Stream temperature and streamside cover 14-17 years after clearcutting along small forested streams, western Oregon

Abstract

Stream temperatures were monitored on seven low-elevation western Oregon streams immediately after clearcut harvesting and 14-17 years later in two studies that examined buffer designs. One study on four streams used no-tree buffers with all trees next to the stream harvested within the clearcut units. The second study on three streams examined partial buffers designed to shade the stream only from direct sun. Streams with no-tree buffers in clearcuts 90 or 180 m long mostly exhibited significantly less warming 16-17 years after harvest than 1-5 years after harvest. Streams with partial buffers had originally shown slight response to harvest, and 14-15 years after harvest temperature trends were not different from pre-harvest trends. Percent cover and estimated radiation 14-17 years after harvesting were mostly similar in harvested and uncut areas. The exceptions were areas close to the streams that were cleared by beavers (*Castor canadensis)*, where streams were wide resulting in canopy openings, and where gravel bars with minimal plant development occurred. Planted conifers in no-tree riparian areas provided less shade than hardwoods and were mostly suppressed by hardwoods or damaged by beavers.

Key words: buffer design, riparian areas, beavers, partial buffers, cover development

Introduction

Current forest management practices in many states require retention of trees and other vegetation (often termed buffers, streamside management zones, or riparian management areas) along streams to mitigate harvest effects on riparian environments and stream temperatures. Implementation of buffers described in Oregon rules (Oregon Department of Forestry, 2009) in most cases results in a “no-harvest” zone (buffer) around streams presumably wide enough to limit warming of streams to $0.3^{o}C$ above pre-harvest temperatures.

Trees in riparian areas provide important inputs into the stream system. Structurally important woody debris, detritus from foliage, and root systems that stabilize banks are provided by bankside trees; buffers minimize stream disturbance during harvesting. Many riparian areas along streams in western Oregon below 600 m elevation are dominated by hardwoods, especially red alder (*Alnus rubra* Bong.). Red alder is a fast-growing species in early years, and adopts a stem form that leans toward openings providing shade for streams. As such, it is effective in restoring shade in streamside clearings even though it is known to be a competitor of planted conifers (Newton et al., 1968). Although red alder can and will provide for coarse woody debris, the logs tend to be small and short-lived within the stream system, in contrast to most local conifers (Cederholm et al. 1997; Bilby et al. 1999). These features provide incentives to maintain both hardwoods and conifers within riparian areas (Connolly and Hall 1999).

Regenerating conifers under an overstory can be problematic, especially within riparian areas. Even shade-tolerant conifers have been shown to have difficulty establishing and growing in these environments because of slow growth and herbivory

(Newton and Cole, 2005). Clearcutting to the edge of a stream can increase the probability of successful conifer regeneration in these areas where protection from beavers is provided (Newton and Cole, 2005). Concerns about the stream-warming effect of clearing to provide site preparation for conifers in riparian areas limit options.

In 1993 and 1994, two studies were established in western Oregon to examine the impacts of buffer designs on stream temperature. Buffers were designed to allow for openings for conifer regeneration. The first of these studies involved small clearcuts 90 or 180 m on both sides of four streams with no-tree buffers, and Dent (1995) reported 0.11-3.75°C increases in maximum temperatures for 1-3 years after harvest. The second study used residual tree cover about 12 m wide only on the south side of the stream as a partial buffer for larger clearcuts comprising 490-790 m of stream length. Zwieniecki and Newton (1999) found little warming (average approximately 1°C) immediately after harvest in streams with partial buffers of this kind. These studies were revisited 14-17 years later to compare stream temperature trends with those reported earlier. We also evaluated cover and radiation to determine if 14-17 years after harvest, levels were similar in harvested and uncut reaches along the streams.

Methods

Both Studies

The original studies examined low-elevation fish-bearing streams located in the Oregon Coast Range and in western foothills of the Oregon Cascades (Table 1). The regional climate is Mediterranean, with moderate winter temperatures with heavy precipitation and moderate to warm summers with little precipitation. Prior to harvest, riparian areas were dominated by hardwoods, primarily red alder and bigleaf maple (*Acer* *macrophyllum* Pursh), 12-27m tall.

No-Tree Buffer Sites

Four streams (Ames, Bark, Buttermilk, and Mosby) were selected as representatives of forest streams subject to Oregon Department of Forestry (2009) rules that normally required residual buffers (15 or 21 m wide depending on stream width, both sides) associated with clearcut harvesting. In each of these streams, a reach at least 1,460 meters long was selected for study of stream warming following clearcut harvesting with no-tree buffers to evaluate the consequences of removing all tree cover to the streambank. Layout for the study reach included an 180-m harvested reach, an uncut reach 300-700 m long, an upper 90-m harvested reach, an uncut reach 100-300 m long, a lower 90-m harvested reach, and an uncut reach of about 300 m downstream of the lowest harvested area (Figure 1a).

