Stream temperature responses to forest harvest and debris flows in western Cascades, Oregon

Sherri L. Johnson and Julia A. Jones

Abstract: Stream temperature controls the rates of many biotic and abiotic processes and is influenced by changes in streamside land use practices. We compiled historic stream temperature data and reestablished study sites in three small basins in the H.J. Andrews Experimental Forest in the western Cascades, Oregon, to reexamine the effects on and recovery of stream temperatures following removal of riparian vegetation. Maximum stream temperatures increased 7°C and occurred earlier in the summer after clear-cutting and burning in one basin and after debris flows and patch-cutting in another. Diurnal fluctuations in June increased from approximately 2 to 8°C. Stream temperatures in both basins gradually returned to preharvest levels after 15 years. The influence of the primary factor controlling stream temperatures, shortwave solar radiation, was amplified following removal of riparian vegetation, and conduction between stream water and nearby soils or substrates also appeared to be an important factor. Shifts in the timing of summer maxima and greater increases in early summer stream temperatures could impact sensitive stages of aquatic biota.

Résumé : La température des cours d'eau régit le rythme de nombreux processus biotiques et abiotiques, et se trouve sous l'influence des changements dans les pratiques d'aménagement du territoire sur les rives. Nous avons compilé les données historiques sur la température des cours d'eau et rétabli des stations d'étude dans trois petits bassins de la forêt expérimentale H.J. Andrews, dans l'ouest des Cascades (Oregon), pour réexaminer les effets de l'enlèvement de la végétation riveraine sur la température des cours d'eau, et le rétablissement subséquent. Les températures maximales des cours d'eau ont augmenté de 7°C, et les augmentations se sont produites plus tôt dans l'été, après la coupe à blanc et le brûlage dans un bassin, et après des apports de débris et du jardinage par bouquets dans un autre. Les fluctuations diurnes en juin ont augmenté d'environ 2 à 8°C. Dans les deux bassins, les températures des cours d'eau sont graduellement revenues aux niveaux pré-exploitation au bout de 15 ans. L'influence du principal facteur régissant la température des cours d'eau, le rayonnement solaire à ondes courtes, a été amplifiée par suite de l'élimination de la végétation riveraine, et la conduction entre l'eau de la rivière et les sols ou les substrats adjacents semblait aussi un facteur important. Les changements dans l'occurrence des maximums d'été, et les augmentations plus fortes des températures des cours d'eau au début de l'été, pourraient avoir un impact sur les stades vulnérables du biote aquatique.

[Traduit par la Rédaction]

Introduction

Stream temperature is a critical parameter in stream ecosystems. Temperature controls rates of metabolism, growth, decomposition, and solubility of gases as well as many processes and biotic interactions (Beitinger and Fitzpatrick 1979; Beschta et al. 1987). As a consequence, increases in stream temperature in regions with cold-water fisheries have been linked to potential fish mortality (Brett 1952; Beschta et al. 1987), increased prevalence of disease (Becker and Fugihara 1978), and changes in interspecific competition (Reeves et al. 1987; Ward and Stanford 1992).

Temporal and spatial variations in stream temperature are the result of multiple factors that interact with one another (Brown 1969). Direct solar radiation on the water surface is a dominant source of heat energy for streams (e.g., Beschta et al. 1987; Sinokrot and Stefan 1993; Webb and Zhang 1997), but other sources and fluxes of energy also contribute to stream temperature at a given point (Fig. 1). These include energy exchange by conduction between stream water and the stream substrata (Crittenden 1978; Hondzo and Stefan 1994; Evans et al. 1995), evaporation and sensible heat exchange with the atmosphere (Sinokrot and Stefan 1993; Webb and Zhang 1997), and energy contributed by advection of water from deep groundwater sources and upstream (Ingebritsen et al. 1992; Webb and Zhang 1997).

Forest harvest in riparian areas has been shown to produce increases in stream temperatures, and the magnitude of these increases varies among sites and regions (Swift and Messer 1971; Anderson 1973; Beschta et al. 1987). Sites where only overstory riparian vegetation was removed generally had smaller increases in stream temperature than where the understory was also removed through burning or herbicide treatments (Levno and Rothacher 1969; Lynch et al. 1984). Responses among sites also varied as a function of the amount of stream surface exposed by harvesting. Most studies of forest harvest effects have been limited to a few post-harvest years (summarized by Anderson 1973; Beschta et al.

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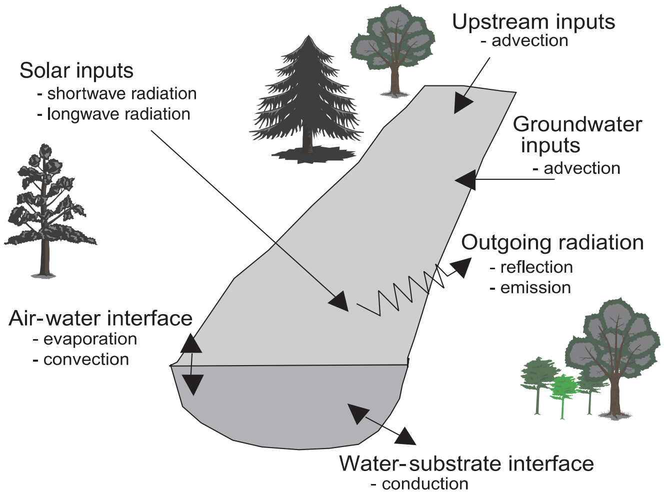
Fig. 1. Factors and mechanisms influencing stream temperature.



1987), and in other studies, the lack of pretreatment data has precluded documentation of stream temperature recovery to preharvest levels (Hostetler 1991). Although, to our knowledge, long-term responses of stream temperature have not been examined, except by Moring (1975), trends of diminishing stream temperatures with forest recovery have been observed or predicted (e.g., Brown and Krygier 1970; Swift 1982; Beschta and Taylor 1988).

Forest harvest and debris flows in small experimental basins in the H.J. Andrews Experimental Forest, western Cascades, Oregon, during the 1960s led to elevated stream temperatures in the years immediately following harvest (Levno and Rothacher 1967, 1969). Continued monitoring of stream temperatures, discharge, vegetation dynamics, and climate allows us to examine the long-term recovery of stream temperatures following forest harvest. Here, we examine (*i*) major mechanisms controlling stream temperatures, (*ii*) effects of riparian vegetation removal and recovery on summer stream temperatures, and (*iii*) changes in the timing of summer maximum stream temperatures following riparian vegetation removal.

Materials and methods

Study site

This study was conducted in three small (<1 km^2) basins in the H.J. Andrews Experimental Forest (Fig. 2). The climate in the lower elevations of the western Cascade Mountains is considered xeric with warm dry summers and cool to cold rainy winters. Mean annual precipitation is 2.4 m, most of which occurs between November and April. Very little rain falls during summer, and stream flows generally decline from June through August (Fig. 3). Stream channels are steep and confined, with unsorted sediment ranging in size from boulders to silt and with large wood and exposed bedrock in some locations.

