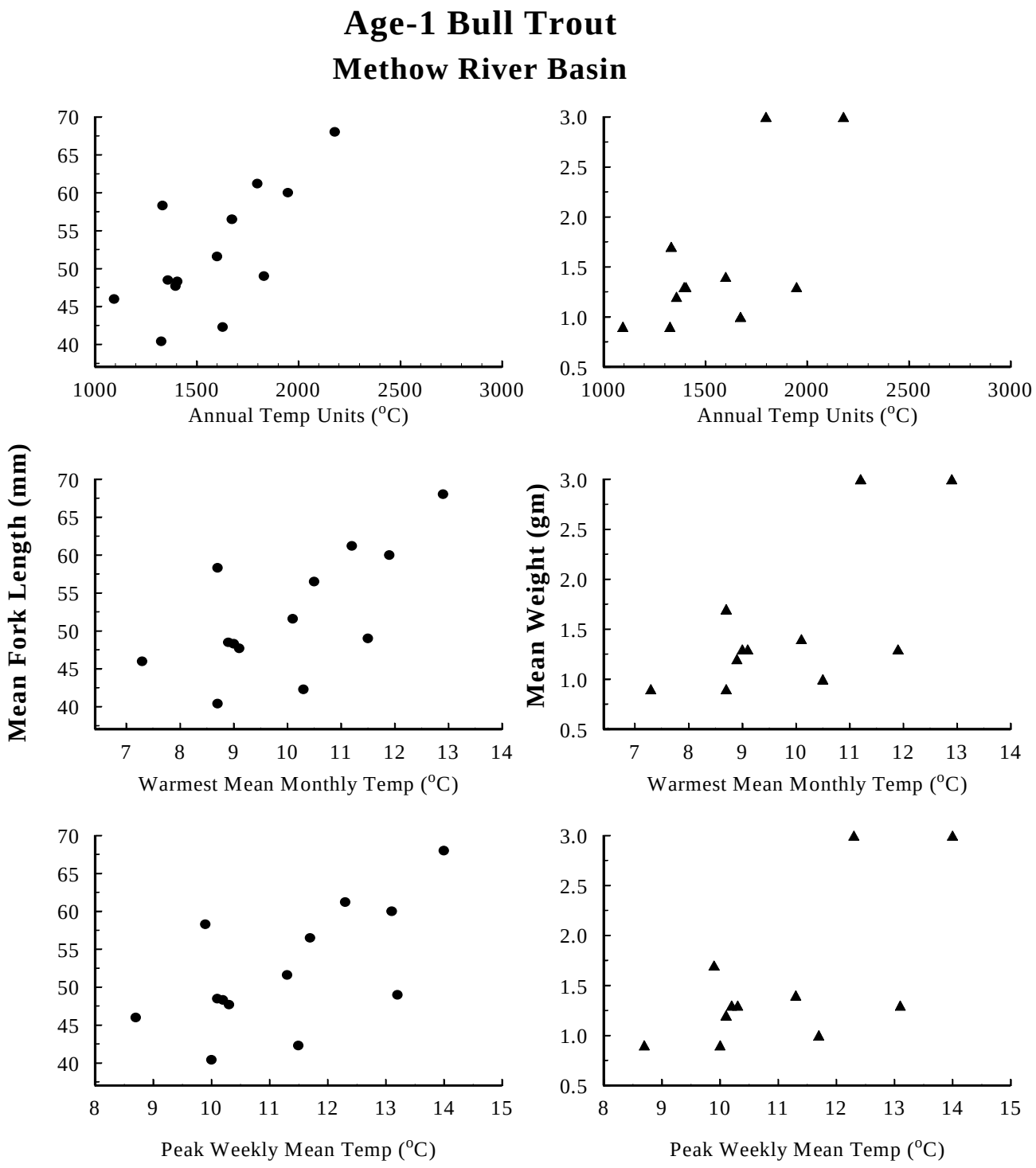


Figure 11. Relationship between mean fork length (mm) and weight (gm) of bull trout and annual temperature units, maximum monthly mean and peak weekly mean temperature (°C) in the Methow River Basin from July to September 1989 (data from Mullan et. al 1992).