For the original study, harvesting occurred in 1993 with all trees removed to the streambank, so that the only woody vegetation remaining was shrubs. Stream temperature recorders (Omnidata or Onset Hobo-Temps®; accuracy 0.5^{o}C) were installed above and at the lower end of the 180-m harvest unit, and above the upper 90-m unit and below the lower 90-m unit (Figure 1a) beginning the first summer after harvest. Stream temperatures were monitored starting June or July and continuing through September or October for five summers. Three years after installation, very little woody cover had developed along the no-tree buffer clearcut units, and net warming (determined by difference between stream temperature downstream of harvested units and stream temperature in uncut reaches upstream of harvested units) of streams was reported (Dent 1995).

These streams were revisited during the summers of 2008 and 2009 to evaluate temperature trends 16 and 17 years after harvest. Thermistors (Onset Tidbit v2; accuracy 0.2^{o}C) were placed in the streams close to the original locations. Cut boundaries were discernible, and temperatures within 3 m up- and downstream of the boundaries were +-0.1°C. Temperatures were monitored from mid-June through mid-September.

The 180-m unit on Buttermilk was located on a tributary rather than the main stem. An additional thermistor was placed above the confluence, and data from that thermistor showed that stream temperatures on the main stem were warmer than those of the tributary. There were no harvested areas without protective buffers on the main stem above our study reaches, but there were large areas where most cover had been removed by beavers (C*astor canadensis*), and several ponds had been formed by beaver dams.

Partial Buffer Sites

Three other streams (Table 1), described by Zwieniecki and Newton (1999), had been selected in 1994 to evaluate a buffer design that left cover only between the sun and open water. These streams had clearcuts that extended for 490 m (Cascade Brush), 550 m (North Mill), and 790 m (Scheele), each having a 12-m buffer situated south of open water to provide shade on the stream continuously between 900-1700 PDT (Figure 1b). If a stream had an east-west orientation, trees were removed completely on the north side of the creek. When the stream had a north-south orientation, then some trees were left on both sides of the creek so that direct radiation from the sun would be intercepted by vegetation between 900-1700 PDT; this resulted in buffers 9-12 m wide. In the original study, stream temperature was recorded before harvest (1994) upstream and downstream from the harvest unit, and for the first year (1995) after harvest from June to September.

Stream temperature was also collected 152 m and 304 m downstream from the harvested unit during the first-year post-harvest to determine whether any heat gained in the unit would persist downstream. Zwieniecki and Newton (1999) had reported little warming with these partial buffers in the first year after harvest. Streams were revisited in the summers of 2008 and 2009, and thermistors placed as close to the original positions as possible.

Vegetation Sampling During Revisit

As part of the original study on the no-tree buffer units, a reforestation study was established which included planting native conifers within the riparian zone. Newton and Cole (2005) reported early observations about the planted conifers, noting losses to beavers and mountain beavers (*Aplodontia rufa*). Due to the loss of seedling identification and precommercial thinning that had occurred in some areas, exact counts of planted saplings could not be re-established along no-tree buffer streams. Partial buffer sites had been planted operationally. Evaluation of streamside plantations near the streams was the same for both studies for the revisit.

For both the partial and no-tree buffer units, sample points (land points) describing plantation and buffer structure were established 4.6 m from the streambank on each side of each stream at 15 m intervals only in harvested units. Land points were not sampled in uncut reaches. At each point, tallies of hardwoods and conifers by species were made using a 2.3 m^2 ha^{-1} (10 BAF) prism. In addition to these land points, sample points for fisheye photos of canopies and cover estimates (visual and by densiometer) were established every 30 m centered in midstream for harvested and uncut areas of each study reach. Fisheye photographs were taken within an hour of dusk or dawn or during overcast conditions. Cover estimates included percent conifer, hardwood, and shrub cover within 5 m of the point, a visual estimate of hemispherical cover (cover estimate from horizon to horizon similar to that obtained through fisheye photographs), densiometer counts in four cardinal directions (Strickler 1959), and percent cover over the stream by log, herbaceous vegetation, and shrubs 5 m up- and downstream of the point. All sample points were evaluated in July 2009.

Analysis

Each stream is a case study; hence statistical analyses could not consider streams as replications. On each stream, we used time series regression to analyze temperature trends for daily maxima, means, and minima for both studies.

For the no-tree buffer sites, time series regressions were developed relating 1) the temperature below the 180-m harvested unit to the temperature above the 180-m harvested unit and 2) the temperature below the second 90-m unit to the temperature above the 180-m unit. In the absence of pre-harvest data, regression time trends were developed for two periods—the first 5 years after harvest and 16-17 years after harvest. The Durbin-Watson statistic was used to test for autocorrelation (similarity of observations as a function of time between the observations), and the Portmanteau Q and Lagrange multiplier statistics were used to test for heteroscedasticity (variability among variances). PROC AUTOREG (SAS 2010) was selected for final trends because these tests indicated both autocorrelation and heteroscedasticity existed in the data sets, and appropriate lags and GARCH (generalized autoregressive conditional heteroscedasticity) models were added to the time series models (SAS 2010). The two time periods were compared by using dummy variables for the different time periods (significance at $p <$

0.05) and by comparing prediction intervals around the regression time trends. Tests for differences among years within time periods indicated that there were some differences for years 1-5, but no differences between years 16 and 17. Therefore, years 16 and 17 were used to develop prediction intervals.

