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Long-term effects of sedimentation and other factors on the brook trout population in Hunt Creek

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Abstract.–I assessed the long-term effects of an experimental addition of sand sediment and subsequent restoration efforts on brook trout *Salvelinus fontinalis* habitat and abundance in Hunt Creek, in Michigan's northern Lower Peninsula. Alexander and Hansen (1988) previously reported on effects of experimental sediment additions during the early 1970s and habitat restoration accomplished through use of sediment traps from 1982 to 1986. In this follow-up study, I compared brook trout abundance, survival, and growth among six periods between 1952 and 2001 (1952–64, open to angling; 1967–71, pretreatment and beginning of permanent closure to angling; 1972–75, transition as sand added to treatment zone [TZ]; 1976–81, post- treatment; 1982–90, sediment basins maintained; and 1991–2001, sediment basins retired). Data were not previously reported for a 9-year sediment basin maintenance period, or an 11-year period after sediment basins were retired. Fall abundance of age-0 trout in the TZ did not recover to pretreatment levels nearly 25 years after habitat was degraded by excess sand bedload. Gravel in the TZ remains heavily embedded with sand and, presumably, spawning habitat remains impaired. Annual survival of age-0 trout recovered to pretreatment levels after sediment traps were constructed and remained at this level during the period when traps were retired. Habitat for age-1 and older trout was apparently restored by sediment traps and natural erosion processes because their fall abundance was similar to their pretreatment level during periods after 1982. Recovery of fall populations of age-1 and older fish occurred within about 6 years after sediment basins were dug, primarily through increased survival of yearling-and-older fish and retention of yearling fish that immigrated into the TZ during spring and summer. This study demonstrated that an increase in sand bedload concentration from 20 ppm to 80 ppm in a small, low-gradient brook trout stream can result in a very large decline in habitat quality and abundance of all age groups of fish. The only partial recovery of age-0 trout to about 55% of pretreatment abundance 25 years after sediment additions ceased emphasizes the importance of erosion control because it is difficult to fully restore habitat damaged by sedimentation. The rapid recovery of age-1 and older trout in Hunt Creek after sand traps were constructed was possible, in part, because abundant juvenile fish in adjacent stream areas and tributaries immigrated into the treatment zone and survived better because deeper habitat (pool) and large woody debris (LWD) cover was restored.

Introduction

Trout streams flowing through Michigan watersheds with sandy geology are particularly vulnerable to sedimentation. Many of these streams have low gradients, and hence, low power to transport excess sand bedload that enters the channel from a variety of natural or human-induced erosion sources. High-quality spawning habitat is often limited in such streams. Excess sand sediment reduces habitat quality for trout via multiple mechanisms. Sediment embedded in spawning gravels lowers survival of embryos by reducing oxygen transport into redds or by blocking interstices that allow fry to emerge (Wickett 1954; Cordone and Kelley 1961; Peters 1965, 1967; Sowden and Power 1985; Curry and MacNeill 2004). Survival to emergence of salmonids is generally negatively proportional to the percentage of fine sediment (Chapman 1988; Reiser and White 1988; Young et al. 1991). Excess sand bedload also aggrades channels, fills pools, and buries woody cover (Alexander and Hansen 1986).

During the 1970s and 1980s, the effects of sand bedload on stream morphology and trout abundance were studied at two small Michigan trout streams. In Poplar Creek, abundance of brown trout and rainbow trout increased significantly when sand bedload concentrations were reduced from 56 ppm to 8 ppm by construction of a sediment basin, i.e., a settling pool excavated in the channel (Alexander and Hansen 1983). Hansen et al. (1983) reported that sediment basins created deeper pools downstream and improved streambed composition through exposure and cleansing of coarser substrates such as spawning gravel. In Hunt Creek, a study of the effects of elevated sand bedload on a brook trout populations and stream morphology was conducted over a 20-year period from 1967 to 1986 (Alexander and Hansen 1988). Background data were collected for the first 5 years, sand was added daily to the stream for the next 5 years, no sand was added for the next 5 years, and finally removal of sand was accelerated by excavation of sediment basins during the final 5 years of the study. Average brook trout abundance declined to about half of the pretreatment abundance level as a result of a four- to five-fold increase in bedload (Alexander and Hansen 1986). The sand treatment caused the channel to become wider and shallower, and eliminated most pools. The change in habitat caused a decrease in survival rates of brook trout, particularly at early life stages (Alexander and Hansen 1986). Excavation of sand traps over a 5-year period (1982–86) largely restored habitat for age-1 and older brook trout within about 6 years (Alexander and Hansen 1988). However, some impairment to habitat for young-of-year (YOY) brook trout was still evident 10 years after experimental additions of sand ceased because YOY abundance had not recovered to pretreatment levels.

In the present study, I re-examine effects of continued maintenance of sediment basins through 1990 on brook trout population characteristics in Hunt Creek. In addition, I compare populations of brook trout during the period from 1991–2001, after sediment traps were retired, to other periods after 1952. Information on the effects of angling and trout migration are also included to aid the interpretation of this long-term data set.

My primary objective was to compare brook trout populations among periods between 1952 and 2001 and attempt to determine if they have fully recovered from effects of the experimental sand additions. A second objective was to compare physical habitat data collected in 2000 to previously published values to determine if stream morphology was similar to pre-sedimentation conditions.

Methods

Study Area

The Hunt Creek watershed is in northern Oscoda and southern Montmorency counties of Michigan's Lower Peninsula (Figure 1). Hunt Creek is a groundwater-dominated stream draining extensive glacial sands and gravels deposited approximately 10,000 years ago (Dorr and Eschman 1970). Hunt Creek has extremely stable discharge: from March 1999 through March 2001, the 90% exceedence flow was 0.75 m^3/s and the 10% exceedence flow was 0.87 m^3/s at the downstream end of the study area.

The study area of Hunt Creek was divided into three sections: a 1.9 km (0.73 ha) upstream reference zone (RZ) and a 1.5 km (0.94 ha) downstream treatment zone (TZ) (Figure 1). Hunt Creek is a second order stream above its confluence with Fuller Creek and a third order stream through the remainder of the study area.

The only common fish species in Hunt Creek are brook trout *Salvelinus fontinalis*, mottled sculpin *Cottus bairdi*, and slimy sculpin

Cottus cognatus (Alexander and Hansen 1986; Nuhfer and Baker 2004). Only brook trout have been carefully monitored over many years, but no large changes in any other species have been observed during trout sampling.

History of Experimental Manipulations and Other Perturbations

The 3.4-km experimental reach of Hunt Creek was used for a variety of experiments from 1952 to 2001. I made judgments of the effects these experiments had on brook trout population dynamics when selecting data for this new analysis. Periods used for fall comparisons of fish abundance, growth, and survival from 1952 to 2001 are as follows:

a. 1952–64-open to angling;
b. 1967–71-pretreatment and closed to angling;
c. 1972–75-transition as sand added to TZ;
d. 1976–81-post treatment;
e. 1982–90-sediment basins maintained;
f. 1991–2001-sediment basins retired.

Note that angling remained closed from b–f.

Periods used for comparisons of spring abundance are slightly different because spring population estimates did not begin until 1959. Some population estimates were not used in the analysis for reasons described below.

Hunt Creek was open to angling harvest from 1952 through 1965. The creel limit was 10 brook trout per day with a minimum size of 178 mm. Most brook trout in Hunt Creek do not grow to this size until they are 2 years old. In 1965, 165 trout longer than 178 mm were transferred from the TZ to diversion channels adjacent to the RZ. Thus, I did not use data for 1965 in my analysis. I also removed data for 1966 from the analysis because it was the first year the stream was closed to fishing and abundance of older fish had not had time to respond to the fishing closure.

A 20-year study of the effects of sand bedload on brook trout and their habitat began in 1967 and was formally concluded in 1986 (Alexander and Hansen 1986, 1988). In that study, data on stream morphology and trout population dynamics were first collected during a pretreatment period extending from 1967 through September 1971. I used the same pretreatment period (B) for my analyses. Experimental additions of sand, which increased the bed load about four times above pretreatment levels (from 20 to 80 ppm), were made to the treatment section from October 1971 through 1975. Sand was added daily on weekdays at the upstream boundary of the TZ and there was a transitional period from 1972 to 1975 as sand became distributed throughout the TZ. During the next five years (1976–81, post-treatment period), sand additions ceased and the stream was allowed to transport and export sand at natural rates from the TZ. A large sand trap at the downstream end of the TZ prevented sediment export from the study area and protected downstream waters. From 1982–90, three sediment basins were excavated within the TZ to accelerate sand removal. Basins were located at approximately, ¼, ½, and ¾ of the distance from the upstream end of the TZ. Sediment basins were retired (not cleaned out periodically) from 1991 to 2001.

In 1989, the channel length of the RZ was increased by 134 m and surface area by 0.04 ha to allow for controlled water diversions around the downstream 1/3 of the zone. Summer discharge (June through August) in the downstream 0.6 km of the RZ was experimentally reduced from 1991 through 1999 to study effects of water withdrawal on brook trout and their habitat (Nuhfer and Baker 2004). Summer water withdrawals had relatively modest or undetectable effects on population dynamics of brook trout so data collected during these years were included in my present analyses.

Scour by water released by the sudden failure of a beaver dam located immediately upstream of the RZ on November 15, 1960 resulted in lower than normal YOY abundance in fall 1961. Failure of a beaver dam at the same location on June 3, 1993 was associated with exceptionally low numbers of September YOY in the upper 1.3 km of the RZ that fall. Effects of the 1993 flood were attenuated in the lower 0.6 km of the RZ because 50% of water was being diverted and sediment transport from the beaver pond was minimal because the dam was quickly rebuilt. I used data from 1993 in my analyses because YOY abundance in the lower end of the TZ was not significantly different from prior years. The beaver dam washed out again on November 30, 1996 but was not rebuilt. Since then, much of the sediment previously trapped behind the dam was transported downstream into the RZ and was associated with lower abundance of YOY after 1997.

Population Estimate Methods

Trout populations were estimated in spring and fall by two-pass, mark-and-recapture electrofishing with a 2-probe, 240-V DC electrofishing unit towed behind wading electrofishers. Sampling was done during the third week of April and September each year. Fish sampling commenced at the downstream end of the 3.4-km study area and proceeded upstream. Recapture collections were made 2 days after marking. Data were recorded separately for the TZ and the RZ (Figure 1). Population estimates and variances were computed using the Bailey modification of the Peterson mark-and-recapture method (Bailey 1951; Ricker 1975). Population estimates were stratified by 25-mm length groups and then summed for a total population estimate. Population estimates were converted to numbers per ha both to account for differences in the surface areas of the zones and to adjust for a small increase in surface area of the TZ in 1989 when the channel was lengthened to allow for water diversion experiments. Age analysis based on brook trout scale samples was used to apportion population estimates by length groups into estimates by age group for each section and sampling period. Survival rates were computed from sequential estimates of abundance of age groups. Weighted mean length by age group was computed by the methods described by Alexander and Ryckman (1976) and Schneider (2000). Annual growth increments were computed by subtraction of sequential estimates of mean fall length at age for each age cohort (e.g., length increment = (mean length year (X + 1) – mean length year (X)).

Stream Morphology Methods (Past and Recent)

Alexander and Hansen (1986) evaluated changes in stream morphology from measurements taken along permanent cross sections spaced 30.5 m apart along the entire study reach. They surveyed at these transects annually from 1971 through 1977, and again in 1980 and 1984. They determined water surface and bed elevations relative to elevations of wooden stakes on the bank using a generalized sag tape procedure similar to that described in Ray and Megahan (1978). They used stakes driven flush with the bottom of the streambed, in midstream, at each transect, as a benchmark for bed elevation. Substrate along each transect was classified into a wide array of bottom types, including mixed types such as various mixes of sand and gravel, gravel and silt, etc. I initially intended to duplicate Alexander and Hansen's (1986) morphology measurements to the extent possible at the same transect locations in 2000 but was unable to locate many of the wooden posts placed as markers nearly 3 decades earlier. Moreover, the raw data for their stream morphology and substrate observations had been sent to a data archive in Minnesota and could not be located. Consequently, I established 109 new transects spaced at 30.5-m intervals throughout the study area (Appendix 1). Wooden stakes were driven into each bank, perpendicular to streamflow direction, and approximately 1 m from the water's edge to mark transect locations. A measuring tape was stretched between the stakes and GPS coordinates (differentially corrected) were recorded at the center of the stream at each transect (Appendix 1). Water depth was measured at 30.5-cm intervals along each transect. The predominant substrate type (defined as the substrate type beneath 50% or more of a 30.5-cm segment) was classified as to principal inorganic particle size (Table 1) or biological materials (wood or detritus). Sand embeddedness of coarse substrates (fine gravel or larger) was rated by a system similar to that described by Platts et al. (1983) (Table 1). Stream morphology measurements were made in June 2000 when stream discharge was 0.68 ± 0.02 m^3/s at the downstream end of the study area. Discharge was determined from water stage data recorded hourly by a Sutron stage height recorder.

A transit and level rod were used to make a longitudinal survey of the elevation of the water surface and streambed in the study reach (Harrelson et al. 1994). Relative elevations were determined for each transect at the midpoint of the stream. The longitudinal survey was conducted during July 2003 when stream discharge was approximately 0.76 m^3/s.

Statistical Methods

Brook trout population characteristics of density, survival, and growth were first compared between experimental periods by analysis of variance using SPSS (SPSS Inc. 2002). Six periods (A–F, defined above) were used for analysis of fall data. Spring population estimates were not made until April 1959; therefore, I used the years 1959–64 as the open to fishing period (A) for analyses of spring data. Period and stream reach type (treatment or reference zone) were treated as fixed effects in ANOVA analyses. Ratios of density in the TZ to the RZ were analyzed in a similar fashion. Within each zone, I compared brook trout density, survival, mean September length-at-age, annual growth increments, and various ratios computed from these parameters among periods. Differences in period means were determined from ANOVA analyses using the Bonferroni-t statistic to make post hoc comparisons among observed means when variance was homogeneous. If the Levine statistic indicated that variance was not homogeneous, I used the Dunnett-C test to make multiple post hoc comparisons because it does not assume equal variances. Differences among means were judged significant for $P \leq 0.05$.

Results

Brook Trout Abundance

Fall abundance of all age groups of brook trout was significantly lower in the TZ during the post-treatment period than during the pretreatment period (Table 2). By contrast, there was no significant difference for these periods in the RZ.

Abundance of YOY in the TZ declined rapidly during the transitional period when sand was added and then stabilized at a lower level in 1976–2001 (Figure 2). In another way of looking at the data, relative densities of YOY in the treatment and reference zones (the TZ:RZ ratio) were similar initially (0.96 prior to 1976) but became much lower (0.57) during the post-treatment period through 2001.