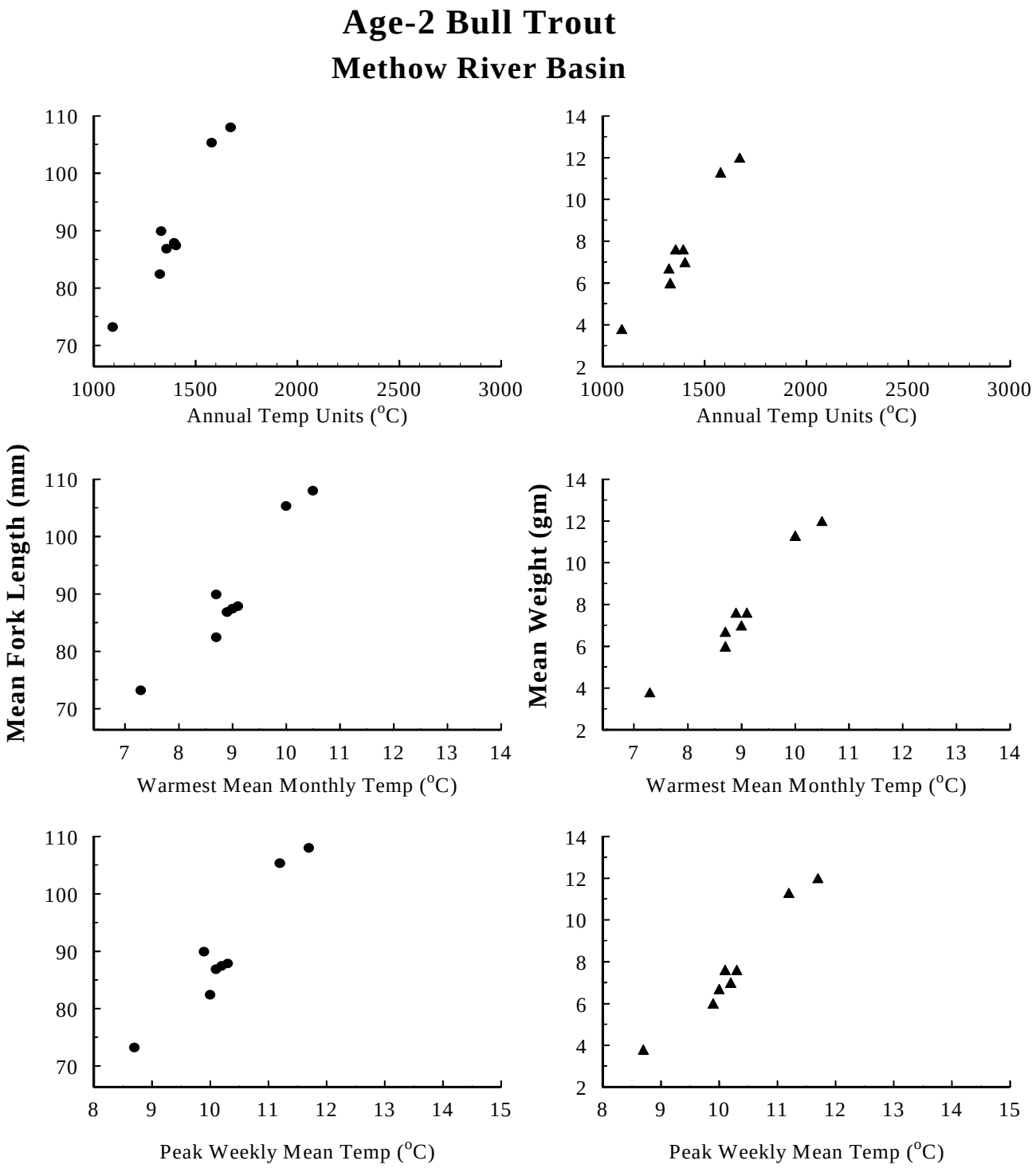


Figure 12. Relationship between mean fork length (mm) and weight (gm) of bull trout and annual temperature units, maximum monthly mean and peak weekly mean temperature (°C) in the Methow River Basin from July to September 1989 (data from Mullan et. al 1992).