For the partial-buffer sites, the availability of pre-harvest data allowed for the development of time series regressions for stream temperature below harvest units relative to above harvest units for pre-harvest temperatures, temperatures the first year after harvesting, and temperatures 14-15 years after harvesting. For each stream, a time series regression was developed using PROC AUTOREG with the temperature at the thermistor below the harvested unit relative to the temperature of the thermistor above the harvested unit. Test statistics and comparisons were the same as those described for the no-tree buffer sites.

The relationship between basal area and cover was evaluated from means of visual estimates of hemispherical cover and in-stream basal area using PROC NLMIXED SAS 2010), with site being the random effect. For the no-tree buffer sites, means of cover and basal area were calculated for the 180-m and each 90-m reach and for the uncut reaches between the harvested reaches. The partial-buffer sites were divided into harvested and uncut reaches and means calculated for those. Linear, quadratic, power, exponential, and Chapman-Richards equations were tested. Based on AIC (Akaike’s information criterion) and r^2 values, the Chapman-Richards model was selected as the best fit model.

Radiation was evaluated from the fisheye photos using WinsCanopy® software. Radiation was estimated daily from June 1 to September 30, 2009 and then averaged over all days and all photo points located within individual harvested and uncut areas.

Cover estimates from visual ratings or densiometer south ratings (densiometer counts when facing south, Strickler 1959) were faster to evaluate than fisheye photos, so we determined if these visual estimates could substitute for fisheye photos. We used PROC CORR (SAS 2010) to provide correlations across and within streams for cover and radiation on July 15, 2009. This date was selected to match timing of stream sampling for cover estimates and fisheye photos.

The relationships between radiation or cover estimates and stream temperature were examined by using PROC MIXED (SAS 2010) with stream being a random variable. For these analyses, the maximum change (daily maximum downstream thermistor – daily maximum upstream thermistor) in stream temperature on July 15, 2009 was calculated for 1) the 180-m units, 2) the uncut below the 180-m unit, 3) the 90-m harvested, uncut, 90-m harvested reach, and 4) the uncut below the downstream 90-m unit for the no-tree buffer sites. For the partial-buffer sites, the change was calculated for 1) the harvested unit, 2) the uncut reach 152 m below the harvested unit, and 3) the uncut reach 152-305 m below the harvested unit. In regressions, maximum change was the dependent variable and total daily radiation (averaged over the sample points) for July 15, visual estimates of hemispherical cover, or densiometer south was the independent variable.

Results

Stream temperature trends

No-Tree Buffer Sites

In the first few years after harvest, streams with no-tree buffers had shown increased daily summer water temperatures immediately below harvest units, especially through the 180-m units (Dent 1995). Sixteen and 17 years after harvest, the magnitude of temperature increase through these units appeared to have lessened (Figure 2), but without pre-harvest data, we could not determine if regressions were similar to pre-harvest conditions.

At Ames Creek, Bark, and Buttermilk, regressions for summer daily means (not shown) and maxima (Figure 2) indicated higher trends for 1-5 years after harvest than for 16-17 years after harvest for the 180-m unit and for all harvest units. At Mosby Creek, only the maxima for the 180-m unit were higher. The only difference for minima was at Buttermilk for all harvest units, with the trend being higher for 1-5 years post harvest than for 16-17 years post-harvest. Bark and Buttermilk Creeks had significant differences among the year-to-year regressions immediately post-harvest (years 1-5) for maxima and means.

Partial-Buffer Sites

Use of time-series regression revealed differences not detected by Zwieniecki and Newton (1999) which identified significant warming of daily summer means and maxima (Figure 3) in Scheele Creek and also slight warming in minima the first year after harvest. The original harvest at Cascade Brush did not lead to changes in mean or minimum temperatures, but there was a slight increase in daily maxima over some of the range (Figure 3). North Mill mean temperature was unchanged after harvest, as nearly as we can tell. Equipment failed in 2009, and North Mill exhibited greater variability than the other creeks in all years of data (Figure 3), and we were unable to determine a reason. Recent temperature regressions for daily maxima (Figure 3), daily means, and daily minima from all three streams showed no significant differences from pre-harvest regressions.

Cover development in riparian areas

No-Tree Buffer Sites

Hardwood basal area evaluated from in-stream sample points was greater than conifer basal area in most no-tree buffer units (Table 2). Uncut reaches indicated that hardwoods were more dominant than conifers prior to cutting. Despite planting conifers, hardwoods were dominant in harvested areas 17 years later.