Changes in spring density of yearling brook trout paralleled those for fall YOY (Figure 3). In the TZ, spring yearling abundance reached a low point during the post-treatment period then partially recovered (Table 3). By comparison, in the RZ yearling abundance declined in the transition period but returned to normal in the last two periods. The TZ:RZ ratios (Figure 3) indicate the sedimentation effect extended through the last three periods.

Fall abundance of yearling brook trout in the TZ was markedly reduced by sedimentation, but fully recovered with sand trap operation. Their fall density declined from 1,145 trout/ha during the pretreatment period to 472 trout/ha in the post-treatment period (Table 2). Density increased shortly after sediment basins were excavated in 1982 and then returned to pretreatment status (Table 2; Figure 4). Fall yearling abundance in the TZ relative to the RZ remained at pretreatment status after sediment traps were retired (Figure 4).

Spring abundance of age-2 and older brook trout in the TZ declined and recovered in synchrony with fall yearlings (Figure 5). They were significantly less abundant during the post-treatment period than during all other periods except the transitional (Table 3). Evaluation of TZ:RZ ratios yielded similar results, namely that abundance in the TZ was significantly lower during the post-treatment period than during the pretreatment period or periods when sediment basins were maintained or retired (Figure 5).

Differences in fall abundance of age-2 and older brook trout occurred in the TZ due to both angler harvest and sedimentation. Abundance in the TZ was lower when the stream was open to angling than during the pretreatment period or periods after sediment traps (Table 2). Ratio analysis showed that abundance of older fish was significantly lower during the post-treatment period than during all other periods except the transition (Figure 6).

Spring and fall standing stocks of brook trout reflected the expected pattern of decline and restoration in the TZ and no change in the RZ (Table 4). In the TZ, biomass declined to about 40% of the pretreatment level by the post-treatment period, then quickly recovered. Temporal increases and decreases in biomass in the TZ and the RZ were relatively synchronous, except during the post-treatment period and during the initial years when sediment basins were excavated (Figure 7). The TZ:RZ ratios affirm the post-treatment effects of sedimentation on trout biomass (Figure 8).

Survival Rates and Movement

Mean annual survival of YOY in the TZ was related to sand loading. Survival rates were depressed during the transitional (23%) and the post-treatment (27%) periods, and doubled (45%) during the last two periods (Figure 9). By contrast, mean annual survival of YOY was remarkably stable in the RZ, averaging 38% over the 49-year period from 1952 to 2001 (Figure 10).

Among age-1 and older trout, annual survival was clearly reduced by angling in both zones (Figures 9 and 10). The effect of sand on their survival was not clear-cut in the TZ, but if statistical significance is ignored, then survival from age 1 to age 2 was lower during sedimentation and recovered to pretreatment levels after sediment basins were dug (Figure 9). There were no significant patterns in the RZ.

These annual estimates were influenced to an unknown degree by substantial seasonal movements of yearling brook trout between spring and fall. Yearlings immigrate into Hunt Creek from small tributaries, and some move between the TZ, the RZ, and other creek sections. This is indicated by estimates of mean survival of yearling trout from April to September that were over 100% during half of the study periods in both the TZ and the RZ (Table 5). Immigration of yearling fish into the TZ resulted in spring-to-fall survival estimates of over 100% in 12 of 19 years from 1982 (when sand traps were first constructed) to 2000 (Figure 11).

Survival of age-2 and older trout from spring to fall in the TZ was similar among most periods except that survival was significantly lower when the stream was open in angling than during the pretreatment period. In the RZ, survival was lower during the open-to-angling period than during all other periods (Table 5).

Growth

Similar changes in brook trout growth occurred in both zones for most ages (Figure 12). Mean lengths of age-0 fish in both zones, but especially in the TZ, tended to decrease during the transition and post-treatment periods and then increase after sediment traps were dug. Growth of age-1, age-2, and age-3 trout showed little effect of sand until a belated decrease occurred after 1982. However, parallel changes also occurred in the RZ.

Annual growth increments exhibited a slightly different temporal pattern than mean length at age data and significant differences between periods were found only for age intervals 0–1 and 1–2 (Figure 13). In the TZ, annual growth increments for age interval 0–1 were larger before sediment traps were dug or after traps were retired. Similar significant differences were observed in the RZ. Significant differences in growth increments for age interval 1–2 did not appear to be related to effects of sedimentation.

Channel Morphology and Substrate

Some changes in channel characteristics have occurred. In 2000, I estimated that mean channel width in the TZ had increased by 0.21 m relative to 1971, prior to sand additions (Table 6). Estimated stream width in the RZ was 0.1 m narrower than the 1971 estimate (Table 6). The channel in the TZ was also shallower in 2000, reducing static water volume about 10% (354 m^3) compared to 1971. Greater depths and water volumes were observed in the TZ in 1982 and 1984 when sediment was intensively trapped. In the RZ, water volume was higher in 2000 than in 1971 due to excavations that increased channel length for the 1991–99 water diversion experiments.

In 2000, there were substrate differences between TZ and RZ. Nearly 78% of substrates in the TZ were sand-and-finer particles in 2000, whereas 67% of substrates in the RZ were fine-gravel-or-larger particles (Table 7). Nearly half of the fine gravel in both zones was 75% or more buried in sand (Table 8). In the RZ, 30% of fine gravel was less than 50% embedded compared to only 11% in the TZ. Less imbedded coarse gravel was far more common in the RZ than in the TZ.

The ratio of gravel in the TZ compared to the RZ was the same in 2000 as in 1971 (Table 9). The TZ:RZ ratio of sand was slightly lower in 2000 (2.27) than in 1971 (2.50) and substantially lower than in 1973 when the ratio was 5.56. However, the data are not strictly comparable over time because Alexander and Hansen (1986) used different methods for classifying substrates (See methods). Furthermore, the TZ:RZ ratios of sand varied up and down between years in the 1970s while sand additions were still occurring, probably indicating there had been some inconsistency in classifying substrates.

Discussion

Abundance and Habitat

Lack of recovery of mean YOY brook trout abundance indicates that reproductive or juvenile habitat was not fully restored by sediment basins and natural export of sediment nearly 25 years after habitat was degraded by high sand bedload. However, sediment basins apparently restored habitat for fall yearling and older brook trout within about 6 years because trout abundance returned to levels observed before sand bedload increased. These findings are very similar to those reported by Alexander and Hansen (1986, 1988) who noted that fall abundance of age-1 and older trout had recovered 10 years after experimental sand additions were discontinued in spite of the lack of recovery of fall YOY populations. Juvenile habitat apparently was not fully restored even though sediment basins removed the volume of sediment added to the TZ during the 1970s. Alexander and Hansen (1988) reported that mean streambed elevation and sand bedload concentrations in the TZ had recovered to pretreatment levels by 1984 after several years of intensive maintenance of three sediment basins in the 1.5-km stream reach. They also reported that total water volume in the TZ had increased by about 4% in 1984 as compared to pretreatment conditions. I could not assess how streambed elevation of the TZ in 2000 compared to earlier measurements because elevation benchmarks used in the earlier study could not be relocated. My estimate of a 10% reduction in water volume in the TZ compared to 1971 pretreatment volume could indicate that the streambed has aggraded. However, it could also have occurred because my habitat transects were in different locations than those used by Alexander and Hansen (1986).

Sediment basins exposed gravel buried by the sand treatment and the gravel remained exposed 10 years after sediment trapping ceased. However, it is not known if gravel is presently more embedded than in the past because embeddedness was not assessed by Alexander and Hansen (1986). It is clear, however, that gravel in the TZ is heavily embedded with sand, and this is a possible reason why fall YOY abundance has not recovered to pretreatment levels. Sediment embedded in spawning gravel reduces oxygen transport into redds and can block emergence of fry (Wickett 1954; Cordone and Kelley 1961; Peters 1965, 1967; Sowden and Power 1985; Curry and MacNeill 2004). Stream power is low in the TZ because channel slope is low, 0.00081 in the upper half and 0.00129 in the downstream half. More powerful flushing flows occur infrequently. Extreme high flows occurred three times during the study due to sudden failures of a beaver dam immediately upstream of the study area. These extreme peaks in discharge carried large volumes of sand (based on observations of sand deposition in the floodplain) and probably increased, rather than decreased, embeddedness. Alexander and Hansen (1983) hypothesized that improvement in habitat and abundance of young (fry to age 1) brown and rainbow trout observed downstream of a sediment trap on Poplar Creek, Michigan resulted from less sand embeddedness. The stream reach below the sediment trap on Poplar Creek had a higher gradient than the TZ of Hunt Creek. The question of whether the lower contemporary abundance of fall YOY brook trout in the TZ of Hunt Creek is due to reduced emergence of fry or reduced survival of fry to fall YOY can not be resolved because I have no estimates of fry abundance in the spring.

Many of the fall YOY in the TZ could originate from fry produced in the RZ upstream or from the tributary Pine Ridge Creek, where there is much high-quality spawning habitat and many YOY. Fry could also immigrate into the

TZ from several other small tributaries that have never been surveyed for trout. During 1943, weirs operating on five tributaries to Hunt Creek captured 1,161 brook trout moving downstream and 292 moving upstream (Carbine and Shetter 1943). They reported that most migrants were fingerlings and fish approaching legal size (178 mm). Although several of the weirs were located a substantial distance upstream of my study area, that study illustrates the potential significance of emigration from tributaries. Year-to-year changes in fall abundance of YOY in the TZ and the RZ are very synchronous, which could indicate a large downstream movement of fry. Hunt (1965) conducted a 5-year study on movement of brook trout fingerlings in Lawrence Creek, Wisconsin, and reported that from 9 to 66% of YOY brook trout present in a downstream study reach in early September originated from upstream reaches where they were marked in June. More fingerlings emigrated when their densities were higher. Lawrence Creek is similar to Hunt Creek in that upstream reaches contain better spawning habitat.

Sedimentation apparently had a greater long-term adverse effect on winter habitat of young fish than on summer habitat. Spring yearling abundance in the TZ relative to the RZ was lower during the post-treatment period and thereafter, than during the pretreatment or transitional period. This suggests that winter carrying capacity for juvenile brook trout (age 0 in fall, and age 1 after January 1) was not fully restored by sediment removal. The smoothing of the stream bottom by sand deposition probably reduced the availability of interstices and the number of sheltered low-velocity areas in the TZ, thereby increasing energetic costs of brook trout. Cooper (1953) observed that in winter, brook trout in Hunt Creek could only be found where they were shielded from the current, such as under banks, and in brush and debris. Small brook trout reduce energy expenditures during cold periods by hiding within rubble or other confined spaces that provide shelter from high velocity water and ice (Cunjak and Power 1986a, 1986b). Similar winter hiding behavior has been documented for other salmonid species such as coho salmon *Oncorhynchus kisutch*, chinook salmon *Oncorhynchus tshawytscha*, Atlantic salmon *Salmo salar*, steelhead trout *Oncorhynchus mykiss*, cutthroat trout *Oncorhynchus clarki*, and brown trout *Salmo trutta* (Hartman 1963; Chapman and Bjornn 1969; Bustard and Narver 1975a, 1975b; Rimmer et al. 1983). Hillman et al. (1987) found that 80% of age-0 chinook salmon emigrated when stream temperatures fell to 4–8 ^{o}C at study sites in an Idaho stream where cobble was heavily embedded with fine sediment. Addition of clean cobble substrate resulted in an eight-fold increase in densities of young chinook salmon, but when the cobble later became embedded with sediment, November densities again declined.

Cunjak (1988) observed that winters were physiologically stressful for brook trout in Ontario streams and that lipid levels were rapidly depleted. Thus, even modest increases in energetic demands due to a paucity of velocity shelters in Hunt Creek could have reduced carrying capacity for juvenile fish during winter. Hunt (1969) observed that overwinter survival of YOY brook trout in Lawrence Creek tended to be higher for larger than smaller fingerlings and suggested that physiological resistance to cold temperature stress was the causal factor. In the Hunt Creek TZ, fall YOY generally grew larger and survived better over winter after sand traps were dug, but the increase in survival was not sufficient to restore abundance of spring yearlings (relative to the RZ) to pre-sedimentation levels.

Sediment basins were very effective in restoring fall abundance of yearling-and-older (YAO) fish. Recovery of the population occurred primarily through increased survival of YAO and immigration during spring and summer. Alexander and Hansen (1988) believed that increased survival observed after sediment removal indicated that habitat had been restored for larger fish. Spring or summer immigration of yearling trout after sediment basins were constructed was a significant factor in the recovery of fall populations of older fish, although I could not determine if most immigrants originated from upstream or from tributaries.

Survival estimates for yearling trout that exceeded 100% from spring to fall could result from several causes. First, such estimates could result from error or imprecision in spring and fall estimates of yearling fish. I believe this is unlikely because the 95% confidence limits for yearling trout averaged about ±11% of population point estimates over the half-century that populations were estimated. Inaccurate aging of scales could also bias yearling estimates, but younger trout are relatively easy to age correctly, so I do not believe this is a significant source of error.

Migration

Immigration from both tributaries and the RZ is probably the reason survival estimates for yearling trout in the TZ between April and September frequently exceeded 100% after deeper habitat was restored by sediment removal. Nuhfer and Baker (2004) reported that average spring-to-fall survival of YAO trout in the lower 600 m of the RZ was 69% for the period from 1991–98. Fish traps were operated at both ends of the reach from June through August during those years and there are no tributaries. If spring to fall natural mortality of yearling fish in other sections of Hunt Creek is similar to this value (31% mortality), then an average of 233 summer-yearling immigrants into the TZ would have been sufficient to produce survival estimates of 100% in the years when this occurred after 1982. The only tributary to the TZ where populations have been estimated is Pine Ridge Creek, which in 1983 supported approximately 500 fall-YOY brook trout in a reach extending 450 m upstream from the creek mouth (Alexander 1985). Baseflow discharge near the mouth is only 0.07 m^3/s and deep habitat for older trout is relatively sparse. I hypothesize that significant downstream movement of Pine Ridge Creek trout to the TZ of Hunt Creek occurs as they grow larger. Thus, I believe that the computed number of migrants (>233) needed to explain the apparent 100% survival in the TZ could easily come from tributaries and upstream sections of the mainstem.

Spring-to-fall survival estimates of yearling trout in the RZ also exceeded 100%, indicating that immigration occurred from the upper mainstem of Hunt Creek, Fuller Creek, and possibly the TZ. Effects of immigration on spring to fall survival estimates were particularly evident when spring yearling densities were low. Semi-annual survival estimates over 100% occurred in the RZ during 10 of 18 years when spring yearling densities were less than 1,550/ha and the highest annual survival estimate (166% in 1975) occurred when spring densities were lowest (512/ha). Spring density of yearling fish in the TZ was also near a record low that year so it is not probable that upstream movement from the TZ into the RZ between spring and fall accounted for the high survival rate. If immigration into the RZ is fairly constant over time, then spring to fall survival estimates would be elevated more when spring densities in the RZ were lower, such as during the transition period when their mean density was 956/ha, than from 1982 to 2001 when spring yearling density averaged 1,900/ha.