Prior to harvest, native vegetation in these small basins was 450-year-old forest dominated by Douglas-fir (*Pseudotsuga menziesii*). Stream flow and other basin characteristics (Table 1) have been monitored since 1952 as part of a paired-basin experiment to examine the effects of forest harvest on stream flow and vegetation. Results of this experiment have been described in other studies (e.g., Dyrness 1973; Jones and Grant 1996).

Forest harvest history differs among the three basins. Watershed 2 (WS 2) is an unharvested, unroaded basin with old-growth vegetation. Watershed 1 (WS 1) was 100% clear-cut between 1962 and 1966, but no roads were constructed. Trees, including those in riparian zone, were removed using cable-logging methods, logging slash was broadcast burned in September 1966, and some wood was removed from the channel (Levno and Rothacher 1969). In watershed 3 (WS 3), 2.6 km of roads were constructed between 1959 and 1961, and in 1963, 25% of the basin was harvested in three "patch cuts," which were then broadcast burned. In December 1964, debris flows scoured upstream sections of the channel to bedrock, removed all riparian vegetation, and deposited sediment and wood in the lower section (Levno and Rothacher 1967).

After harvest, herbaceous and shrub vegetation on hillslopes established rapidly, reaching preharvest levels of cover within 5 years and continuing to increase to twice the preharvest cover conditions over the next 10–20 years in both WS 1 and WS 3 (Halpern and Spies 1995). However, tree cover on hillslopes reestablished more slowly, with less than 10% cover after 5 years, 25% cover after 15 years, and 80–90% cover 30 years after harvest (Halpern and Spies 1995). In the riparian zone in WS 1, a dense stand of red alder (*Alnus rubra*) developed, creating canopy closure approximately 15 years after harvest. Alder stand development along the stream channel of WS 3 was less vigorous and limited by bedrock outcrops (F. Swanson, U.S. Forest Service, Forestry Sciences Laboratory, 3200 SW Jefferson Way, Corvallis OR 97331, U.S.A., personal observation). Riparian vegetation in WS 3 was removed by debris flows in February 1996 that again scoured the upper 1 km of channel and deposited sediment and large wood in the lower 200-m reach (Swanson et al. 1998).

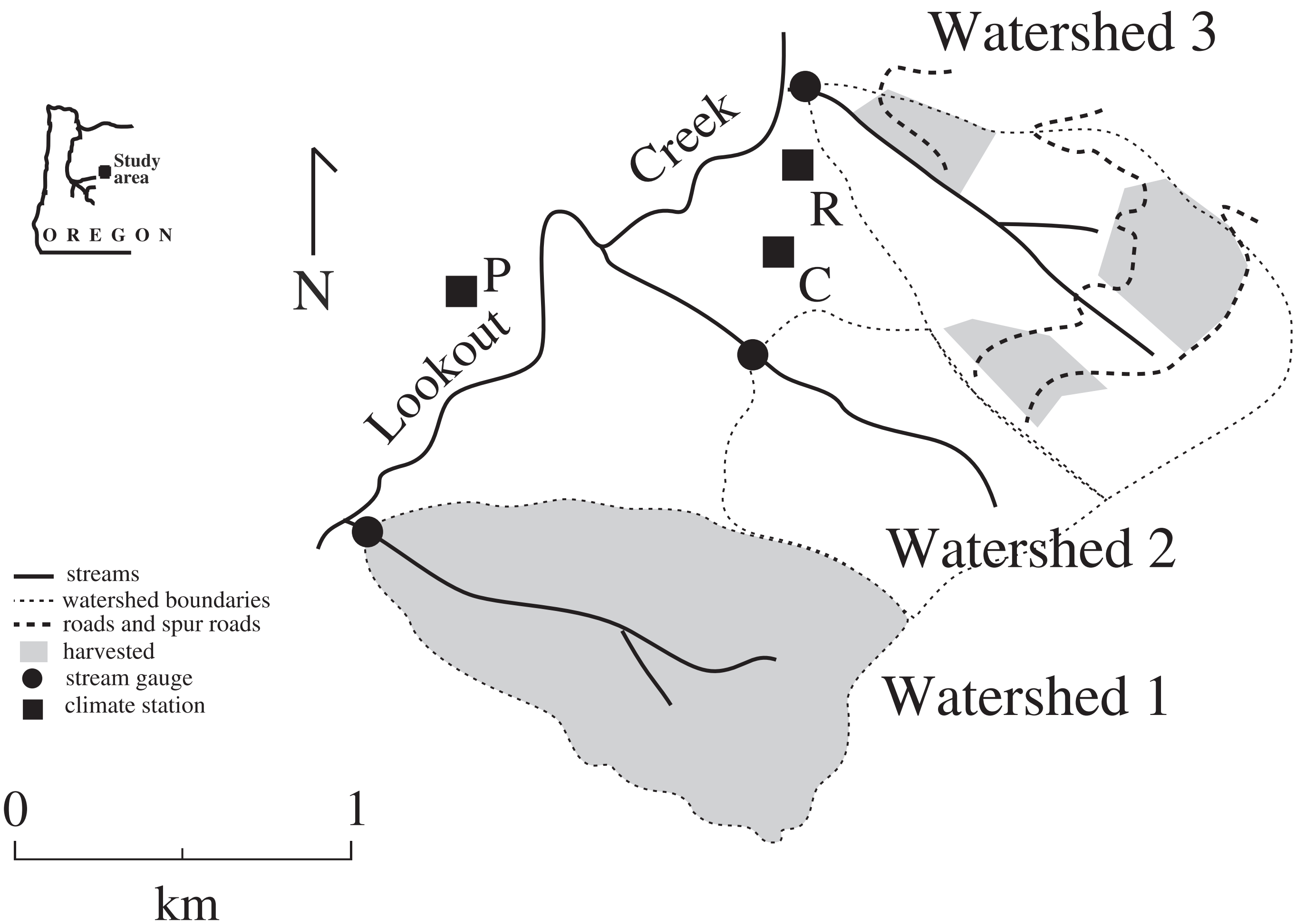
Data acquisition

Stream temperature, discharge, air temperature, precipitation, solar radiation, and soil temperatures have been monitored over varying periods, with increased temporal resolution in the later years (Table 1). Stream temperature was monitored just above the stream gauging stations (Fig. 2). Precipitation and air temperature data were collected at the WS 2 climate station (C, Fig. 2), while solar radiation and soil temperature data were collected at the primary climate station (P, Fig. 2). Additional soil temperature data were collected in the WS 2 reference stand (R, Fig. 2). For the summer of 1967, when no solar radiation sensors were in place, solar radiation was modeled based on a multiple regression for the period 1979–1991, which estimated solar radiation as a function of solar angle, precipitation, and air temperature (Forest Science Data Bank, Corvallis, OR 97331, U.S.A.). Stream temperature data were suited for analysis at several temporal scales: (*i*) the 23-year record of summer maximum temperatures from 1959 to 1982, (*ii*) the 6-year record of weekly maximum and minimum temperatures from the summers of 1960, 1967–1970, and 1997, (*iii*) daily maximum and minimum summer temperatures in 1967 and 1997, and (*iv*) hourly summer stream temperatures in 1967 and 1997. Prior to 1997, stream temperatures were measured in degrees Fahrenheit to the nearest whole number. We converted all values to Celsius and report stream temperatures to the nearest 0.1°C, recognizing that slight differences in historic values would not have been detectable at this level of precision.