Radiation levels on the stream at Ames Creek (Table 3) and estimates of cover from in-stream observations (Table 4) were similar between harvested and uncut units by 17 years after cutting. At the other streams, radiation and cover levels were similar for some harvested and uncut units. Where beavers had maintained clearings in harvested units (Bark all harvested units and Buttermilk 90-m units), these units had higher radiation and lower cover than some of the uncut areas (Tables 3 & 4).

Partial-Buffer Sites

Partial buffers remained dominated by mature red alder, as when established. Basal area on the harvested side had returned to a level almost identical to the buffered side (Table 5). Observations indicated that gaps in the buffers did occur, but shrub species provided cover over the streams in most of these gaps, as indicated by radiation estimates from the fisheye photos (Table 3) and cover estimates (Table 4). For the partial-buffer streams, average radiation 15 years after harvesting was similar between harvested and uncut reaches.

Both Studies

Regression analyses of visual estimates of cover and in-stream basal area indicated a significant relationship ($r^2 = 0.79$) (Figure 4). When an outlier point which had low basal area but 70% shrub cover was deleted, r^2 increased to 0.86. Once basal area exceeded 20 m^2 ha^{-1}, cover estimates were all greater than 60%. Greater than 60% cover was found with lower basal areas, but not as consistently. For these streams, it appeared that little gain in tree cover occurred once in-stream basal areas reached that level.

Visual estimates of hemispherical cover and densiometer south were moderately well-correlated with estimates of radiation from fisheye photographs, with densiometer south having slightly higher correlations. Combining all streams resulted in r values of -0.77 for visual hemispherical cover and -0.83 for densiometer south. Looking at streams individually, the correlations at Scheele were not significant for either cover estimate. Correlations for the other streams were significant, and r values ranged from -0.40 to -0.83 for visual hemispherical cover and -0.57 to -0.87 for densiometer south.

Regression analyses indicated no significant pattern with radiation, hemispherical cover, or densiometer south and maximum temperature change. Cover data were not collected immediately after harvest, so data were only available from 15 or 17 years after harvesting for this analysis.

Discussion

Removal of shade at the stream surface has long been recognized as a causative force in modification of stream temperature (Greene 1950; Brown 1969; Brown and Krygier 1970; Beschta and Taylor 1988). Several reports revealed that clearcutting to the streambank led to elevated stream temperatures (e.g., Burton and Likens 1973; Wilkerson et al. 2006; Quinn and Wright-Stow 2008). These studies were short-term and did not include monitoring of stream temperature after vegetation may have regrown. Longer term data from the Alsea Watershed Study in coastal Oregon indicated that stream temperature increases immediately after harvest decreased as vegetation developed over the stream (Hale 2008). Brown and Krygier (1970) reported stream temperature increases of over 12°C after clearcutting to the stream, yarding in the streambed, and burning in the Needle Branch watershed of the Alsea Watershed Study. Twenty-five years later, maximum stream temperatures were near pretreatment levels for Needle Branch (Ice 2008). Forty years after harvest, Needle Branch had the lowest temperatures of the three watersheds in the study and 96% stream shade (Hale 2008).

The 180-m harvested areas and full length of harvested areas from most of the no-tree buffer streams exhibited decreases in mean and maximum temperature trends 16-17 years after harvesting compared to 1-5 years after harvesting. We cannot determine whether temperatures had returned to pre-harvest levels in the absence of pre-harvest data. Our analyses were a reflection only that whatever temperature the units were, the warming trend had been reduced in time.

Although cover and radiation were highly correlated, radiation or cover and change in the maximum stream temperature were not significantly correlated. The lack of correlation may be related to cover over most reaches averaging >65% between thermistors in 2009 and little variability in rate of warming. Dent et al. (2008) reported that the rate of change for the 7-day moving maximum ranged from -1.6 °C/300m to +3.6 °C/300m for unlogged reaches of headwater streams in the Oregon Coast Range. Adjusting our data to a similar scale resulted in maximum changes ranging from -1.1

°C/300m to 1.9 °C/300m for the 2009 data. Although cover in some of the 90-m harvested units was less than 65%, our thermistor locations did not allow us to segregate those units from the uncut areas in between the harvested units. The lowest cover and highest radiation occurred in the 180-m unit at Bark, which exhibited a decrease in change in maximum temperature possibly attributable to deep beaver ponds and potential thermal stratification. The impact of beaver activity on stream temperature could not be quantified.

Aside from cover development, other factors can influence the change in stream temperature response through time. Stream features, such as width, velocity, channel morphology, beaver dams, groundwater inputs, and hyporheic exchange all vary in time and can impact the magnitude of temperature response (McRae and Edwards 1994; Moore et al. 2005; Gomi et al. 2006; Quinn and Wright-Stow 2008). We did not have data on these factors from the years immediately post-harvest, so we could not determine what changes had occurred over time.