Regardless of the relative contributions of changes in survival or movement to the recovery of the population in the TZ, it is clear that adverse effects of sedimentation estimated in this study were lower than would be expected in a stream without such high densities of fish in adjacent stream reaches or tributaries. Thus, even though fall YOY and spring yearling abundance in the TZ did not recover to pretreatment levels relative to the RZ, fall populations of YAO fish did recover. Winter habitat for older trout was presumably restored because survival of fall age-1 fish to fall age 2 increased after sediment basins were dug. Sediment basins very rapidly restored overall carrying capacity of the stream, as indicated by the remarkable similarity between zones of spring and fall standing stock estimates (kg/ha) from 1985 to 2001 (Figure 7).

Effects of Fishing

The primary effects of angling on trout populations were reduced abundance of age-2 and older fish and reduced survival of these fish from spring to fall. Alexander and Nuhfer (1993) showed that reduced abundance and survival of age-2 and older trout were directly attributable to heavy cropping of brook trout by anglers when they grew to legal size. Similar effects of angler harvest have been demonstrated in Lawrence Creek (Hunt 1970).

Growth

The high similarity in temporal changes in growth between the TZ and the RZ probably indicates that factors other than sedimentation had greater effects on growth rates. The most notable change over time was a large decrease in the fall mean length of yearling trout during the sand-trap period and post-sand-trap period as compared to earlier periods. Water temperature and ration are major factors influencing growth of trout (Elliott 1994), and Hinz and Wiley (1997) found that mean daily temperature fluctuation in July explained nearly 50% of the variation in juvenile brook trout growth rates among Michigan stream sites. However, temporal changes in temperature are an unlikely cause of the changes in growth observed in Hunt Creek because both July and mean annual temperatures appear very similar for periods beginning in 1972. Mean monthly temperatures from 1972 to 1988 were measured at the boundaries of both zones by maximum-minimum thermometers (read weekly) and from 1993 to 2001 from electronic thermographs set at a measurement interval of 60 minutes.

Slower growth in the RZ compared to the TZ was probably due, in part, to colder water temperatures, although fish density and rations may have played a role. Mean July water temperature at the upstream end of the RZ was an average of 1.6°C colder than at the downstream end of the TZ. However, July temperatures in the lower 600 m of the RZ were similar to temperatures in the TZ because of warming by Fuller Creek. Hinz and Wiley (1998) found a positive relation between temperature and macroinvertebrate standing stock and further reported that available ration had a significant effect on growth rate of juvenile brook trout. Similar declines in growth of juvenile trout in both zones after 1982, in the absence of obvious changes in thermal regime, suggest that food production has declined throughout the study area. Kohler and Wiley (1997) reported large fluctuations in macroinvertebrate abundance in the RZ of Hunt Creek associated with cyclic population collapses of G*lossosoma nigrior* caddisflies. Cooper (1953) asserted that an inadequate food supply was a contributing factor to the slow growth rates of Hunt Creek brook trout. Alexander and Hansen (1988) reported that by 1985 benthos in the TZ had recovered to about 50% of pretreatment numbers and 80% of pretreatment volume. The lower recovery level for benthic numbers suggests that a paucity of smaller benthic organisms, which are the predominant food eaten by young brook trout in Hunt Creek (Alexander and Gowing 1976), contributed to slower growth rates after 1982. Alexander and Gowing (1976) found that mean quantity of food per stomach accounted for 80% of the variation in annual trout growth regardless of trout species or habitat (lake or stream). Thus, the slower growth from age 0 to age 1 after 1982 may indicate that benthos eaten by trout of this age was less abundant in both zones, than during earlier periods.

I found some evidence of inverse density dependent growth for YOY brook trout during their first 6 months of life but density dependent growth was not evident for older fish. Density dependent growth was most evident in the TZ where habitat had been altered and where the range of fall density of YOY varied 5.2 times from 1952 to 2001. The regression of YOY mean length against fall density of YOY accounted for 40% of the variation in mean length in the TZ ($P < 0.001$). By contrast, only 7% of the variation in mean length of YOY was related to density in the RZ, where density of YOY varied by 2.5 times during the study ($P = 0.008$). Alexander and Hansen (1988) previously suggested that growth of YOY in Hunt Creek was density dependent based on data collected through 1986. Density dependent growth was not evident for age-1 brook trout in either zone even thought their abundance varied by a similar magnitude as YOY over the same time. Inverse density dependent growth of trout has been documented in small, oligotrophic lakes in Michigan (Gowing 1974) but is rarely evident in Michigan trout streams (Clark et al. 1979). Previous investigations of density and growth rates of the Hunt Creek brook trout suggest that emigration or mortality result in adjustments of the population to its food supply that reduce variation in growth rates (McFadden et al. 1967; Alexander and Hansen 1988). If large numbers of fall YOY or spring yearlings immigrated into the TZ after 1982, then apparent growth increments from age 0 to 1 in the TZ would have been reduced because immigrants from upstream waters or tributaries are smaller at a given age.

Management Implications

This study demonstrated that relatively modest increases in sand bedload concentrations, from 20 ppm to 80 ppm, in small, low-gradient streams could induce very large declines in habitat quality and abundance of all age groups of brook trout. Fall age-1, and age-2 and older brook trout abundance was reduced to about 40% and 30% of their pre-sedimentation levels, respectively. Intensive removal of sand from the channel via sand traps (three traps/1.5 km) restored habitat and abundance of age-1 and older trout within about 6 years. Abundance of age-1 and older brook trout remained at the restored level during the 11 years after sediment basins were retired. The only partial recovery of age-0 trout to about 55% of pretreatment abundance 25 years after sediment additions ceased emphasizes the importance of erosion control because it is difficult to fully restore habitat damaged by sedimentation. I believe that a persistent high level of embeddedness of sand in gravels was a major impediment to full recovery of YOY. Thus, land and water managers should emphasize prevention of the entry of excess sand sediment into channels because damaged habitat is difficult to fully restore. The rapid increase in age-1 and older trout abundance observed in Hunt Creek after sand traps were constructed was possible, in part, because abundant juvenile fish in adjacent stream areas and tributaries immigrated into the treatment zone, remained resident, and survived better because deeper habitat and LWD cover was restored. Sediment traps provided excellent deep-water habitat while they were maintained.

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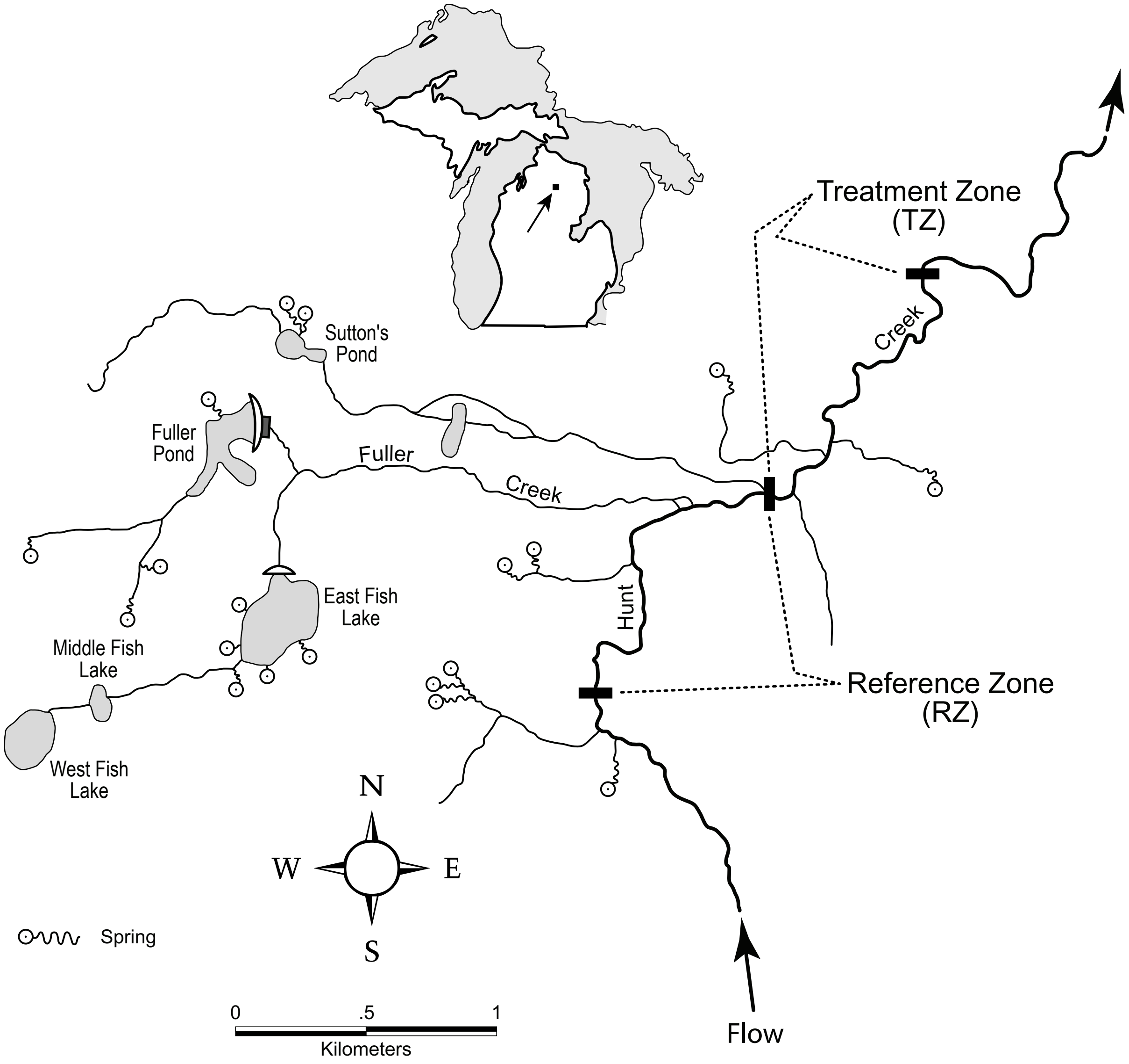

Figure 1.–Map of upper Hunt Creek, Michigan.

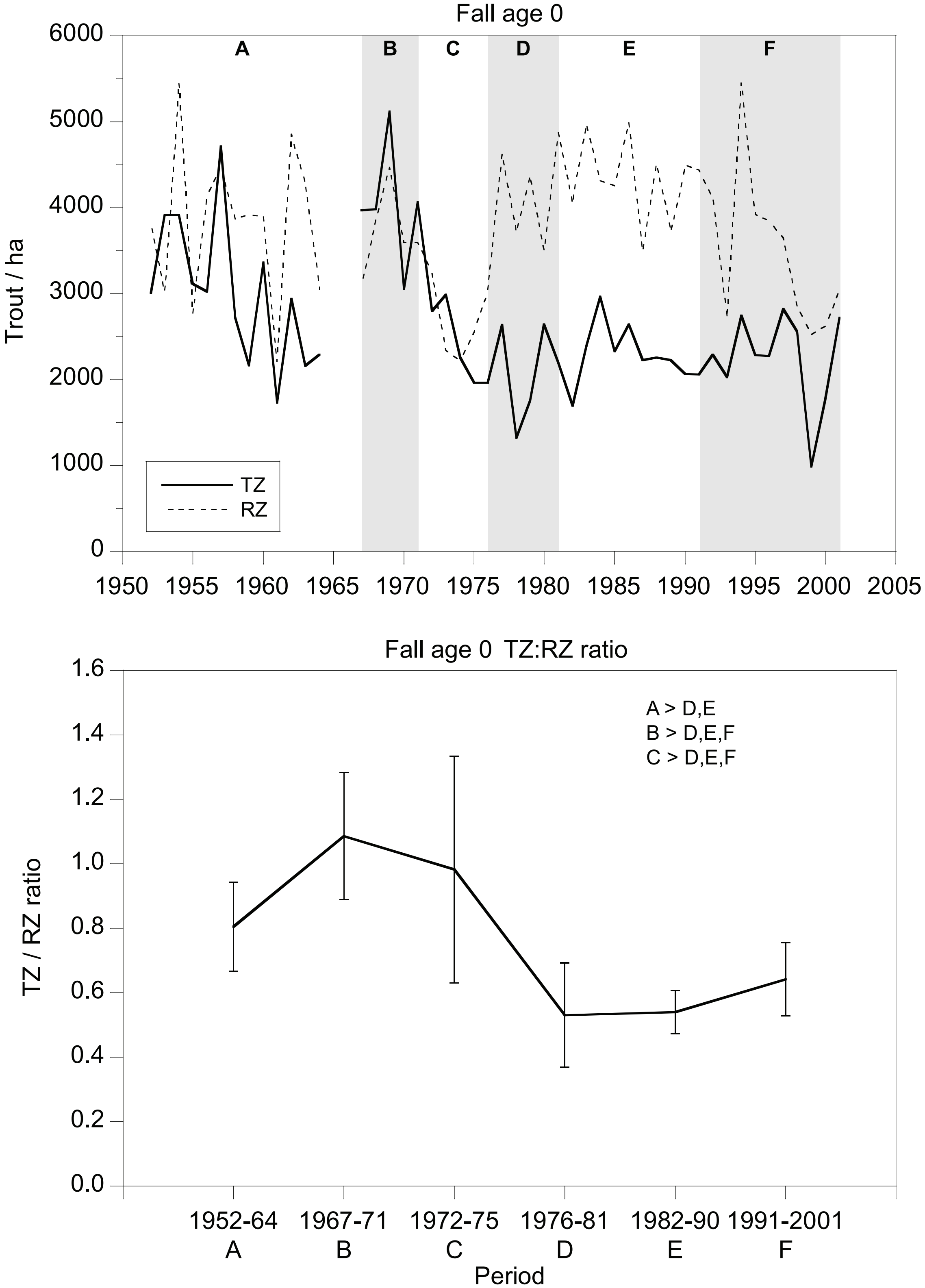

Figure 2.–Annual fall estimates of age-0 brook trout per ha in treatment (TZ) and reference (RZ) zones of Hunt Creek (top panel) and mean ratio of their abundance in the TZ to abundance in the RZ during six periods (bottom panel). Vertical bars are 95% confidence bounds of the mean ratios. Inset identifies significant differences ($P \leq 0.05$) among ratios between periods.