Statistical analysis

Statistical analyses were conducted to compare mean weekly maximum and minimum stream temperatures among years and months in WS 1, WS 2, and WS 3. Because daily stream temperatures are autocorrelated, and preharvest maximum and minimum stream temperatures had been collected at weekly time steps, the daily data from 1967 to 1970 and from 1997 were subsampled to obtain maximum and minimum stream temperatures for approxi-

Fig. 2. Location of experimental basins in the H.J. Andrews Experimental Forest, western Cascades, Oregon. WS 1 was clear-cut and burned, WS 2 was unharvested, and WS 3 was patch-cut but debris flows scoured the channel.



mately weekly intervals (ranging from 5 to 8 days) corresponding to those sampled in 1960. Hence, data consisted of 17 observations per summer of weekly maximum (minimum) stream temperatures, with four observations for June, four for July, five for August, and four for September. Statistical analyses were conducted using complete factorial analysis of variance (ANOVA) with post hoc tests using multiple comparisons (Neter et al. 1990). Interannual variation in stream temperatures from the unharvested basin (WS 2) was examined using weekly maximum or minimum stream temperature as the dependent variable and year and month as the independent variables. Interannual and monthly changes associated with clear-cutting or patch-cutting and debris flows were analysed using differences between harvested and unharvested basins. The dependent variable in these analyses was the difference between the maximum (or minimum) weekly stream temperatures in the harvested basins (WS 1 or WS 3) and the unharvested basin (WS 2); year and month were the independent variables. Post hoc tests of effects were conducted to identify significant differences. Because multiple years and months were compared, probabilities were conservatively adjusted using Tukey's highest significant difference test to guarantee an overall protection of $\alpha = 0.05$ (Neter et al. 1990; SPSS, Inc. 1998).

Results

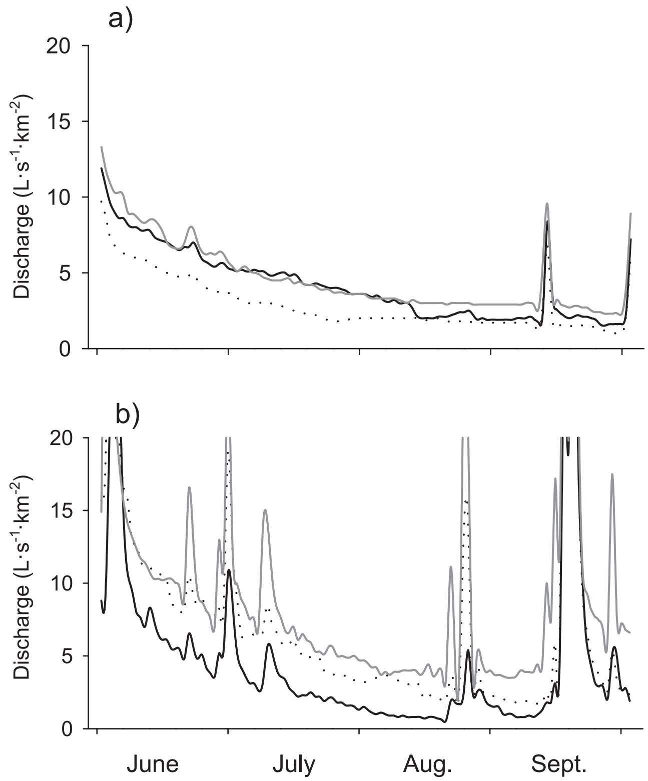
Interannual and seasonal variability

In the unharvested basin, WS 2, summer temperatures varied among years and among months. Maximum summer temperatures ranged from 15 to 19°C, with a mean of 16.7°C from 1959 to 1982 (Fig. 4). In WS 2, mean weekly maximum stream temperatures were not significantly different among the six years (1960, 1967–1970, and 1997) (F = 1.7, p = 0.129) but were significantly higher in July and August than in June or September (F = 19.1, p < 0.001). Mean weekly minimum stream temperatures were significantly higher in 1967 than in 1960 (Table 2).

Despite differences in disturbances (timing and extent of forest harvest treatment and debris flows), maximum summer temperatures WS 1 and WS 3 had very similar trajectories from 1966 to 1982 (Fig. 4). In WS 1, summer maximum temperature increased to 23.9°C in 1967 and 1968, after clear-cutting and burning, and returned to preharvest levels by the early 1980s. In WS 3 in 1965, 2 years after patch-cutting and 6 months after debris flows, the maximum stream temperature increased to 21.7°C, and in 1968, the summer maximum stream temperature reached 23.9°C.

Weekly maximum stream temperature differences between WS 1 and WS 2 increased significantly during the first several summers after clear-cutting and burning (F = 285.1, p < 0.001) (Table 3). Differences in weekly minimum stream temperatures also increased in the first summers after harvest (F = 33.2, p < 0.001). Prior to harvest and again 30

Fig. 3. Mean daily stream discharge measured at the stream gauging weirs in WS 1 (black line), WS 2 (dotted line), and WS 3 (grey line) during (*a*) 1967 and (*b*) 1997.



years after harvest, mean weekly maximum and minimum temperatures differed by less than 1°C (Table 3). In the first 4 years after clear-cutting, mean maximum weekly stream temperatures for the summer were 5.4–6.4°C higher in WS 1 than in WS 2, and mean minimum weekly stream temperatures were 1.6–2.0°C higher in WS 1 than in WS 2 (Table 3). Mean weekly maximum stream temperature differences in June and July were significantly greater than in September (F = 3.6, p < 0.001). After clear-cutting and burning, maximum stream temperature in June increased to 23.3°C and in July to 23.9°C. In September, maximum temperature was 20.1°C.

Weekly maximum stream temperature differences between WS 3 and WS 2 increased significantly after patch-cutting combined with debris flows (F = 186.6, p < 0.001) (Table 3). Mean weekly minimum temperature differences increased in 1967 (F = 11.1, p < 0.001). Prior to harvest and debris flows, weekly maximum and minimum stream temperatures in WS 3 and WS 2 differed by less than 1.1°C; WS 3 had slightly lower maxima and higher minima than WS 2 (Table 3). In 1967–1969, mean weekly maximum stream temperatures for the summer were 3.5–5.2°C higher in WS 3 than in WS 2 and significantly different (p < 0.001) from those in 1960 (Table 3). Mean weekly maximum stream temperature differences were larger in June and July than in September (F = 4.9, p < 0.001). In 1997, stream temperatures in WS 3 reflected the recent channel disturbance by debris flows. Mean weekly maximum stream temperature differences from WS 2 were more than 2.0°C higher than in 1960 (p < 0.05) but less than in 1967–1969, after the 1964 debris flow (Table 3). Mean weekly minimum stream temperatures in 1997 were 1.5°C higher in WS 3 than in WS 2 and significantly different (p < 0.01) from those in 1960.