We noticed considerable year-to-year variation in stream temperature, which appeared to affect peak temperature 1-2°C independent of treatment. It also clouded any estimate of gaining or reducing temperature with time. This variation can complicate determination of harvest effects (Groom et al. 2011), and we found that the year-to-year variation limited our ability to detect differences when comparing immediately post-harvest trends to recent trends for the no-tree buffer streams. The two streams with high levels of beaver activity (Bark and Buttermilk) appeared to have the greatest annual variability in temperature trends. It is possible that changes in channel morphology related to beaver dams altered the relationship between the upstream and downstream thermistors. Because we did not collect information on dams, stream cover, or stream width and depth in the years immediately post-harvest, we cannot determine if beaver activity accounted for some of the annual variability in stream temperature trends. The impact of beaver dams on stream temperature is difficult to generalize, because other factors, such as shading, groundwater, and stream volume, have an influence (McRae and Edwards 1994).

The three streams with partial buffers exhibited small or negligible elevations of daily maximum or mean temperature in large (490-790-m-long) clearcuts immediately after harvest. The largest increase over predicted values was 2.6°C for daily maximum and 0.8° C for daily mean. In British Columbia, Gomi et al. (2006) reported increases of 0.0-0.8^{o}C with 10-m buffers and no significant increases at 30-m width, and Rex et al. (2012) reported increases of up to 6°C for variable retention buffers. Wilkerson et al. (2006) reported mean weekly maximum increases of 1.0-1.4^{o} C with 11-m buffers and negligible increases with 23-m or partially cut buffers in Maine. Recent trends of post-harvest means and maxima from our three streams showed little difference from pre-harvest trends, and all streams had shade cover comparable to uncut conditions. Moreover, despite removal of nearly all cover on the north side of streams, cover of both sides was nearly identical after 15 years, and partial-buffer units had equal or less radiation in harvested units compared to uncut.

Cover development for both types of buffers returned radiation levels to uncut conditions in 15 years or less unless gaps in cover south of streams were large. Hardwoods and shrubs dominated cover, even in harvested areas where conifers had been planted. Cover development was similar to that reported by Summers (1982) and Andrus and Froehlich (1988) for riparian areas in western Oregon that had been clearcut and broadcast burned. Ten years after clearcutting, stream shading approached levels typical of old-growth and second-growth forests (Andrus and Froehlich, 1988), and Summers (1982) calculated shading would reach 75% of pre-harvest levels by 7 and 17 years for the western hemlock vegetation zone in the Coast and Cascade Ranges, respectively. Vegetation development along most of our streams indicated similar rates of growth, except in areas where beavers removed streamside vegetation (Bark, Buttermilk, and Ames) or other stream characteristics affected vegetation development (Mosby). Mosby Creek had been placer-mined in the early 1900's. Flooding, including events during our study period, had kept cover from developing toward the stream. Mosby was wider than the other streams (Table 1), with stretches 6-7 m wide. Wide openings between bank-growing shrubs and sprouts existed even in some of the uncut reaches.

Protection from beavers remained a key element in re-establishment of tree cover. Attempts to minimize beaver activity by installing poultry wire fences to keep animals in the stream were effective until fences were damaged by floods or falling trees. When fences failed, beavers damaged or removed trees. Beavers did not damage most of the large trees in the partial buffers or other large residuals, but we noted less presence of beavers along those streams. Partial hardwood buffers were largely intact despite loss of some hardwoods to wind and ice. Although we were not able to re-sample the planted seedlings on the no-tree buffer steams, we observed that herbivory by beavers was continuing after 15 years, and this had led to large and perhaps increasing gaps in plantations and other tree vegetation. We did not have enough thermistors placed along the stream to see if these openings affected local stream temperatures.

Current regulations for protecting cold waters require that forest practices limit stream temperatures increases to 0.3°C above pre-harvest level. The State of Oregon (Oregon Department of Forestry, 2009) has established and maintains forest practice buffer rules that require buffers presumed to meet the temperature standard. Although this standard was designed to protect cold-water habitat for fish, stream productivity has been positively tied to photosynthesis (Murphy et al. 1981; Boothroyd et al. 2004; Kiffney et al. 2004) that is dependent on energy from the sun. Stream productivity in both no-tree and partial buffers was observed to be nearly twice as high in harvested as in uncut reaches of these same streams in terms of benthic insect abundance (Walsh 1996; Newton and Cole 2005). No major changes in relative abundance of six orders of benthic insects were observed. Ice et al. (2004) pointed out that the rules about stream buffers were keyed on absolute temperature criteria without regard for what was possible, presumably by integrating stream productivity with water temperature. They also identified relevance of using natural warming trends as a basis for numerical criteria. Discovery of buffer designs that maintain temperature within bounds that allow productivity is a priority, if indeed that is possible.

Conclusions

Streams that had clearcut units to the streambank exhibited increased stream warming immediately after harvest. Most of these increases had decreased by 16-17 years after harvesting and appeared related to closure of cover over the streams. Streams with partial buffers exhibited no differences in temperature trends when comparing pre-harvest to 14-15-year post-harvest trends. Conditions that limit streamside cover development along the streams led to elevated radiation. Prior evidence from these streams suggest future focus on the interaction of stream buffer design, including different orientations relative to the sun, and stream productivity to include evaluation of season-long integration of temperature and productivity trends.