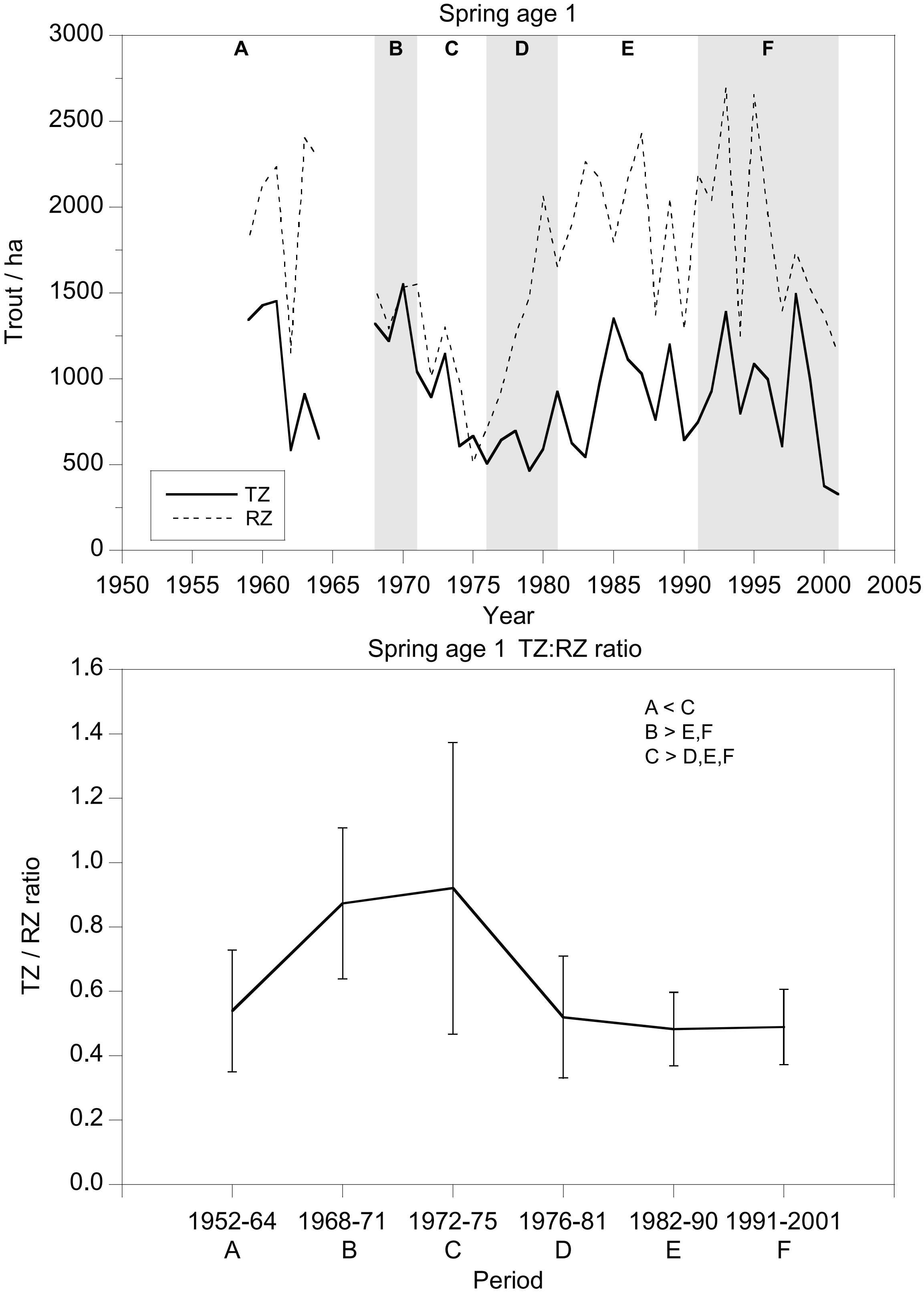

Figure 3.–Annual spring estimates of age-1 brook trout per ha in treatment (TZ) and reference (RZ) zones of Hunt Creek (top panel) and mean ratio of their abundance in the TZ to abundance in the RZ during six periods (bottom panel). Vertical bars are 95% confidence bounds of the mean ratios. Inset identifies significant differences ($P \leq 0.05$) among ratios between periods.

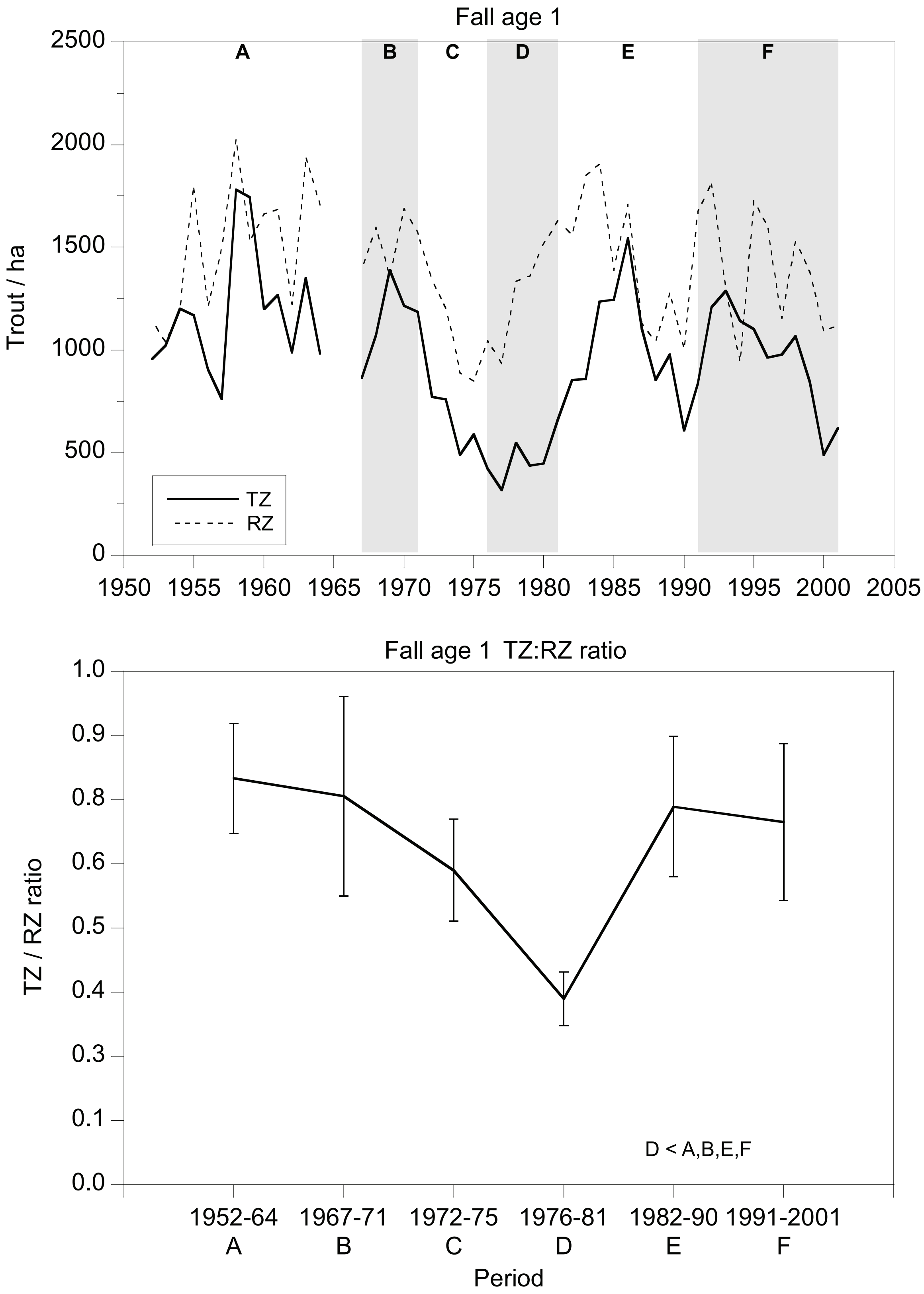

Figure 4.–Annual fall estimates of age-1 brook trout per ha in treatment (TZ) and reference (RZ) zones of Hunt Creek (top panel) and mean ratio of their abundance in the TZ to abundance in the RZ during six periods (bottom panel). Vertical bars are 95% confidence bounds of the mean ratios. Inset identifies significant differences ($P \leq 0.05$) among ratios between periods.

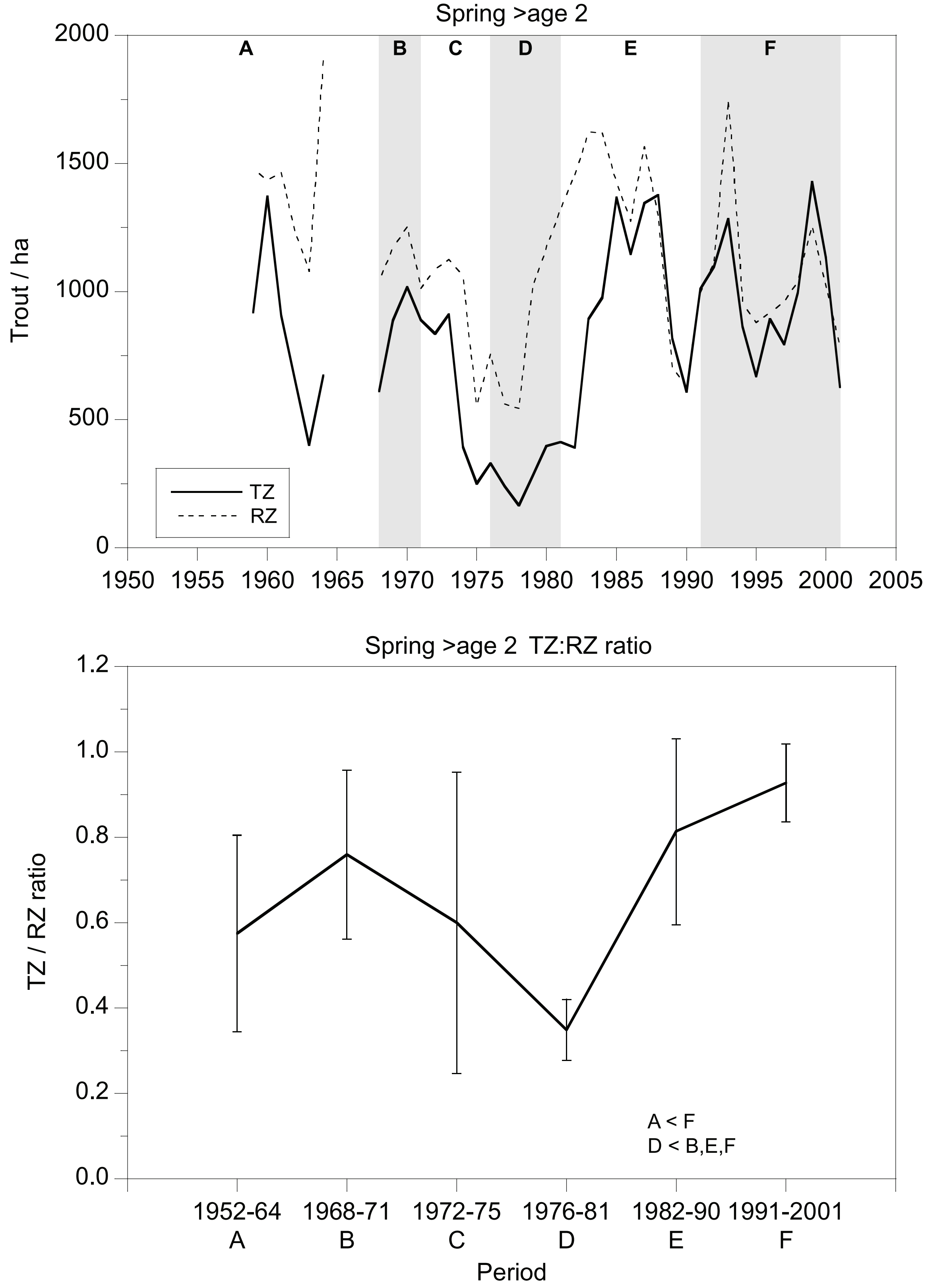

Figure 5.–Annual spring estimates of age 2 and older brook trout per ha in treatment (TZ) and reference (RZ) zones of Hunt Creek (top panel) and mean ratio of their abundance in the TZ to abundance in the RZ during six periods (bottom panel). Vertical bars are 95% confidence bounds of the mean ratios. Inset identifies significant differences ($P \leq 0.05$) among ratios between periods.

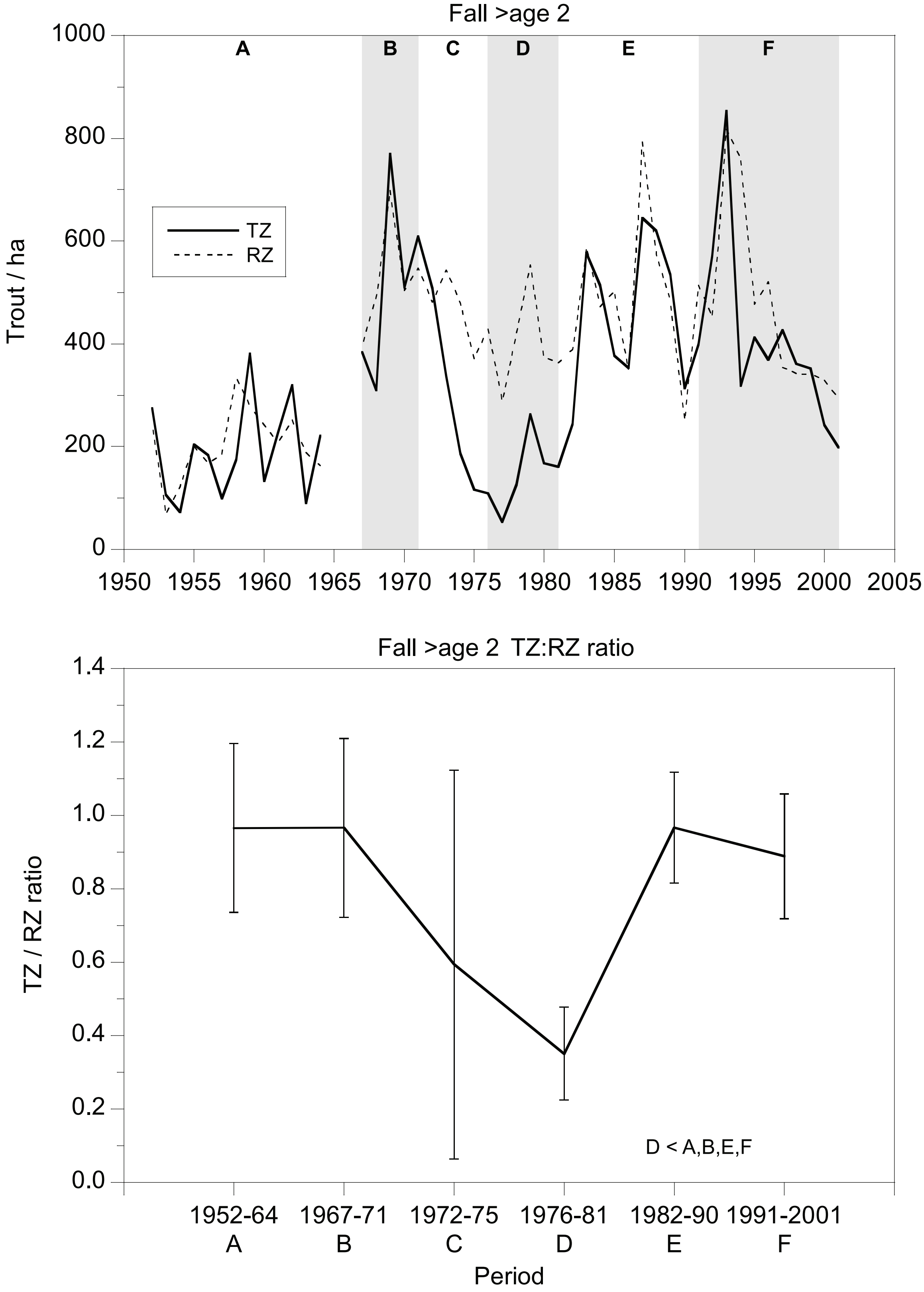

Figure 6.–Annual fall estimates of age 2 and older brook trout per ha in the TZ and RZ of Hunt Creek (top panel) and mean ratio of their abundance in the TZ to abundance in the RZ during six periods (bottom panel). Vertical bars are 95% confidence bounds of the mean ratios. Inset identifies significant differences ($P \leq 0.05$) among ratios between periods.