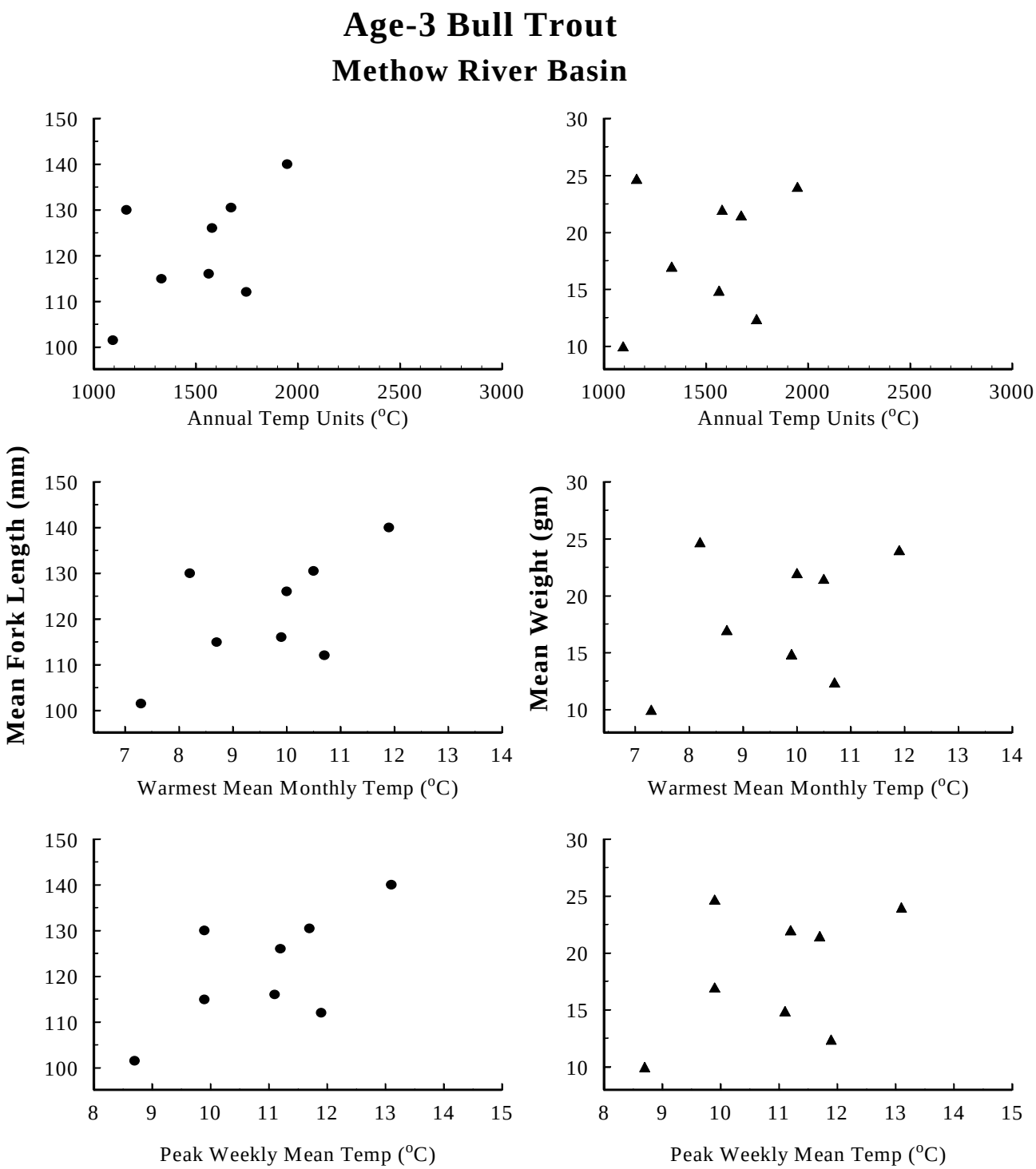


Figure 13. Relationship between mean fork length (mm) and weight (gm) of bull trout and annual temperature units, maximum monthly mean and peak weekly mean temperature (°C) in the Methow River Basin from July to September 1989 (data from Mullan et. al 1992).