Stream temperatures in the unshaded streams (WS 1 and WS 3) responded more dramatically to solar inputs than temperatures in the unharvested basin (WS 2). Differences in daily maximum stream temperatures between WS 1 and WS 2 and between WS 3 and WS 2 were amplified during periods of high solar inputs and reduced during periods of cloud cover in 1967 (Figs. 5*c* and 5*d*). Differences between daily maximum stream temperature in harvested and unharvested basins (WS 1 and WS 2 or WS 3 and WS 2) were greatest in late June and early July and decreased through the summer (Fig. 5*c*).

Diurnal and hourly variability

Stream temperatures in the unshaded streams had wider diurnal fluctuations than in the unharvested basin. In 1967, the maximum diurnal range of stream temperatures was 6–8°C in WS 1 and 5–6°C in WS 3 but only 1–2°C in WS 2 (Figs. 5*a* and 5*b*). By 1997, the diurnal range of stream temperatures was 1–2°C in all three basins (Figs. 6*a* and 6*b*). The timing of daily maxima also changed following clear-cutting in WS 1. In mid-July 1967, daily maximum stream temperatures occurred at 13:00, 6 h earlier than in the old-growth unharvested basin, where stream temperatures peaked at 19:00. Daily minimum stream temperatures occurred at 05:00 in WS 1, whereas in WS 2, they occurred at 08:30. In 1997 in both WS 1 and WS 2, daily maxima occurred between 18:30 and 19:30 and minima occurred at 08:00.

Based on daily mean stream temperatures starting on June 1, degree-days accumulated more rapidly in the clear-cut basin and the basin affected by debris flows than in the unharvested basin. In WS 1 in 1967, 1000 degree-days had accumulated by July 29, 2 weeks earlier than in WS 2 (Fig. 7*a*), whereas in 1997, degree-days accumulated at similar rates in both basins (Fig. 7*b*). In WS 3 in 1967, 1000 degree-days had accumulated 10 days earlier than in WS 2 and 8 days earlier in 1997 (Fig. 7).

Soil temperatures

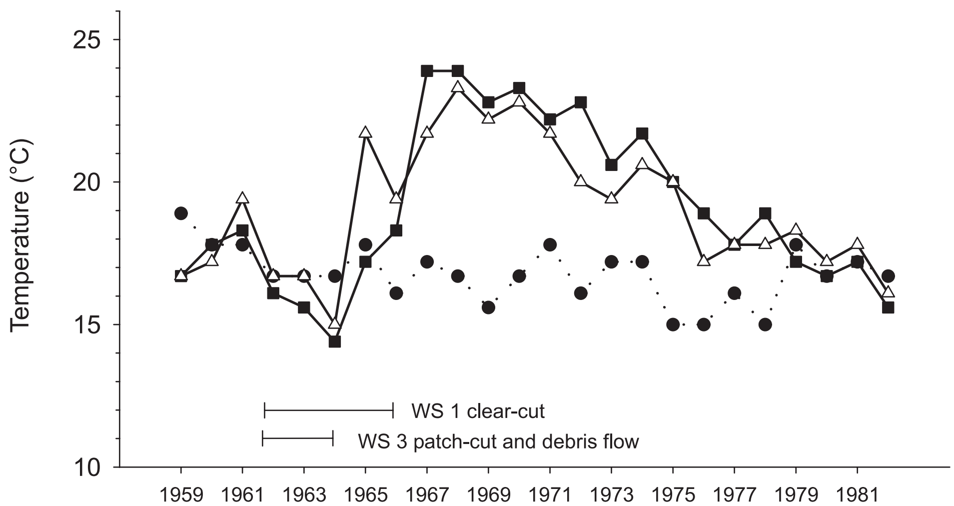
Diurnal temperature fluctuations in shaded versus unshaded streams were quite similar to soil temperature fluctuations in an old-growth forest stand versus a forest gap (Figs. 5 and 8). In a forest gap, surface soil temperatures (10 cm depth) showed wide diurnal fluctuations and reached summer maxima exceeding 25°C (Fig. 8*a*). Under forest canopy in an old-growth forest stand, surface soil temperatures had narrower diurnal fluctuations and were generally 5°C cooler than temperatures in forest gaps (Fig. 8*b*). Soil temperatures at depth at both sites were cooler than at the surface, had reduced diurnal fluctuations, and were temporally lagged; maximum values at 100 cm occurred in early September, whereas those nearer the surface occurred in mid-August (Fig. 8*a*). In the old-growth forest, stream temperatures were slightly lower than soil temperatures at 30 cm; temperatures in the stream and at 30 cm reached maximum values in mid-August.

Table 1. Locations, devices, and extent and resolution of data records used in this study.

Variable	Location	Device	Extent of record	Resolution
Stream temperature	WS 1, WS 2, WS 3 stream gauges	"U" tube max.–min. thermometers	1959–1966 (summers)	Weekly max.–min.
	WS 1, WS 2, WS 3 stream gauges	Transducer thermometers and punch tape recorders	1967–1982	Hourly*
	WS 1, WS 2, WS 3 stream gauges	Optic Stowaways	1997–present	30 min
Stream discharge	WS 1, WS 2, WS 3 stream gauges	Stevens A-35 recorder	1952–present	Hourly
Air temperature	WS 2 climate station	Hi-Q hygrothermograph	1958–present	Daily max.–min.
Precipitation	WS 2 climate station	Universal recording rain gauge	1957–present	Daily
Solar radiation	Primary climate station	Pyranometer with thermopyle sensor, data logger	1972–present	Hourly
Soil temperature	Primary climate station at 10, 20, 50, 100 cm	Thermistor probes and data logger	1994–present	Dourly
Soil temperature	WS 2 reference stand	Thermistor probes at 10, 20, 30 cm	1987–present	Daily max.–min.

*Only summer maximums are available from 1971 to 1982.

Fig. 4. Maximum summer season stream temperature (June 1 – September 30) from 1959 through 1982. WS 1(squares) was clear-cut between 1962 and 1966 and then slash burned. WS 2 (circles) was unharvested. WS 3 (triangles) had roads constructed between 1959 and 1961, was patch-cut during 1962–1963, and had debris flows scour the channel in 1964.



Discussion

Stream temperature responses to removal of riparian vegetation occurred at multiple temporal scales, including increases in maximum and minimum daily, weekly, and summer stream temperatures, increased diurnal fluctuations, and shifts in the timing of stream temperature maxima to earlier in the summer season and on a given day. The magnitude and timing of temperature changes are a result of the multiple mechanisms that interact to control stream temperature dynamics.