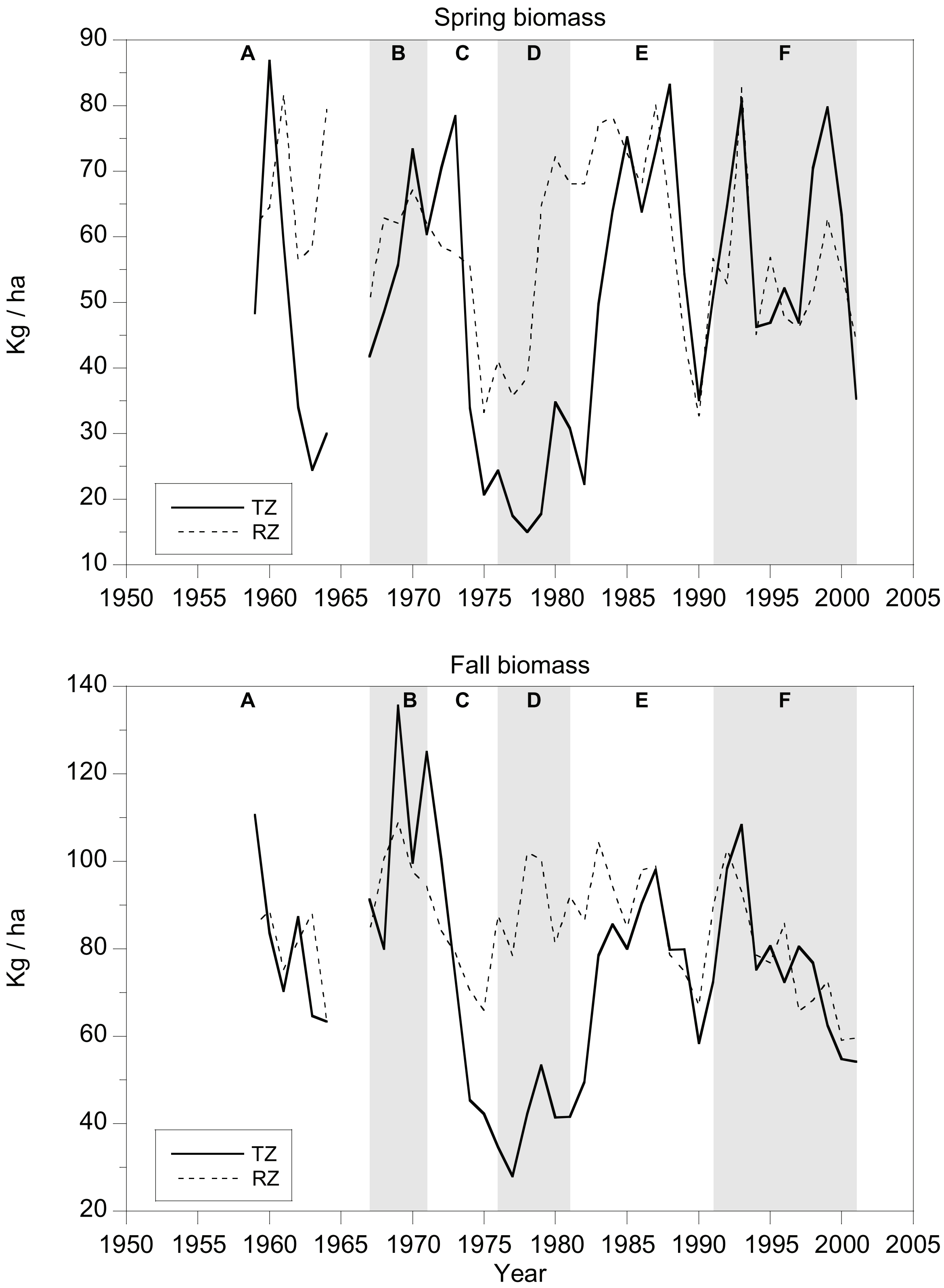

Figure 7.–Spring (top panel) and fall (bottom panel) biomass (kg/ha) of brook trout in treatment (TZ) and reference (RZ) zones of Hunt Creek.

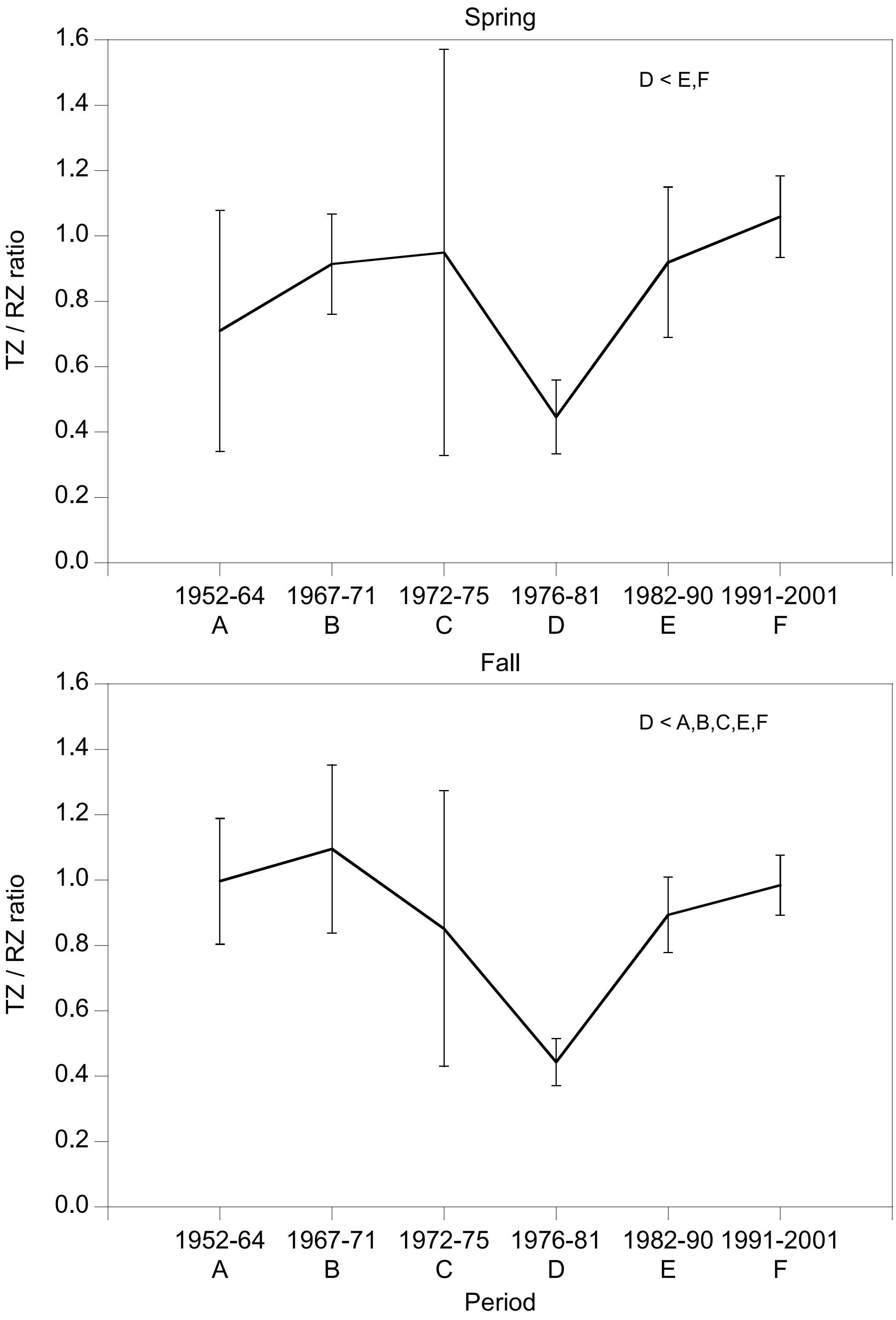

Figure 8.–Mean ratio of spring biomass (kg/ha) in the TZ to that in the RZ during six periods (top panel) and mean ratio of fall biomass (kg/ha) in the TZ to that in the RZ during six periods (bottom panel). Vertical bars are 95% confidence bounds of the mean ratios. Inset identifies significant differences ($P \leq 0.05$) among ratios between periods.

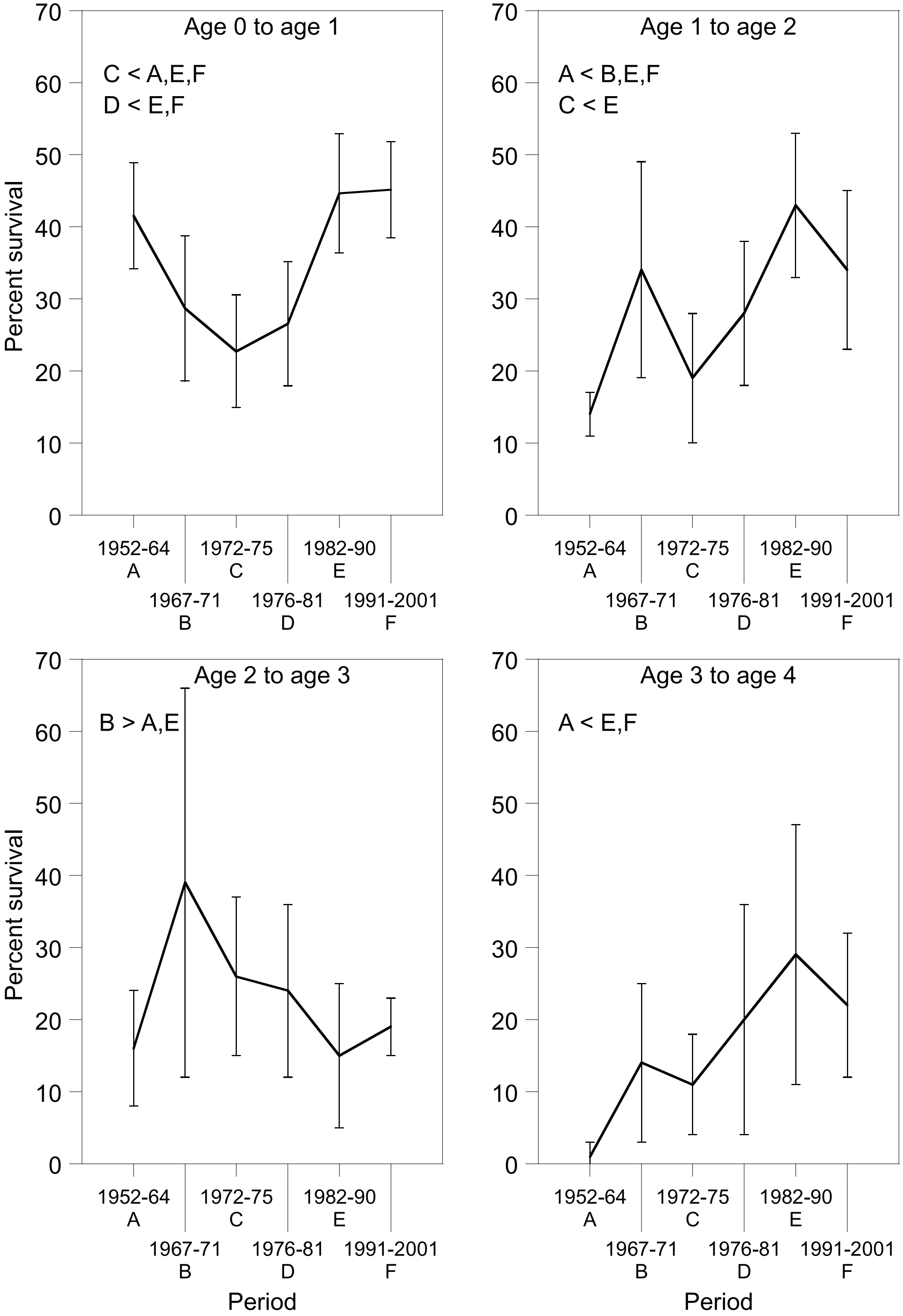

Figure 9.–Mean annual survival (September to September) of brook trout in the treatment zone of Hunt Creek for six time periods. Vertical lines are 95% confidence bounds of the mean. Significant differences ($P \leq 0.05$) among periods (identified by letter on the x axis) are shown inside each panel.