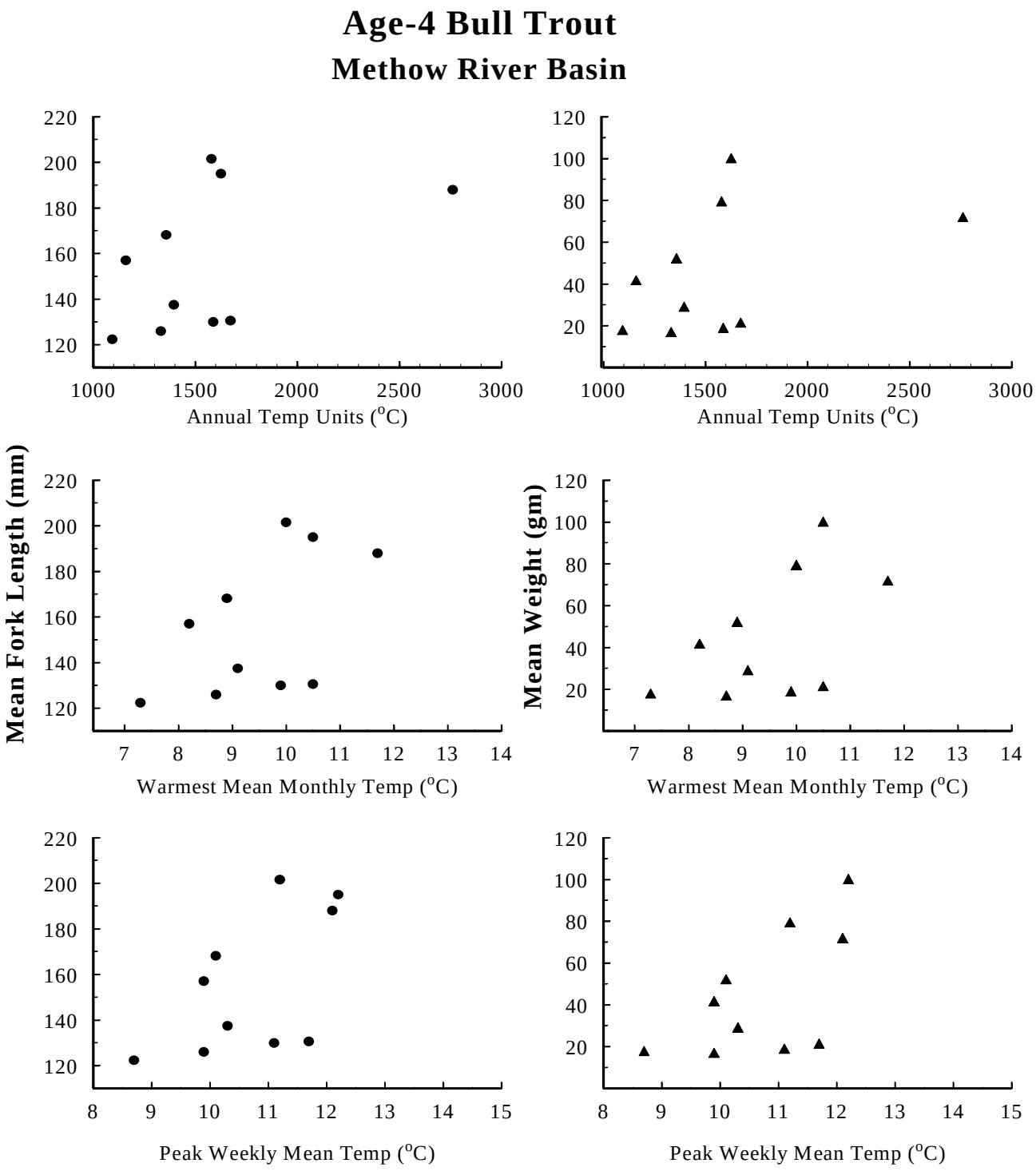


Figure 14. Relationship between mean fork length (mm) and weight (gm) of bull trout and annual temperature units, maximum monthly mean and peak weekly mean temperature (°C) in the Methow River Basin from July to September 1989 (data from Mullan et. al 1992).