Physical controls

This study highlighted the importance of solar radiation as a primary driver of stream temperatures and the increased influence of radiation when riparian vegetation was removed, either by clear-cutting and burning or by debris flows. The direct mechanism by which solar radiation warms exposed stream water and soils is radiative exchange (Brown 1969; Monteith and Unsworth 1980). In this study and in others (Brown and Krygier 1970; Holtby 1988), the largest increases in stream temperature after riparian removal occurred not at the usual time of maximum stream temperatures, but in early summer, which coincided with the timing of maximum solar inputs. The shift in timing of increased temperatures was not readily discernable in the daily maximum–minimum temperature records but became apparent in the differences between maximum daily temperatures in shaded and unshaded streams. This pattern of differences between daily maxima parallels the daily magnitude of summer solar radiation that was able to penetrate to the stream surfaces in WS 1 and WS 3 when riparian vegetation had been removed.

Conduction between water and alluvial substrates is often underestimated as an important mechanism influencing stream temperature (Brown 1969; Beschta et al. 1987), and

Table 2. Average summer conditions (June 1 – September 30) in the unharvested basin, WS 2, during the years indicated.

	Stream temperature (°C)		Air temperature (°C)		Mean daily precipitation (mm)	Mean daily Q ($L \cdot s^{-1} \cdot km^{-2}$)
	Mean max.	Mean min.	Mean max.	Mean min.		
1960	15.2 *a*	10.3 *a*	26.0	9.6	1.0	7.5
1967	15.2 *a*	12.3 *b*	28.9	10.7	0.8	2.8
1968	14.1 *a*	11.1 *ab*	24.2	10.5	2.7	5.8
1969	14.2 *a*	11.2 *ab*	25.5	9.9	1.8	7.2
1970	14.5 *a*	10.8 *ab*	26.4	9.4	1.0	4.3
1997	14.6 *a*	11.7 *ab*	23.3	10.3	2.3	6.0

Note: Stream temperatures are averages of weekly maxima or minima. Air temperatures are the averages of daily maxima or minima. Precipitation is the average of daily totals for the summer. Discharge (Q) is the average of daily means. Stream temperatures were compared among years using ANOVA; values within a column followed by the same letter are not significantly different (Tukey's highest significant difference test, $p < 0.05$).

Table 3. Average differences in weekly maximum or minimum stream temperatures between basins.

		WS 1 and WS 2		WS 3 and WS 2	
	n	Maximum	Minimum	Maximum	Minimum
1960	17	–0.8 *a*	0.5 *a*	–1.1 *a*	0.4 *a*
1967	17	5.8 *b*	2.0 *b*	3.5 *b*	1.0 *b*
1968	17	6.2 *b*	2.0 *b*	5.2 *c*	–0.1 *a*
1969	17	6.4 *b*	1.8 *b*	5.1 *c*	0.1 *a*
1970	17	5.4 *b*	1.8 *b*	—	—
1997	17	–0.4 *a*	0.1 *a*	1.6 *d*	1.5 *b*

Note: The weekly maxima or minima in the unharvested basin (WS 2) were subtracted from those of the clear-cut basin (WS 1) or of the basin with patch cuts and debris flows (WS 3). Data were not available for WS 3 in 1970. Differences were compared among years using ANOVA; values within a column followed by the same letter are not significantly different (Tukey's highest significant difference test, $p < 0.05$).

we suggest that, in reaches without advective inputs, conduction may be second in importance after solar inputs. Conduction from near stream soils and alluvial substrates may account for more of the stream temperature dynamics than is generally recognized (Hondzo and Stefan 1994). Several physical factors contribute to these fluxes of heat. First, heat exchange occurs from materials at higher temperatures to those at lower temperatures, and second, the rate of heat transfer between water and substrates is three orders of magnitude greater than the rate between water and air (Monteith and Unsworth 1980). Moreover, a large amount of stream water may be in contact with substrates, especially during subsurface and hyporheic flow. In this study, stream temperatures under forest cover were cooler than surface or subsurface soil temperatures in the daytime or at night. In forest gaps or disturbed riparian areas, direct solar radiation increases the temperature of soils and alluvial substrates that could conduct heat to the streams (Hondzo and Stefan 1994; Evans et al. 1995). Conduction from alluvial substrates might explain the observed increases in minimum stream temperatures after forest harvest.

Conduction can have different a magnitude of influence on stream temperature in bedrock versus alluvial reaches. Large variations in maximum and minimum stream temperatures presently occur along the length of the recently disturbed channel in WS 3; these temperature variations coincide with erosional and depositional areas and corresponding changes in types of substrates and flow paths of water (S.L. Johnson, unpublished data). Debris flows in 1996 resulted in less increase in stream temperatures at the downstream gauging station than the 1964 debris flows. Conduction between stream water and continuous bedrock, especially relating to minimum temperatures, would have different dynamics than conduction in alluvial substrates, possibly as a function of temperature gradients within bedrock.

Stream discharges, which decline through the summer in western Oregon, have been suggested as an influence of the timing of maximum summer stream temperatures (Brown 1969). In these forested basins, there is a temporal lag between maximum solar inputs in June and maximum stream temperatures in late summer. However, we found the timing of stream maxima to be unrelated to the seasonal pattern of discharge in unshaded streams. If the timing of summer high stream temperatures was driven by low stream flows, and given that flows declined in a similar manner in both harvested and unharvested basins, then the highest temperatures in both basins should have occurred at the time of lowest flows. Instead, stream temperatures in the clear-cut basin reached high levels by late June, while those in the shaded channel increased more slowly through the summer. Discharge is a factor in stream temperature budgets (Brown 1969), as a function of the volume and the residence time of water, but increased direct solar inputs appeared to be the dominant influence of the timing of maximum temperatures in streams without riparian vegetation.

Stream temperatures returned to preharvest levels in WS 1 approximately 15 years after clear-cutting, coinciding with canopy closure in the riparian zone. Although some studies have observed a trend of decreasing maxima with each year postharvest (Moring 1975; Swift 1982), our results fit more closely to the temperature recovery trajectory postulated by Beschta and Taylor (1988), who suggested that limited riparian vegetation regrowth during the first 5 years postharvest would not affect high maximum stream temperatures but that during the next 15 years, the recovery of riparian vegetation would lead to a linear decrease in stream temperatures. Although our sites had similar trajectories of temperature recovery and returned to preharvest levels, the species composition of the overstory riparian vegetation shifted from primarily conifer to deciduous. Because of potential variation in factors influencing riparian vegetation recovery among sites and regions, the timing of riparian vegetation establishment and stream temperature recovery

Fig. 5. In 1967, (*a*) maximum and minimum daily stream temperatures for the clear-cut basin (WS 1) (black line) and unharvested basin (WS 2) (grey line) from June through September, (*b*) maximum and minimum daily stream temperatures for the basin with patch cuts and debris flows (WS 3) (black line) and the unharvested basin (WS 2) (grey line), (*c*) differences between daily maximum stream temperature for WS 1 and WS 2 (black line) and WS 3 and WS 2 (grey line), and (*d*) calculated daily solar radiation.