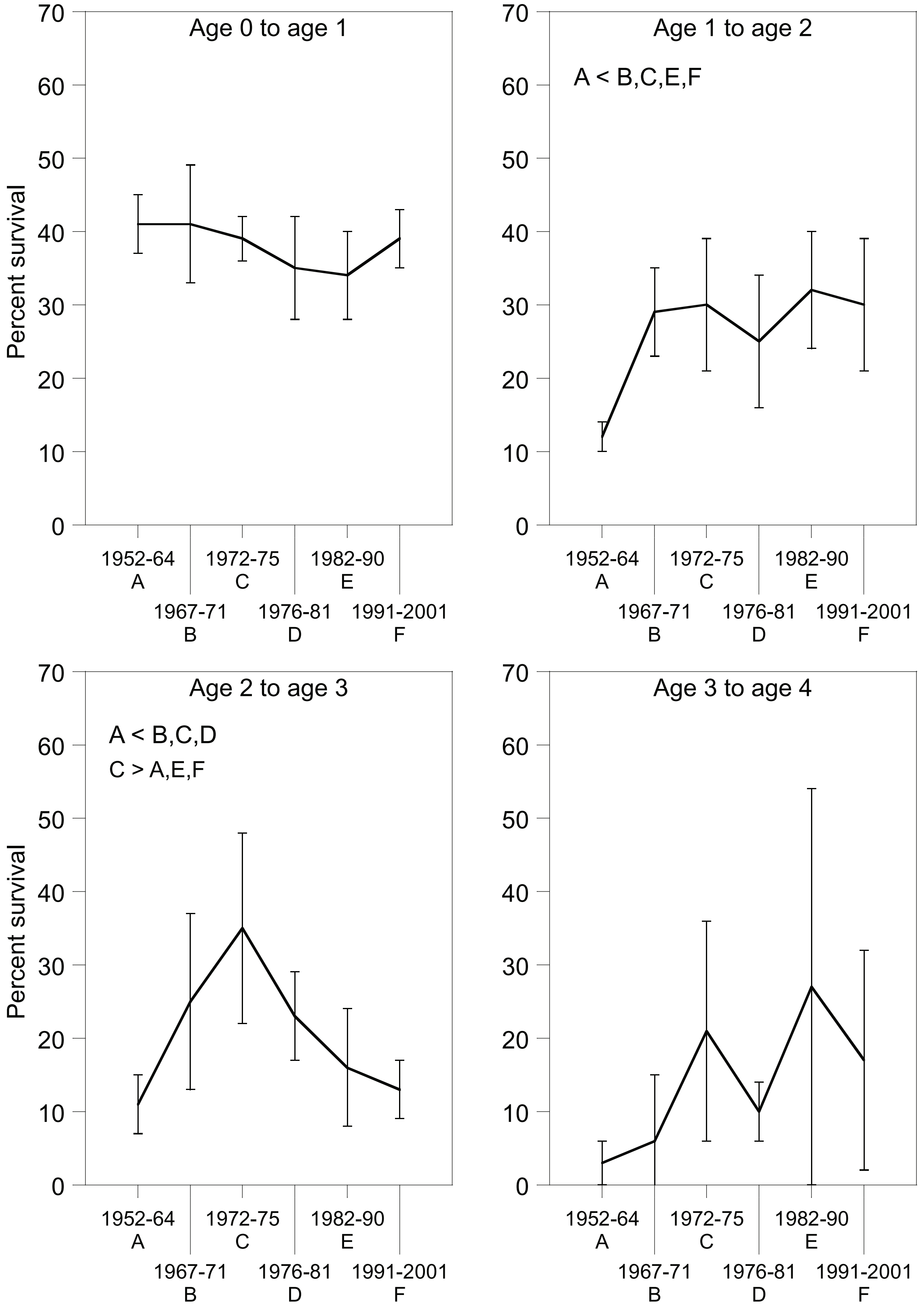

Figure 10.–Mean annual survival (September to September) of brook trout in the reference zone of Hunt Creek for six time periods. Vertical lines are 95% confidence bounds of the mean. Significant differences ($P \leq 0.05$) among periods (identified by letter on the x axis) are shown inside each panel.

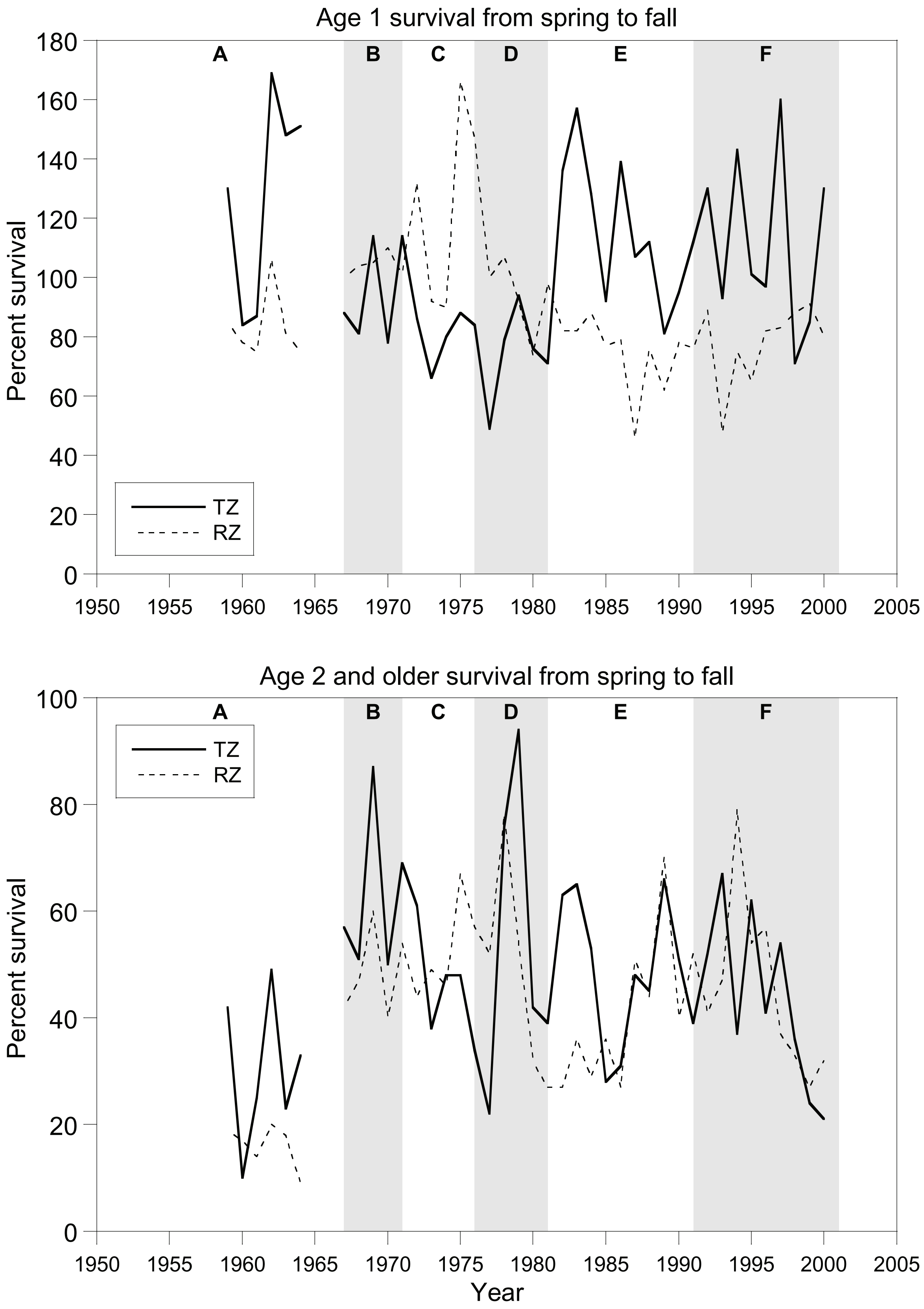

Figure 11.–Semi-annual survival rates of brook trout in the TZ and the RZ of Hunt Creek from 1959 to 2000.

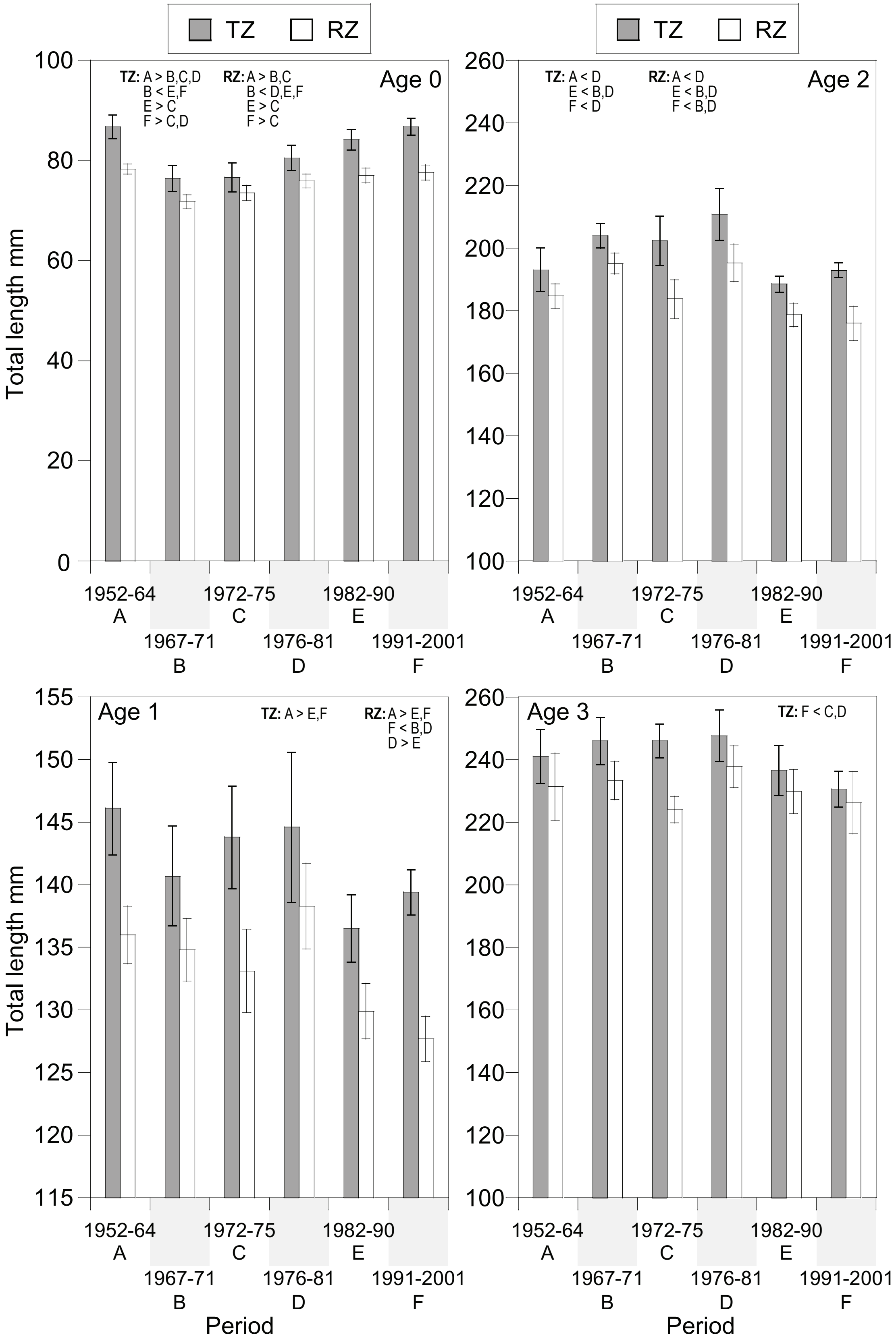

Figure 12.–Mean total length at age in mm in September (± 2 standard errors of the mean) for four age groups of brook trout during six periods. Significant differences ($P \leq 0.05$) among periods (identified by letter on the x axis) are shown inside each panel.

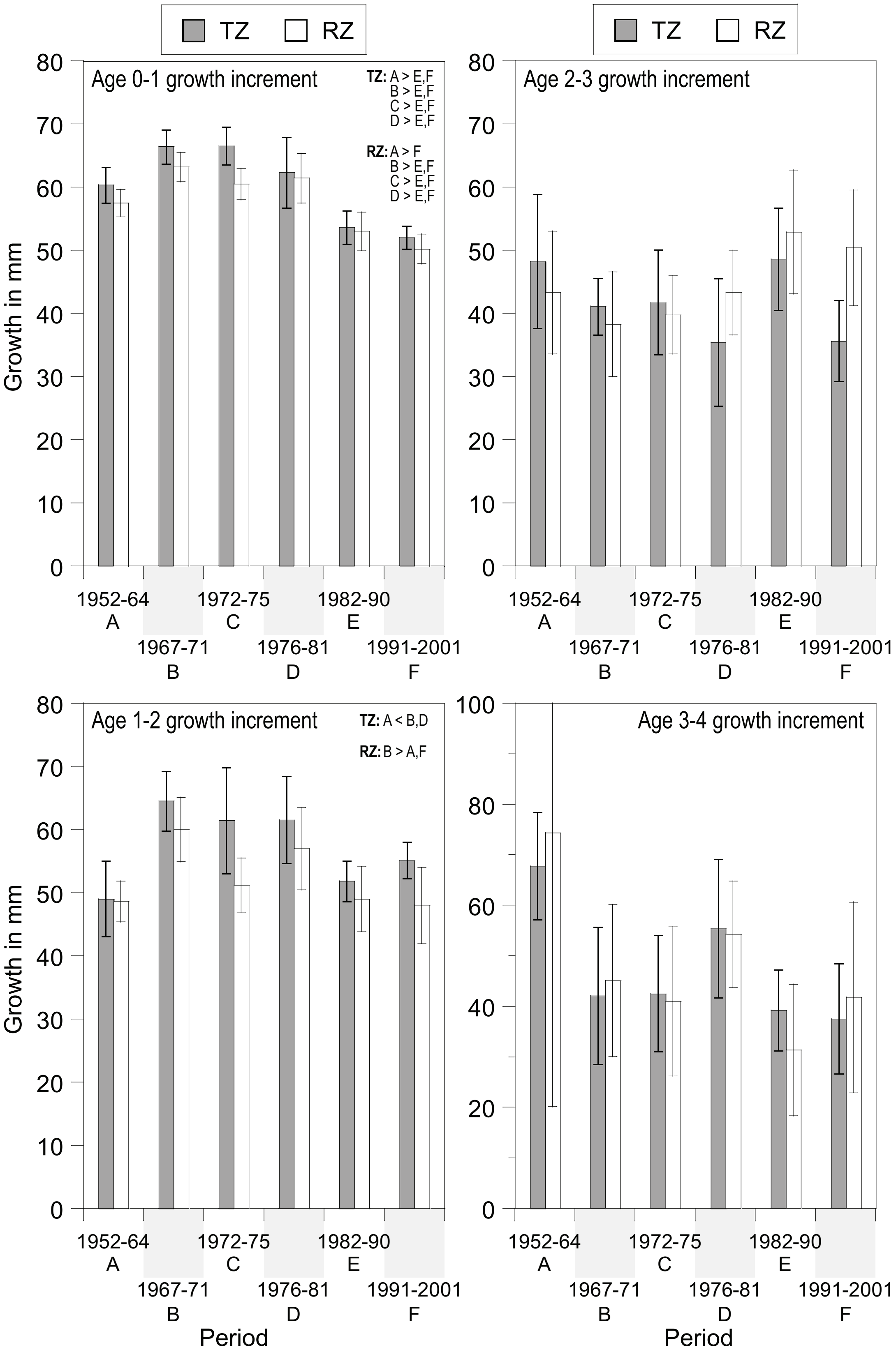

Figure 13.–Mean annual total length growth increments (± 2 SE) for four age groups of brook trout during six time periods. Significant differences ($P \leq 0.05$) among periods (identified by letter on the x axis) are shown inside each panel.

Table 1a.–Inorganic particle size ranges used to describe stream substrate type.

Substrate type	Size range (mm)
Silt or clay	<0.002 – 0.04
Sand	0.05 – 1.99
Fine gravel	2 – 24
Coarse gravel	25 – 64
Small and medium cobble	65 – 128

Table 1b.–Rating descriptions used to describe the degree of embeddedness of gravel or cobble substrates with sand.