References:

ANDRUS, C. AND H.A. FROEHLICH. 1988. Riparian forest development after logging or fire in the Oregon Coast Range: wildlife habitat and timber value. P. 139-152 in *Streamside Management: Riparian Wildlife and Forestry Interactions*, Raedeke, K.J. (ed.). University of Washington Institute of Forest Resources Contribution #59, Seattle, WA.

BESCHTA, R.L., AND R.L. TAYLOR. 1988. Stream temperature increases and land use in a forested Oregon watershed. *Water Resources Bulletin.* 24:19-25.

BILBY, R.E., J.T. HEFFNER, B.R. FRANSEN, J.W. WARD, AND P.A. BISSON. 1999. Effects of immersion in water on deterioration of wood from five species of trees used for habitat enhancement projects. *Am. J. Fish. Manag.* 19(3):687-695.

BOOTHROYD, I.K.G., J.M. QUINN, E.R. LANGER, K.J. COSTLEY, AND G. STEWARD. 2004. Riparian buffers mitigate effects of pine plantation logging on New Zealand streams 1. On riparian vegetation structure, stream geomorphology and periphyton. *For. Ecol. Manage*. 194: 199-213.

BROWN, G. W. 1969. Predicting temperatures of small streams. *Water Resources Research* 5:68-75.

BROWN, G.W., AND J.T. KRYGIER. 1970. Effects of clear-cutting on stream temperature. *Water Resour. Res*. 6:1133-1139.

BURTON, T.M., AND G.E. LIKENS. 1973. The effects of strip-cutting on stream temperatures in the Hubbard Brook Experimental Forest, New Hampshire. *Bioscience* 23: 433-435.

CEDERHOLM, C.J., R.E. BILBY, P.A. BISSON, T.W. BUMSTEAD, B.R. FRANSEN, W.J. SCARLETT, AND J.W. WARD. 1997. Response of juvenile coho salmon and steelhead to placement of large woody debris in a coastal Washington stream. *N. Am. J. Fish. Manag.* 17(4):947-963.

CONNOLLY, P.J. AND J. D. HALL. 1999. Biomass of coastal cutthroat trout in unlogged and previously clear-cut basins in the central Oregon Coast Range. *Trans. Am. Fish. Soc.* 128(5):89-899.

DENT, L. 1995. Influence of small clearcut openings in riparian areas on summer stream temperatures on coastal Oregon and western Cascade streams. Oregon State University College of Forestry. *COPE Report* 8(3):4-8

DENT, L., D. VICK, K. ABRAHAM, S. SCHOENHOLTZ, AND S. JOHNSON. 2008. Summer temperature patterns in headwater streams of the Oregon coast range. *Journal of the American Water Resources Association* 44: 803-813. DOI: 10.1111/j.1752-1688.2008.00204.x.

GOMI, T., R.D. MOORE, AND A.S. DHAKAL. 2006. Headwater stream temperature response to clear-cut harvesting with different riparian treatments, coastal British Columbia. *Water Resources Bulletin* 42: WO8437, doi:10.1029/2005WR004162.

GREENE, G.E. 1950. Land use and trout streams. *Journal of Soil and Water Conservation* 5:125-126.

GROOM, J.D., L. DENT, AND L.J. MADSEN. 2011. Stream temperature change detection for state and private forests in the Oregon Coast Range. *Water Resour. Res.* 47:W01501:

HALE, V.C. 2008. *A physical and chemical characterization of stream water draining* *three Oregon Coast Range catchments*. M.Sc. thesis, Oregon State University, Corvallis, OR. 110 p.

ICE, G.G. 2008. Stream temperature and dissolved oxygen. P. 37-54 in *Hydrological and Biological Responses to Forest Practices: The Alsea Watershed Study*, Stednick, J.D. (ed.). Springer, New York, NY.

ICE, G.G., J. LIGHT, AND M. REITER. 2004. Use of natural temperature patterns to identify achievable stream temperature criteria for forest streams. *West. J. Appl. For.* 19(4):252-259.

KIFFNEY, P.M., J.S. RICHARDSON, AND J.P. BULL. 2004. Establishing light as a causal mechanism structuring stream communities in response to experimental manipulation of riparian buffer width. *J. N. Am. Benthol. Soc*. 23: 542-555.

MCRAE, G. AND C.J. EDWARDS. 1994. Thermal characteristics of Wisconsin headwater streams occupied by beaver: implications for brook trout habitat. *Trans.Am. Fish. Soc.* 123:641-656.

MONTGOMERY, D.R., AND J.M. BUFFINGTON. 1997. Channel-reach morphology in mountain drainage basins. *GSA Bulletin* 109:596-611.