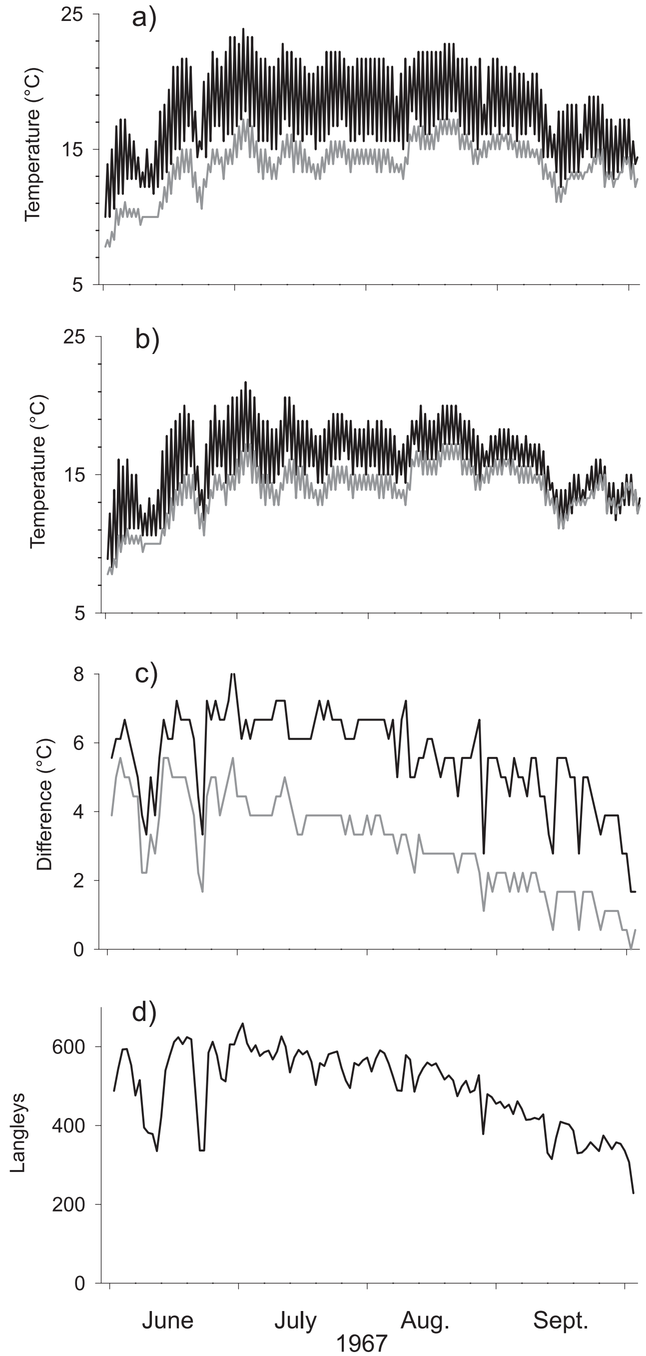
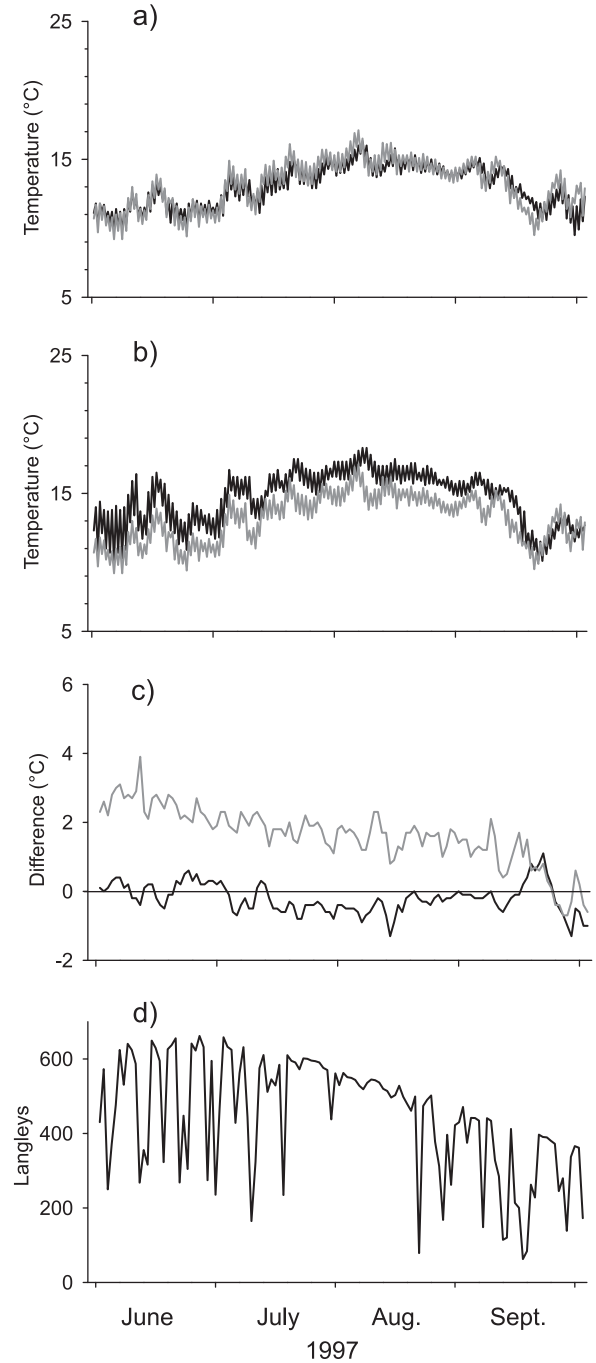


Fig. 6. In 1997, (*a*) maximum and minimum daily stream temperatures for the clear-cut basin (WS 1) (black line) and unharvested basin (WS 2) (grey line) from June through September, (*b*) maximum and minimum daily stream temperatures for the basin with patch cuts and debris flows (WS 3) (black line) and the unharvested basin (WS 2) (grey line), (*c*) differences between daily maximum stream temperature for WS 1 and WS 2 (black line) and WS 3 and WS 2 (grey line), and (*d*) measured daily solar radiation.



cannot necessarily be extrapolated to other locations without consideration of specific processes and mechanisms.

Biotic implications

Changes in the seasonal timing of increased temperatures may have subtle but important effects on stream biota. The greater increases in early summer stream temperatures documented in this study coincide with early developmental stages of many organisms, possibly leading to different types of impacts than if temperature increases primarily oc-

Fig. 7. Cumulative degree-days, calculated beginning June 1, using mean daily stream temperature for the clear-cut basin (WS 1) (black line), unharvested basin (WS 2) (dotted line), and the basin with patch cuts and debris flows (WS 3) (grey line) in (*a*) 1967 and (*b*) 1997.