Embeddedness rating	Rating description
4	0–24% of gravel covered with sand
3	25–49% of gravel or cobble covered with sand
2	50–74% of gravel or cobble covered with sand
1	Over 75% of gravel or cobble covered with sand

Table 2.–Mean September abundance of brook trout per ha in the treatment (TZ) and reference zone (RZ) by age during six periods and significant differences ($P \leq 0.05$) between periods.

	Treatment zone		Reference zone	
Period	Number	Differences	Number	Differences
	Age 0			
A-1959–64 Open to angling	3,006	A < B	3,831	
B-1967–71 Pretreatment, closed to angling	4,038		3,727	
C-1972–75 Transition as sand added to TZ	2,503	C < B	2,587	
D-1976–81 Post treatment	2,088	D < B	4,021	
E-1982–90 Sediment basins maintained	2,311	E < B	4,312	C < E
F-1991–2001 Sediment basins retired	2,231	F < B	3,566	
	Age 1			
A-1959–64 Open to angling	1,179		1,513	
B-1967–71 Pretreatment, closed to angling	1,145		1,523	
C-1972–75 Transition as sand added to TZ	652	C < A	1,070	
D-1976–81 Post treatment	472	D < all others	1,304	
E-1982–90 Sediment basins maintained	1,031		1,429	
F-1991–2001 Sediment basins retired	958		1,393	
	Age 2 and older			
A-1959–64 Open to angling	192	A < B, E, F	205	A <all others
B-1967–71 Pretreatment, closed to angling	517		527	
C-1972–75 Transition as sand added to TZ	287		469	
D-1976–81 Post treatment	147	D < B, E, F	405	
E-1982–90 Sediment basins maintained	464		489	
F-1991–2001 Sediment basins retired	409		473	

Table 3.–Mean April abundance of brook trout per ha in the treatment (TZ) and reference (RZ) zones by age during six periods and significant differences ($P \leq 0.05$) between periods.

	Treatment zone		Reference zone	
Period	Number	Differences	Number	Differences
	Age 1			
A-1959–64 Open to angling	1,062		2,002	
B-1967–71 Pretreatment, closed to angling	1,283		1,477	
C-1972–75 Transition as sand added to TZ	830		956	C < A, E, F
D-1976–81 Post treatment	638	D < B	1,347	
E-1982–90 Sediment basins maintained	915		1,938	
F-1991–2001 Sediment basins retired	886		1,815	
	Age 2 and older			
A-1959–64 Open to angling	820		1,432	
B-1967–71 Pretreatment, closed to angling	851		1,119	
C-1972–75 Transition as sand added to TZ	597		957	
D-1976–81 Post treatment	304	D < A, B, E, F	897	D < A
E-1982–90 Sediment basins maintained	992		1,289	
F-1991–2001 Sediment basins retired	982		1,061	

Table 4.–Mean spring and fall standing crops of brook trout (kg/ha) in the treatment (TZ) and reference (RZ) zones by age during six periods and significant differences ($P \leq 0.05$) between periods.

	Treatment zone		Reference zone	
	Biomass	Differences	Biomass	Differences
	Spring			
A-1959–64 Open to angling	47.1		67.0	
B-1967–71 Pretreatment, closed to angling	56.0		60.8	
C-1972–75 Transition as sand added to TZ	50.9		51.2	
D-1976–81 Post treatment	23.4	D < B, E, F	53.4	
E-1982–90 Sediment basins maintained	57.9		65.0	
F-1991–2001 Sediment basins retired	57.9		54.7	
	Fall			
A-1959–64 Open to angling	80.0		80.4	
B-1967–71 Pretreatment; closed to angling	106.3		97.0	
C-1972–75 Transition as sand added to TZ	65.4	C < B	74.9	
D-1976–81 Post treatment	40.2	D < A , B, E, F	90.3	
E-1982–90 Sediment basins maintained	77.8		87.5	
F-1991–2001 Sediment basins retired	76.0	F < B	77.4	

Table 5.–Mean percent survival of brook trout by age groups from April to September in the treatment (TZ) and reference (RZ) zones during six periods, and significant differences (P ≤ 0.05) between periods.

	Treatment zone		Reference zone	
	Survival	Differences	Survival	Differences
Age 1				
A-1959–64 Open to angling	128		83	
B-1967–71 Pretreatment, closed to angling	95		104	
C-1972–75 Transition as sand added to TZ	80		120	
D-1976–81 Post treatment	75	D < A	103	
E-1982–90 Sediment basins maintained	116		74	E < B
F-1991–2001 Sediment basins retired	112		78	F < B
Age 2 and older				
A-1959–64 Open to angling	30	A < B	16	A < all others
B-1967–71 Pretreatment; closed to angling	63		49	
C-1972–75 Transition as sand added to TZ	49		52	
D-1976–81 Post treatment	51		50	
E-1982–90 Sediment basins maintained	50		40	
F-1991–2001 Sediment basins retired	43		46	

Table 6.–Changes in stream width (m) and water volume (m^3) relative to the June 1971 base period in reference (RZ) and treatment (TZ) zones. Initial stream widths and water volumes are shown for the base period. Data shown for 1971–84 are from Alexander and Hansen (1988).

	Stream width		Water volume				
	RZ	TZ	RZ		TZ		
Year			m^3	percent	m^3	percent	Period
1971	4.08	5.91	1,273	100.0	3,564	100.0	Pretreatment (1967–71)
1972	0.06	0.09	28	2.2	-357	-10.0	Sand added (1972–75) (Transitional)
1973	0.06	0.27	–	–	–	–	
1974	0.06	0.46	–	–	–	–	
1975	0.09	0.43	49	3.8	-675	-19.0	
1976	0.00	0.40	9	0.7	-869	-24.4	
1980	0.03	-0.09	-31	-2.4	-463	-13.0	Post treatment (1976-81)
1982	–	0.03	–	–	60	1.7	Sediment traps dug and maintained (1982–90)
1984	-0.03	0.03	-61	-4.8	132	3.7	
2000	-0.10	0.21	86[a]	6.8	-354	-9.9	Sediment traps retired (1991–2001)

[a] This increase in volume is attributable to an increase of 134 m in the length of the RZ in 1989 when the channel was lengthened to accommodate water diversion experiments in the lower 0.6 km of the RZ from 1991–99.

Table 7.–Hunt Creek streambed substrate composition as percent of area in June 2000.

	Substrate type						
Stream section	Organic detritus	Clay	Sand	Fine gravel	Coarse gravel	Small cobble	Wood (LWD)
Treatment	9.8	0.0	68.1	10.5	4.3	0.5	6.8
Reference	3.0	0.4	29.7	37.2	19.0	6.0	4.7

Table 8.–Embeddedness of gravel or cobble substrates with sand in the treatment (TZ) and reference (RZ) zones expressed as percentage of observations within four embeddedness categories during June 2000.

		Substrate		
Embeddedness (%)	Zone	Fine gravel	Coarse gravel	Small cobble
> 75	TZ	47	12	0
	RZ	46	14	13
50 – 74	TZ	42	41	25
	RZ	24	19	11
25 – 49	TZ	8	21	0
	RZ	19	33	24
0 – 24	TZ	3	26	75
	RZ	11	34	51

Table 9.–Comparisons of percentages of sand and gravel over time. Ratios were computed by dividing percentages of substrate in the treatment zone (TZ) by those in the (RZ). Data from the 1970s are from Alexander and Hansen (1986).

	Reference		Treatment		Ratio of TZ:RZ	
Year	Sand	Gravel	Sand	Gravel	Sand	Gravel
1971	16	63	40	17	2.50	0.27
1972	16	57	52	12	3.25	0.21
1973	9	58	50	9	5.56	0.16
1974	20	61	59	7	2.95	0.11
1975	14	59	68	5	4.86	0.08
2000	30	56	68	15	2.27	0.27

References

Alexander, E. L. 1985. Comparisons of alkalinity, pH and brook trout (*Salvelinus fontinalis*) populations of selected Upper and Lower Peninsula streams of Michigan. M.S. thesis, Michigan State University, East Lansing.

Alexander, G. R., and H. Gowing. 1976. Relationships between diet and growth in rainbow trout (*Salmo gairdneri*), brook trout (*Salvelinus fontinalis*), and brown trout (*Salmo trutta*). Michigan Department of Natural Resources, Fisheries Research Report 1841, Ann Arbor.

Alexander, G. R., and E. A. Hansen. 1983. Sand sediment in a Michigan trout stream Part II. Effects of reducing sand bedload on a trout population. North American Journal of Fisheries Management 3:365-372.

Alexander, G. R., and E. A. Hansen. 1986. Sand bed load in a brook trout stream. North American Journal of Fisheries Management 6: 9-23.

Alexander, G. R., and E. A. Hansen. 1988. Decline and recovery of a brook trout stream following an experimental addition of sand sediment. Michigan Department of Natural Resources, Fisheries Research Report 1943, Ann Arbor.

Alexander, G. R., and A. J. Nuhfer. 1993. Population dynamics of wild brook trout in Hunt Creek, Michigan, with and without fishing. Michigan Department of Natural Resources, Institute for Fisheries Research Report 1996, Ann Arbor.

Alexander, G. R., and J. R. Ryckman. 1976. Trout production and catch under normal and special angling regulations in the North Branch of the Au Sable River, Michigan. Michigan Department of Natural Resources, Fisheries Research Report 1840, Ann Arbor.

Bailey, N. J. J. 1951. On estimating the size of mobile populations from recapture data. Biometrika 38:293-306.

Bustard, D. R., and D. W. Narver. 1975a. Aspects of the winter ecology of juvenile coho salmon (*Oncorhynchus kisutch*) and steelhead trout (*Salmo gairdneri*). Journal of the Fisheries Research Board of Canada 32:667-680.

Bustard, D. R., and D. W. Narver. 1975b. Preferences of juvenile coho salmon (*Oncorhynchus kisutch*) and cutthroat trout (*Salmo clarki*) relative to simulated alteration of winter habitat. Journal of the Fisheries Research board of Canada 32:681-687.

Carbine, W. F. and D. S. Shetter. 1943. Examples of the use of two-way fish weirs in Michigan. Transactions of the American Fisheries Society 73:70-89.

Chapman, D. W. 1988. Critical review of variables used to define effects of fines in redds of large salmonids. Transactions of the American Fisheries Society 117:1-21.

Chapman, D. W., and T. C. Bjornn. 1969. Distribution of salmonids in streams, with special reference to food and feeding. Pages 153–176 *in* T. G. Northcote, editor. Symposium on salmon and trout in streams. H. R. MacMillan Lectures in Fisheries, University of British Columbia, Vancouver.

Clark, R. D., Jr., G. R. Alexander, and H. Gowing. 1979. Mathematical description of trout stream fisheries. Michigan Department of Natural Resources, Fisheries Research Report 1869, Ann Arbor.

Cooper, E. L. 1953. Periodicity of growth and change of condition of brook trout (*Salvelinus fontinalis*) in three Michigan trout streams. Copeia 2:107–114.

Cordone, A. J., and D. E. Kelly. 1961. The influence of inorganic sediment on the aquatic life of streams. California Fish and Game 47:189–228.

Cunjak, R. A. 1988. Physiological consequences of overwintering in streams: the cost of acclimatization? Canadian Journal of Fisheries and Aquatic Sciences 45:443–452.

Cunjak, R. A., and G. Power. 1986a. Seasonal changes in the physiology of brook trout, *Salvelinus fontinalis* (Mitchill), in a sub-Arctic river system. Journal of Fisheries Biology 29:279–288.

Cunjak, R. A., and G. Power. 1986b. Winter habitat utilization by stream resident brook trout (*Salvelinus fontinalis*) and brown trout (*Salmo trutta*). Canadian Journal of Fisheries and Aquatic Sciences 43:1970–1981.

Curry, R. A., and W. S. MacNeill. 2004. Population-level responses to sediment during early life in brook trout. Journal of the North American Benthological Society 23: 140–150.

Dorr, J. S., Jr., and D. F. Eschman. 1970. Geology of Michigan. The University of Michigan Press, Ann Arbor.

Elliott, J. M. 1994. Quantitative ecology and the brown trout. Oxford University Press. New York.

Gowing H. 1974. Survival, growth, diet, and production of hatchery trout stocked in six pothole lakes in Michigan. Michigan Department of Natural Resources, Fisheries Research Report 1816, Ann Arbor.

Hansen, E. A., G. R. Alexander, and W. H. Dunn. 1983. Sand sediment in a Michigan trout stream Part I. A technique for removing sand bedload from streams. North American Journal of Fisheries Management 3:355–364.

Harrelson, C. C., Rawlins, C. L., and J. P. Potyondy. 1994. Stream channel reference sites: an illustrated guide to field techniques. U. S. Department of Agriculture, Forest Service, General Technical Report RM-245. Rocky Mountain Forest and Range Experiment Station, Fort Collins.

Hartman, B. F. 1963. Observations on behavior of juvenile brown trout in a stream aquarium during winter and spring. Journal of the Fisheries Research Board of Canada 20:769–787.

Hillman, T. W., J. S. Griffith, and W. S. Platts. 1987. Summer and winter habitat selection by juvenile chinook salmon in a highly sedimented Idaho stream. Transactions of the American Fisheries Society 116:185–195.

Hinz, L. C., Jr., and M. J. Wiley. 1997. Growth and production of juvenile trout in Michigan streams: Influence of temperature. Michigan Department of Natural Resources, Fisheries Research Report 2041, Ann Arbor.

Hinz, L. C., Jr., and M. J. Wiley. 1998. Growth and production of juvenile trout in Michigan streams: Influence of potential ration and temperature. Michigan Department of Natural Resources, Fisheries Research Report 2042, Ann Arbor.

Hunt, R. L. 1965. Dispersal of wild brook trout during their first summer of life. Transactions of the American Fisheries Society 94:186–188.

Hunt, R. L. 1969. Overwinter survival of wild fingerling brook trout in Lawrence Creek, Wisconsin. Journal of the Fisheries Research Board of Canada 26:1473–1483.

Hunt, R. L. 1970. A compendium of research on angling regulations for brook trout conducted at Lawrence Creek, Wisconsin. Wisconsin Department of Natural Resources, Research Report 54, Madison.

Kohler S. L. and M. J. Wiley. 1997. Pathogen outbreaks reveal large-scale effects of competition in stream communities. Ecology 78:2146–2176.

McFadden, J. T., G. R. Alexander, and D. S. Shetter. 1967. Numerical changes and population regulation in brook trout, *Salvelinus fontinalis*. Journal of the Fisheries Research Board of Canada 24:1425–1459.

Nuhfer, A. J., and E. A. Baker. 2004. A long-term field test of habitat change predicted by PHABSIM in relation to brook trout population dynamics during controlled flow reduction experiments. Michigan Department of Natural Resources, Institute for Fisheries Research Report 2068, Ann Arbor.

Peters, J. C. 1965. The effects of stream sedimentation on trout embryo survival. Pages 275–279 *in* C. M. Tarzwell, editor. Transactions of the 3rd seminar on biological problems in water pollution. U.S. Department of Health, Education, and Welfare, Public Health Service Publication 999-WP-2, Washington, D.C.