MOORE, R. D., D.L. SPITTLEHOUSE, AND A. STORY. 2005. Riparian microclimate and stream temperature response to forest harvesting: a review. *Journal of the American Water Resources Association* 41: 813-834.

MURPHY, M.L., C.P. HAWKINS, AND N.H. ANDERSON. 1981. Effects of canopy modification and accumulated sediment on stream communities. *Trans. Am. Fish. Soc.* 110: 469-487.

NEWTON, M., J. ZAVITKOVSKI AND B.A. EL HASSAN. 1968. Role of red alder in western Oregon forest succession. P. 73-84 in *Biology of Alder*. Trappe, J. M., J. F. Franklin, R. F. Tarrant, and F. M. Hansen (eds.). PNW For. and Range Exp. Sta., Portland, and N.W. Scientific Assn.

NEWTON, M. AND E. C. COLE. 2005. Linkage between riparian buffer features and regeneration, benthic communities and water temperature in headwaters streams, western Oregon. P. 81-101 in *Productivity of Western Forest A Forest Products Focus*. C. Harrington and S. Schoenholtz (eds.). USDA Forest Service General Technical Report PNW-GTR-642.

OREGON DEPARTMENT OF FORESTRY. 2009. Water Protection Rules: Vegetation retention along streams. OAR 629-640-0000. Salem, OR.

QUINN, J.M., AND A.E. WRIGHT-STOW. 2008. Stream size influences stream temperature impacts and recovery rates after clearfell logging. *For. Ecol. Manage.* 256: 2101-2109.

REX, J.F., D.A. MALONEY, P.N. KRAUSKPF, P.G. BEAUDRY, AND L.J. BEAUDRY. 2012. Variable-retention riparian harvesting effects on riparian air and water temperature of sub-boreal headwater streams in British Columbia. *For. Ecol. Manage.* 269: 259-270. doi: 10.1016/j.foreco.2011.12.023.

SAS. 2010. SAS 9.3 User’s Guide. Cary, NC.

STRICKLER, G.S. 1959. *Use of the densiometer to estimate density of forest canopy on permanent sample plots*. USDA Forest Service Research Note, PNW-RN-180.

SUMMERS, R.P. 1982. *Trends in riparian vegetation regrowth following timber harvesting in western Oregon watersheds*. M.Sc. thesis, Oregon State University, Corvallis, OR. 151 p.

WALSH, J.B.S. 1996. *Effects of streamside riparian forest management on Ephemeroptera and Trichoptera community structure in four western Oregon streams*. M.Sc. thesis, Oregon State University, Corvallis, OR. 189 p.

WILKERSON, E., J.M. HAGAN, D. SIEGEL, AND A.A. WHITMAN. 2006. The effectiveness of different buffer widths protecting headwater stream temperatures in Maine. *For. Sci.* 52: 221-231.

ZWIENIECKI, M., AND M. NEWTON. 1999. Influence of streamside cover and stream features on temperature trends in forested streams of western Oregon. *West. J. Appl. For*. 14(2):106-113

Figure Captions

Figure 1. Layout of (a) no-tree buffer study and (b) partial-buffer study. Stars denote thermistor placement.

Figure 2. Daily maxima stream temperatures above and below the 180-m units and above the 180-m and below the lower 90-m units for Ames, Bark, Buttermilk, and Mosby creeks. Symbols are for the first 5 years post-harvest (1993-1997) and lines represent the 95% prediction intervals around time series regressions based on recent years (2008-2009), using the first 5 years post-harvest values.

Figure 3. Daily maxima stream temperatures above and below unit with partial buffer for post-harvest (1995, 2008, and 2009) for Cascade Brush, Scheele, and North Mill. Lines represent the 95% prediction intervals around time series regressions based on pre-harvest data and using post-harvest values. Due to equipment failure, North Mill 2009 is not shown.

Figure 4. Percent hemispherical cover and in-stream basal area relationship for the seven study streams. Outlier denoted by solid circle was deleted from the data set prior to creating regression line. Curve is based on Chapman-Richards model and has been averaged over all of the sites.

Table Headings.

Table 1. Stream characteristics for the seven study streams in western Oregon.

Table 2 Basal area (m^2 ha^{-1}) and standard errors (in parentheses) in 2009 for land points 4.6 m from each side of the stream and from in-stream points for harvested units on the no-tree buffer sites.

Table 3. Total radiation (Mj m^{-2} day^{-1}), standard errors (in parentheses), and number of sample points (in brackets) for in-stream points within harvested and uncut units averaged over points within a unit and averaged from June 1 - September 30, 2009 for all sites.

Table 4. Mean cover and standard errors (in parentheses) based on visual estimates evaluated at in-stream points July 2009 for each harvested and uncut unit for each stream.

Table 5. Basal area in m^2 ha^{-1} and standard errors (in parentheses) in 2009 for land points 4.6 m from each side of the stream for partial buffer streams.

Table 1. Stream characteristics for the seven study streams in western Oregon.