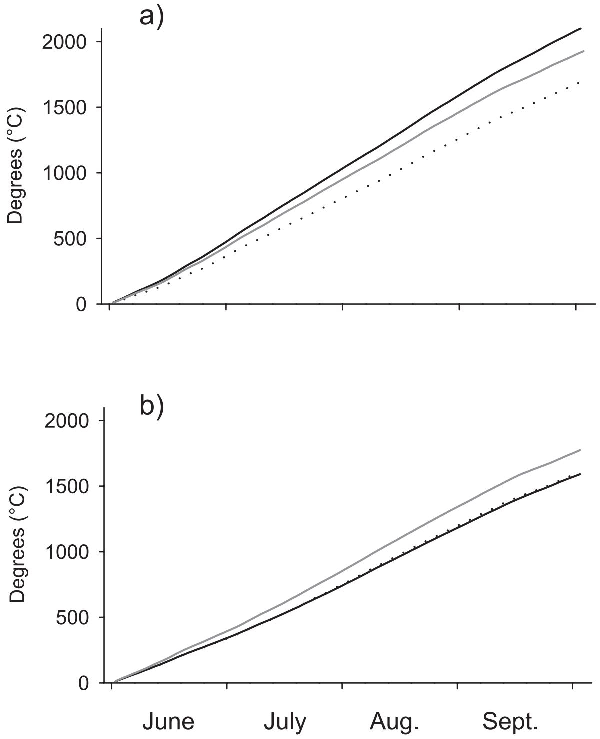
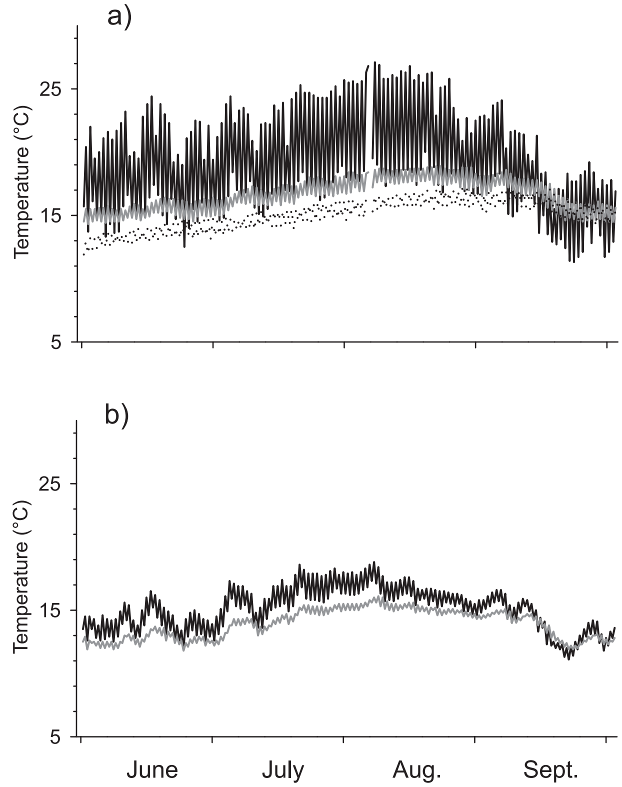


Fig. 8. Maximum and minimum daily soil temperature in 1997 (*a*) 10 (black line), 50 (grey line), and 100 cm (dotted line) below the surface in the forest gap (primary climate station), and (*b*) 10 (black line) and 30 cm (grey line) below the surface in an old-growth forest (WS 2 reference stand).



curred at times of historical maximum summer temperatures. Aquatic organisms are quite sensitive to changes in stream temperatures (e.g., Beitinger and Fitzpatrick 1979; Vannote and Sweeney 1980; Ward and Stanford 1992); increases in maximum stream temperature can be lethal, but increases of sublethal temperature result in changes in metabolism and growth rates (Medvick 1979; Thomas et al. 1986) as well as changes in food web dynamics and competitive interactions (Brett 1952; Reeves et al. 1987). Higher temperatures require more energy from biota to sustain increased rates and processes and can deplete the energy reserves of individual fish (Thomas et al. 1986). Increased temperature can also lead to greater virulence of bacterial diseases (Becker and Fugihara 1978) at a time when individuals are being subjected to thermal stress and have reduced resistance (Thomas et al. 1986). Upper thermal limits for organisms vary by species and life stage of the organism (Brett 1952; Coutant 1977), with the young generally being most sensitive to increases in the temperature of their environment.

Increased rates of accumulation of thermal degree-days, as observed in this study, have been shown to affect life history patterns and timing of emergence of biota. Following forest harvest in a coastal Oregon stream, an average subsurface stream temperature increase of 1.5°C in coho salmon (*Oncorhynchus kisutch*) spawning beds was estimated to shorten the incubation period of salmon eggs by 13 days (Ringler and Hall 1975). In a stream in British Columbia, juvenile coho salmon smolts grew more rapidly following clear-cutting and an increase in stream temperatures and migrated earlier to the ocean than before forest harvest (Holtby 1988). Earlier migration of these smolts may have led to reduced survival rates due to increased exposure to migrating predators (Holtby 1988). Aquatic macroinvertebrates are also impacted by changes in stream temperatures (Vannote and Sweeney 1980; Ward and Stanford 1992). Higher stream temperatures resulted in more rapid growth of invertebrates through their instar phases and hatching at smaller sizes (Vannote and Sweeney 1980).

The increased range of variation in stream temperature at diurnal, weekly, and seasonal time scales shown in this study could have important biological impacts (Medvick 1979; Thomas et al. 1986). Generally, in undisturbed forested streams, the range of temperature variation increases with length of time over which data are evaluated, leading to greater variation at the seasonal scale than at the diurnal scale. However, after clear-cutting and burning, the diurnal range of temperature in early summer (6–8°C) was as great as the seasonal range in an unharvested basin (8°C). Similar diurnal increases have been found in other regions (Swift 1982; Lynch et al. 1984). These rapid fluctuations in temperature could lead to stress for organisms (Thomas et al. 1986), although the specific tolerances and responses of most organisms to rapid temperature fluctuations are not well known.

In summary, not only were maximum and minimum stream temperatures higher following clear-cutting, but the temperature differences between shaded and unshaded streams were greatest early in the summer season. Our results support the hypotheses that stream temperatures in these basins are driven by fluxes of shortwave solar radiation that can be modified by riparian shading and that conduction from the soils and alluvial substrates is of greater importance than generally recognized. Although regrowth of deciduous riparian vegetation resulted in a return to preharvest stream temperatures approximately 15 years postharvest, site-specific factors may produce shorter or longer recovery times for stream temperatures at other sites. There is a need to better understand the spatial and temporal factors influencing the direct shading of stream channels for successful riparian restoration activities to moderate high stream temperatures. Research on the potential for heat dissipation through interaction of stream water with shaded alluvial substrates is also needed. In addition, studies of the effects of wide diurnal stream temperature fluctuations on aquatic biota would be very valuable.