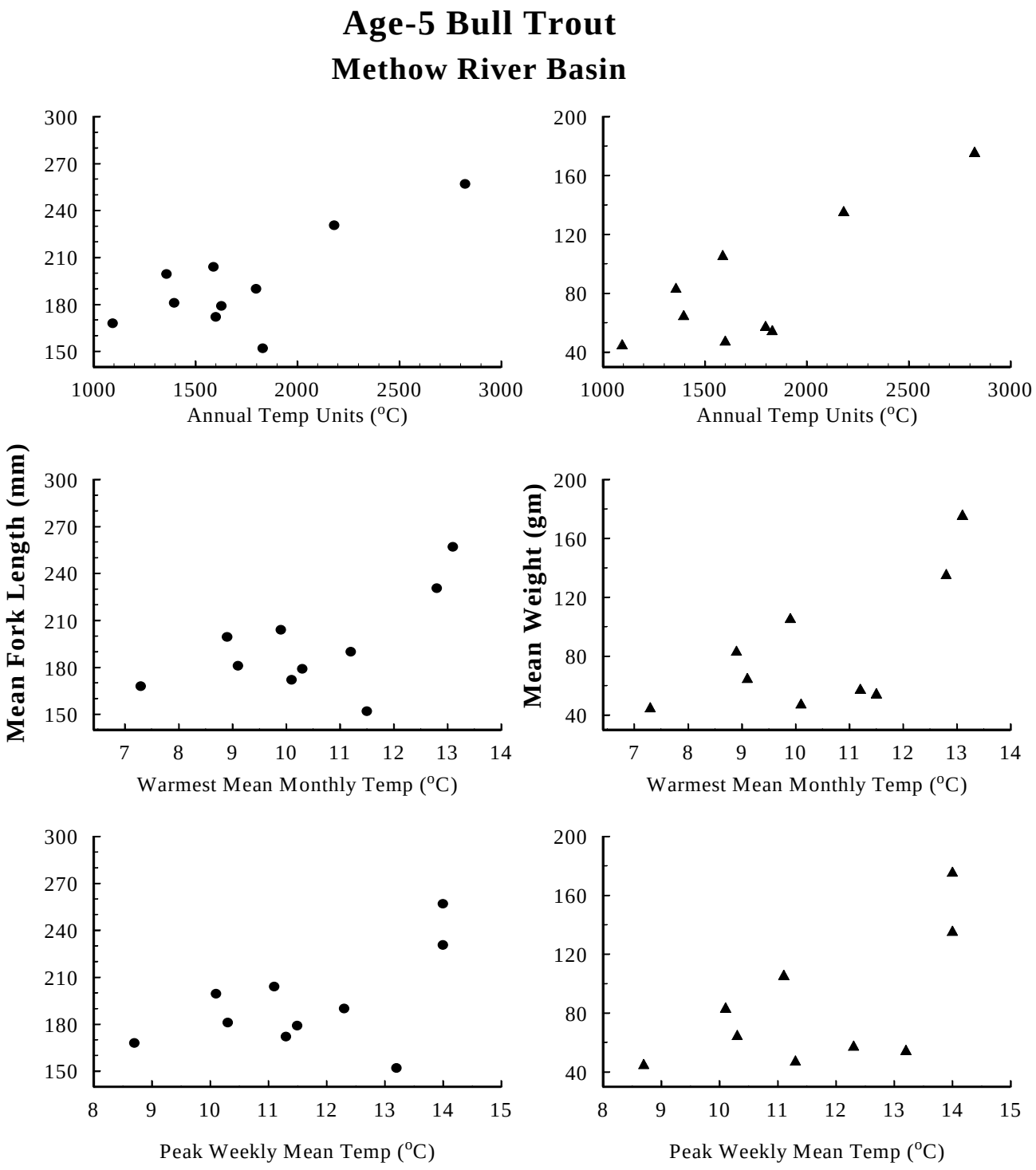


Figure 15. Relationship between mean fork length (mm) and weight (gm) of bull trout and annual temperature units, maximum monthly mean and peak weekly mean temperature (°C) in the Methow River Basin from July to September 1989 (data from Mullan et. al 1992).