Peters, J. C. 1967. Effects on a trout stream of sediment from agricultural practices. Journal of Wildlife Management 31:805–812.

Platts, W. S., W. F. Megahan, and G. W. Minshall. 1983. Methods for evaluating stream, riparian, and biotic conditions. U. S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, General Technical Report INT-138, Ogden, Utah.

Ray, G. A., and W. F. Megahan. 1978. Measuring cross sections using a sag tape: a generalized procedure. U.S. Department of Agriculture, Forest Service General Technical Report INT-47, Ogden, Utah.

Reiser, D. W., and R. G. White. 1988. Effects of two sediment size-classes on survival of steelhead and chinook salmon eggs. North American Journal of Fisheries Management 8:432–437.

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

Rimmer, D. M., U. Paim, and R. L. Saunders. 1983. Autumnal habitat shift of juvenile Atlantic salmon (*Salmo salar*) in a small river. Canadian Journal of Fisheries and Aquatic Sciences 40:671–680.

Schneider, J. C. 2000. Weighted average length and weighted age composition. Chapter 15 *in* J. C. Schneider, editor. Manual of fisheries survey methods II: with periodic updates. Michigan Department of Natural Resources, Fisheries Special Report 25, Ann Arbor.

Sowden, T. K., and G. Power. 1985. Prediction of rainbow trout embryo survival in relation to groundwater seepage and particle size of spawning substrates. Transactions of the American Fisheries Society 114:804–812

SPSS Inc. 2002. SPSS Base Users Guide 11.5. SPSS inc., Chicago.

Wickett, P. W. 1954. The oxygen supply to salmon eggs in spawning beds. Journal of the Fisheries Research Board of Canada 11:933–953.

Young, M. K., W. A. Hubert, and T. A. Wesche. 1991. Selection of measures of substrate composition to estimate survival to emergence of salmonids and to detect changes in stream substrates. North American Journal of Fisheries Management 11:339–346.

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Appendix 1.–Substrate composition along Hunt Creek transects spaced at 30.5-m intervals perpendicular to the stream banks throughout the study area beginning 30.5 m up from the downstream end of the treatment zone (TZ). Transects 1 through 49 were located in the TZ and transects 50 through 109 were in the reference zone (RZ). Latitude and longitude were measured by a differentially corrected GPS unit at the midpoint of the wetted stream bottom in June 2001. Water depth was measured at 30.5-cm intervals along each transect from water's edge to water's edge. Predominant substrate type (defined as the substrate type beneath 50% or more of each 30.5-cm segment was classified as to principal inorganic particle size (Table 1) or biological materials (wood or detritus). Transects that were not representative of the 30.5-m reach where they were located were treated as outliers and not used for habitat summaries. Explanations for removal of transects from analyses are given in footnotes.

			Mean		Frequency of each substrate in a transect							
Transect	Latitude	Longitude	depth (cm)	wetted width (m)	Detritus	Clay	Sand	Fine gravel	Gravel	Small cobble	Cobble	Wood
1[a]	N44.872783151	W84.141582920	65.0	12.3	10	0	40	0	0	0	0	0
2[a]	N44.872530460	W84.141702812	60.5	10.0	13	0	20	0	0	0	0	0
3[a]	N44.872286291	W84.141546421	41.9	7.9	18	0	5	2	1	0	0	0
4	N44.872033431	W84.141421471	26.9	5.3	4	0	1	4	6	0	0	2
5	N44.871781144	W84.141350297	48.3	7.2	0	0	12	2	5	4	0	1
6	N44.871575303	W84.141127305	32.2	5.2	0	0	6	2	4	0	0	5
7	N44.871433091	W84.140827459	30.9	7.0	7	0	9	6	0	0	0	1
8	N44.871171366	W84.140777790	32.2	5.4	0	0	6	9	3	0	0	0
9	N44.870940012	W84.140915289	34.4	6.2	4	0	16	0	0	0	0	0
10	N44.870892140	W84.141313077	30.1	5.1	3	0	7	7	0	0	0	0
11	N44.870727531	W84.141542460	35.1	5.9	4	0	8	5	0	0	0	2
12	N44.870466658	W84.141561536	22.7	6.4	1	0	1	5	14	0	0	0
13	N44.870519251	W84.141803518	52.1	4.4	2	0	8	3	0	0	0	1
14	N44.870644095	W84.142110439	48.0	6.2	6	0	12	0	0	0	0	2
15	N44.870455200	W84.142412766	36.6	6.2	2	0	16	0	0	0	0	2
16	N44.870210038	W84.142523023	31.2	6.2	4	0	13	0	0	0	0	3
17	N44.869945302	W84.142637398	21.0	6.8	1	0	5	7	6	0	0	3
18	N44.870023338	W84.142941930	39.5	5.8	4	0	14	0	0	0	0	1
19	N44.869985520	W84.143273827	23.5	8.6	2	0	26	0	0	0	0	0
20	N44.869761204	W84.143487315	37.4	6.5	2	0	19	0	0	0	0	0
21	N44.869757412	W84.143839377	29.6	7.0	0	0	23	0	0	0	0	0
22	N44.869826334	W84.144208062	49.8	4.4	0	0	13	0	0	0	0	1
23	N44.869717153	W84.144551835	39.7	5.4	0	0	18	0	0	0	0	0
24	N44.869253890	W84.144386799	33.3	6.8	3	0	17	0	0	0	0	2
25	N44.868994525	W84.144321550	49.4	4.8	3	0	12	0	0	0	0	1

Appendix 1.–Continued.

Transect	Latitude	Longitude	Mean		Frequency of each substrate in a transect							
			depth (cm)	wetted width (m)	Detritus	Clay	Sand	Fine gravel	Gravel	Small cobble	Cobble	Wood
26	N44.868838895	W84.144586328	27.3	7.8	0	0	26	0	0	0	0	0
27	N44.868786283	W84.144955870	25.4	7.2	0	0	24	0	0	0	0	0
28	N44.868708789	W84.145326715	46.1	5.0	2	0	14	0	0	0	0	0
29	N44.868535840	W84.145370358	31.3	6.7	5	0	17	0	0	0	0	0
30	N44.868406010	W84.145044826	26.7	7.7	2	0	23	0	0	0	0	0
31	N44.868140150	W84.144886265	41.8	5.9	5	0	14	0	0	0	0	0
32	N44.867924836	W84.145068782	33.9	5.9	0	0	19	0	0	0	0	0
33	N44.867631673	W84.145143054	41.9	5.1	0	0	17	0	0	0	0	0
34	N44.867430450	W84.145391623	36.2	5.9	0	0	19	0	0	0	0	0
35	N44.867185289	W84.145528792	44.1	4.5	0	0	14	1	0	0	0	0
36	N44.866978544	W84.145735562	31.3	6.8	1	0	16	1	0	0	0	4
37	N44.866711477	W84.145766924	22.3	8.2	1	0	18	8	0	0	0	0
38	N44.866454362	W84.145859922	38.6	5.7	1	0	14	0	0	0	0	4
39	N44.866224938	W84.145640776	34.2	6.3	3	0	15	2	0	0	0	1
40	N44.865999766	W84.145798412	37.5	6.4	2	0	18	0	0	0	0	1
41	N44.865783038	W84.146005659	37.1	5.4	4	0	11	1	0	0	0	2
42	N44.865695545	W84.146367170	50.8	4.8	0	0	10	3	0	0	0	3
43	N44.865798235	W84.146722092	33.2	6.9	0	0	20	0	0	0	0	3
44	N44.865838452	W84.147035343	29.4	6.0	0	0	6	9	0	0	0	5
45	N44.865630146	W84.147276563	40.1	5.8	0	0	10	7	0	0	0	2
46	N44.865376641	W84.147229783	24.8	6.9	4	0	11	8	0	0	0	0
47	N44.865137653	W84.147442866	25.5	6.3	3	0	5	4	0	0	0	8
48[b]	N44.864927638	W84.147617461	49.8	5.6	4	0	14	0	0	0	0	2
49[b]	N44.864974255	W84.147981889	44.9	3.7	0	0	10	0	3	0	0	0
50	N44.865230020	W84.148516884	33.9	4.0	1	0	5	4	0	0	0	3
51	N44.865302163	W84.148868343	15.8	5.1	0	0	5	10	1	0	0	1
52	N44.865268648	W84.149212525	17.5	4.6	0	0	4	4	6	0	0	1
53	N44.865116405	W84.149516586	35.9	4.1	0	0	10	3	0	0	0	0
54	N44.865118308	W84.149890343	15.8	5.5	0	0	2	16	0	0	0	0
55	N44.864981333	W84.150212057	14.0	7.0	0	0	2	21	0	0	0	0

Appendix 1.–Continued.

Transect	Latitude	Longitude	Mean		Frequency of each substrate in a transect							
			depth (cm)	wetted width (m)	Detritus	Clay	Sand	Fine gravel	Gravel	Small cobble	Cobble	Wood
56	N44.864822252	W84.150524865	26.8	6.0	0	0	10	9	0	0	0	1
57	N44.864637835	W84.150794270	13.2	4.9	0	0	4	12	0	0	0	0
58	N44.864429754	W84.151015803	25.7	4.7	0	0	3	9	0	0	0	3
59	N44.864357418	W84.151333701	21.4	4.2	0	0	2	12	0	0	0	0
60	N44.864384907	W84.151699640	24.1	4.3	0	0	3	11	0	0	0	0
61	N44.864479414	W84.152049351	21.7	5.5	0	0	2	10	5	0	0	1
62	N44.864479823	W84.152399888	24.6	5.5	0	0	12	2	3	1	0	0
63	N44.864361501	W84.152694349	33.2	4.9	0	0	7	1	7	0	0	1
64	N44.864344247	W84.153080580	18.6	4.6	1	0	0	10	3	0	0	1
65	N44.864421402	W84.153420016	28.7	3.4	0	0	2	3	5	0	0	1
66	N44.864648258	W84.153570843	43.2	4.5	5	2	8	0	0	0	0	0
67	N44.864887966	W84.153743059	40.8	2.8	0	1	6	2	0	0	0	0
68	N44.865037989	W84.154051490	22.3	3.1	0	0	1	4	5	0	0	0
69[b]	N44.864939558	W84.154383546	65.0	7.0	3	0	19	0	0	0	0	0
70[b]	N44.864853566	W84.154711780	33.3	8.7	9	0	18	0	0	0	0	0
71	N44.864592688	W84.154840386	24.4	3.2	3	0	3	0	0	2	2	0
72	N44.864344699	W84.154909102	14.7	5.1	2	0	6	4	1	0	0	4
73	N44.864062514	W84.154864713	15.0	3.5	0	0	4	7	0	0	0	0
74	N44.863973065	W84.155218209	11.3	4.0	0	0	0	7	5	0	0	1
75	N44.863965228	W84.155594491	11.0	3.2	1	0	0	3	5	0	0	1
76	N44.863953406	W84.155970698	10.0	3.8	0	0	3	6	3	0	0	1
77	N44.863776881	W84.156183230	12.5	3.5	0	0	4	5	3	0	0	0
78	N44.863521414	W84.156302319	12.7	3.8	0	0	2	11	0	0	0	0
79[c]	N44.863242548	W84.156298762	25.0	9.4	7	0	15	6	3	0	0	0
80	N44.862966538	W84.156241092	19.1	3.3	2	0	6	2	0	0	0	0
81[c]	N44.862707339	W84.156209333	28.7	4.8	0	0	7	3	2	0	3	1
82	N44.862668357	W84.156450310	11.0	3.9	0	0	2	0	8	0	0	3
83	N44.862462903	W84.156381557	13.4	4.0	0	0	1	5	4	3	0	0
84	N44.862234536	W84.156198280	15.0	3.0	0	0	4	1	3	2	0	0
85	N44.861960255	W84.156163145	8.7	4.9	0	0	4	2	8	2	0	0

Appendix 1.–Continued.

			Mean		Frequency of each substrate in a transect							
Transect	Latitude	Longitude	depth (cm)	wetted width (m)	Detritus	Clay	Sand	Fine gravel	Gravel	Small cobble	Cobble	Wood
86	N44.861692022	W84.156071966	18.4	2.7	0	0	1	3	1	2	2	0
87	N44.861627634	W84.155817670	19.4	3.0	2	0	4	3	0	0	0	1
88	N44.861657300	W84.155595034	11.0	2.1	0	0	1	0	6	0	0	0
89	N44.861432672	W84.155442915	12.7	3.0	0	0	1	9	0	0	0	0
90[c]	N44.861173556	W84.155436115	18.8	4.0	0	0	0	5	8	0	0	0
91	N44.860942548	W84.155265291	12.2	2.7	0	0	2	1	1	5	0	0
92	N44.860657210	W84.155236259	8.2	3.4	0	0	1	9	1	0	0	0
93[c]	N44.860434633	W84.155367095	26.1	5.1	0	0	5	2	0	2	8	0
94	N44.860158214	W84.155500990	22.6	2.9	0	0	7	2	0	0	0	0
95	N44.859918994	W84.155609251	19.1	3.8	0	0	7	0	4	2	0	0
96	N44.859652798	W84.155765988	27.2	3.2	0	0	4	0	5	2	0	0
97	N44.859623022	W84.156120791	16.2	4.7	1	0	5	2	5	2	0	0
98	N44.859599932	W84.156484533	15.6	2.7	0	0	1	0	8	0	0	0
99	N44.859714043	W84.156808068	9.1	4.2	0	0	2	1	3	7	0	1
100	N44.859944442	W84.157107627	25.7	2.2	0	0	1	2	1	3	0	0
101	N44.859926361	W84.157329551	10.2	3.5	0	0	0	0	4	8	0	0
102[c]	N44.859909397	W84.157725383	20.0	5.4	1	0	10	2	2	0	0	3
103	N44.859611332	W84.157824573	12.9	4.4	0	0	9	5	0	0	0	0
104	N44.859388885	W84.157828783	19.1	4.5	0	0	6	9	0	0	0	0
105	N44.859226335	W84.157708382	14.7	3.7	2	0	0	2	8	0	0	0
106	N44.858990368	W84.157759130	29.0	4.1	0	0	11	1	2	0	0	0
107	N44.858748084	W84.157771720	26.4	5.1	0	0	7	0	3	0	0	7
108	N44.858511012	W84.157837946	19.0	3.3	0	0	8	3	0	0	0	0
109	N44.858293975	W84.158044574	13.5	3.2	3	0	1	4	2	0	0	0

[a] Widths and substrates were not representative of the reach because these three transects spanned the large sand trap dug at the downstream end of the study area to prevent sediment from damaging downstream habitat.

[b] Widths and substrates were not representative of the reach due to localized alteration of habitat to accommodate previous water diversion experiments.

[c] Widths and substrates were representative of less than 10% of habitat in these segments due to the influence of bulkheads or structures constructed for previous experiments.