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References

Anderson, H.W. 1973. The effects of clearcutting on stream temperature: a literature review. DNR Rep. No. 29. Washington Department of Natural Resources, Olympia, Wash.

Becker, C.D., and Fugihara, M.P. 1978. The bacterial pathogen, *Flexibacter columnaris*, and its epizootiology among Columbia River fish: a review and synthesis. Am. Fish. Soc. Monogr. No. 2.

Beitinger, T.L., and Fitzpatrick, L.C. 1979. Physiological and ecological correlates of preferred temperature in fish. Am. Zool. **19**: 319–329.

Beschta, R.L., and Taylor, R.L. 1988. Stream temperature increases and land use in a forested Oregon watershed. Water Resour. Bull. **24**: 19–25.

Beschta, R.L., Bilby, R.E., Brown, G.W., Holtby, L.B., and Hofstra, T.D. 1987. Stream temperature and aquatic habitat: fisheries and forestry interactions. *In* Streamside management: forestry and fishery interactions. *Edited by* E.O. Salo and T.W. Cundy. Institute of Forest Resources, University of Washington, Seattle, Wash. pp. 191–232.

Brett, J.R. 1952. Temperature tolerances in young Pacific salmon, *Oncorhynchus*. J. Fish. Res. Board Can. **9**: 268–323.

Brown, G.W. 1969. Predicting temperatures of small streams. Water Resour. Res. **5**: 68–75.

Brown, G.W., and Krygier, J.T. 1970. Effects of clear-cutting on stream temperature. Water Resour. Res. **6**: 1133–1139.

Coutant, C.C. 1977. Compilation of temperature preference data. J. Fish. Res. Board Can. **34**: 739–745.

Crittenden, R.N. 1978. Sensitivity analysis of a theoretical energy balance model for water temperatures in small streams. Ecol. Model. **5**: 207–224.

Dyrness, C.T. 1973. Early stages of plant succession following logging and burning in the western Cascades of Oregon. Ecology, **54**: 57–69.

Evans, E.C., Greenwood, M.T., and Petts, G.E. 1995. Short communication: thermal profiles within river beds. Hydrol. Processes, **9**: 19–25.

Halpern, C.B., and Spies, T.A. 1995. Plant species diversity in natural and managed forests of the Pacific Northwest. Ecol. Appl. **5**: 913–934.

Holtby, L.B. 1988. Effects of logging on stream temperatures in Carnation Creek, British Columbia, and associated impacts on the coho salmon (*Oncorhynchus kisutch*). Can. J. Fish. Aquat. Sci. **45**: 502–515.

Hondzo, M., and Stefan, H.G. 1994. Riverbed heat conduction prediction. Water Resour. Res. **30**: 1503–1513.

Hostetler, S.W. 1991. Analysis and modeling of long-term stream temperatures on the Streamboat Creek basin, Oregon: implications for land use and fish habitat. Water Resour. Bull. **27**: 637–647.

Ingebritsen, S.E., Sherrod, D.R., and Mariner, R.H. 1992. Rates and patterns of groundwater flow in the Cascade range volcanic arc, and the effect on subsurface temperature. J. Geophys. Res. **97**: 4599–4627.

Jones, J.A., and Grant, G.E. 1996. Peak flow responses to clearcutting and roads in small and large basins, western Cascades, Oregon. Water Resour. Res. **32**: 959–974.

Levno, A., and Rothacher, J. 1967. Increases in maximum stream temperatures after logging in old-growth Douglas-fir watersheds. U.S. For. Serv. Pac. Northwest For. Range Exp. Stn. Res. Note PNW-65.

Levno, A., and Rothacher, J. 1969. Increases in maximum stream temperatures after slash burning in a small experimental watershed. U.S. For. Serv. Pac. Northwest For. Range Exp. Stn. Res. Note PNW-110.

Lynch, J.A., Rishel, G.B., and Corbett, E.S. 1984. Thermal alterations of streams draining clearcut watersheds: quantification and biological implications. Hydrobiologia, **111**: 161–169.

Medvick, P.A. 1979. Growth rates of juvenile maomao, *Abudefduf abdominalis*, at constant and cyclic temperatures. Trans. Am. Fish. Soc. **108**: 293–298.

Monteith, J.L., and Unsworth, M. 1980. Principles of environmental physics. 2nd ed. Routledge, Chapman, and Hall, London, U.K.

Moring, J.R. 1975. The Alsea watershed study: effects of logging on aquatic resources of three headwater streams of the Alsea River, Oregon. Part II. Changes in environmental conditions. Fish. Res. Rep. No. 9. Oregon Department of Fish and Wildlife, Corvallis, Oreg.

Neter, J., Wasserman, W., and Kutner, M.H. 1990. Applied linear statistical models: regression, analysis of variance, and experimental designs. 3rd ed. Irwin, Homewood, Ill.

Reeves, G.H., Everest, F.H., and Hall, J.D. 1987. Interactions between the redside shiner (*Richardsonius balteatus*) and the steelhead trout (*Salmo gairdneri*) in western Oregon: the influence of water temperature. Can. J. Fish. Aquat. Sci. **44**: 1603–1613.

Ringler, N.H., and Hall, J.D. 1975. Effects of logging on water temperature and dissolved oxygen in spawning beds. Trans. Am. Fish. Soc. **104**: 111–121.

Sinokrot, B.A., and Stefan, H.G. 1993. Stream temperature dynamics: measurements and modeling. Water Resour. Res. **29**: 2299–2312.

SPSS, Inc. 1998. Systat, version 8.0. SPSS, Inc., Chicago, Ill.

Swanson, F.J., Johnson, S.L., Gregory, S.V., and Acker, S.A. 1998. Flood disturbance in a forested mountain landscape. BioScience, **48**: 681–689.

Swift, L.W., Jr. 1982. Duration of stream temperature increases following forest cutting in the southern Appalachian mountains. International Symposium on Hydrometeorology. American Water Resources Association, Urbana, Ill. pp. 273–275.

Swift, L.W., and Messer, J.B. 1971. Forest cuttings raise temperatures of small streams in the southern Appalachians. J. Soil Water Conserv. **26**: 111–116.

Thomas, R.E., Gharrett, J.A., Carls, M.G., Rice, S.D., Moles, A., and Korn, S. 1986. Effects of fluctuating temperature on mortality, stress, and energy reserves of juvenile coho salmon. Trans. Am. Fish. Soc. **115**: 52–59.

Vannote, R.L., and Sweeney, B.W. 1980. Geographical analysis of thermal equilibria: a conceptual model for evaluating the effect of natural and modified thermal regimes on aquatic insect communities. Am. Nat. **115**: 667–695.

Ward, J.V., and Stanford, J.A. 1992. Thermal responses in the evolutionary ecology of aquatic insects. Annu. Rev. Entomol. **27**: 97–117.

Webb, B.W., and Zhang, Y. 1997. Spatial and seasonal variability in the components of the river heat budget. Hydrol. Processes, **11**: 79–101.