	Orientation	Gradient (%)	Width (cm)	Depth (cm)	Soils	Montgomery-Buffington (1997) Classification
Ames	NW	4	267	10	clay loam, basalt	pool riffle
Bark	N	2	317	21	silt loam, Eocene sedimentary	dune ripple
Buttermilk	NW	4	254	10	silt loam, Eocene sedimentary	colluvial (tributary) riffle bar (main stem)
Mosby	NW	3	416	13	clay loam, basalt	pool riffle
Cascade Brush	W	4	195	8	clay loam, basalt	step pool
North Mill	W	3	302	15	silt loam, Eocene sedimentary	pool riffle
Scheele	NW	4	276	10	Jory clay loam, basalt	cascade

Table 2. Basal area in m^2 ha^{-1} and standard errors (in parentheses) in 2009 for land points 4.6 m from each side of the stream and from in-stream points for harvested units on the no-tree buffer sites.

		Land		In-stream			
		Clearcut		Clearcut		Uncut	
		Hardwood	Conifer	Hardwood	Conifer	Hardwood	Conifer
		------------------------------m^2 ha^{-1}------------------------------					
Ames	180m	10.0 (1.1)	4.1 (0.8)	14.4 (3.1)	1.3 (1.3)	17.9 (2.0)	7.7 (34)
	Up 90m	7.1 (4.4)	2.8 (0.8)	10.3 (3.9)	2.3 (2.3)	27.5 (3.5)	4.6 (1.4)
	Low 90m	11.0 (2.5)	1.1 (0.7)	23.0 (5.3)	0 (0)	20.5 (3.9)	3.3 (1.5)
Bark	180m	1.9 (0.6)	2.7 (0.7)	0.7 (0.7)	0.7 (0.7)	24.1 (2.3)	0.4 (1.1)
	Up 90m	8.0 (3.3)	1.1 (0.5)	7.6 (7.6)	0 (0)	20.2 (4.2)	0 (0)
	Low 90m	4.3 (1.2)	0.8 (0.3)	2.8 (2.8)	0 (0)	17.5 (4.4)	0 (0)
Buttermilk	180m	4.1 (1.1)	3.9 (0.8)	5.1 (2.4)	0.5 (0.6)	21.3 (2.6)	1.9 (1.0)
	Up 90m	6.4 (1.7)	2.0 (0.7)	0.8 (0.8)	0.8 (0.8)	17.6 (5.0)	9.2 (4.4)
	Low 90m	5.7 (1.2)	4.1 (0.7)	6.9 (4.4)	1.2 (1.2)	30.0 (3.4)	3.3 (1.3)
Mosby	180m	8.7 (1.3)	2.7 (0.6)	5.6 (2.9)	1.5 (0.8)	11.2 (2.3)	1.5 (1.1)
	Up 90m	13.9 (1.9)	5.6 (1.6)	3.4 (1.2)	1.2 (1.2)	8.5 (2.6)	1.3 (0.8)
	Low 90m	3.0 (1.1)	2.3 (0.9)	0 (0)	1.2 (1.2)	3.2 (1.5)	3.7 (2.3)

[a] 1 m^2 ha^{-1} is approximately 4.36 ft^2 ac^{-1}.

Table 3. Total radiation (Mj m^{-2} day^{-1}). standard errors (in parentheses). and number of sample point (in brackets) for in-stream points within harvested and uncut units averaged over points within a unit and averaged from June 1 - September 30, 2009 for seven study streams.

Unit	**Ames**	**Bark**	**Buttermilk**	**Mosby**
		--------------------Mj m^{-2} day^{-1}--------------------		
180m	5.12 (1.12) [7]	13.15 (2.12) [7]	2.6 (0.79) [8]	11.12 (2.17) [9]
Uncut1	3.12 (0.25) [28]	6.20 (0.81) [27]	3.52 (0.55) [22]	5.79 (0.45) [9]
Upper 90m	2.85 (0.27) [4]	10.93 (3.59) [3]	10.99 (3.19) [6]	7.52 (0.75) [4]
Uncut2	4.37 (0.37) [10]	3.99 (1.11) [5]	3.75 (0.85) [6]	5.30 (1.41) [7]
Lower 90m	2.86 (0.36) [3]	9.07 (3.34) [5]	6.06 (2.36) [4]	17.38 (1.43) [4]
Uncut3	4.52 (0.50) [11]	7.59 (1.73) [11]	3.97 (0.49) [11]	9.50 (1.39) [10]
	Cascade Brush	**North Mill**	**Scheele**	
Partial Buffer	3.56 (0.55) [17]	5.55 (1.07) [18]	3.57 (0.22) [26]	
Uncut to 150m	5.30 (0.72) [6]	6.01 (2.18) [6]	3.25 (0.36) [6]	
Uncut 150m-300m	5.03 (0.42) [5]	6.36 (1.77) [5]	3.78 (0.52) [5]	

Table 4. Mean cover and standard errors (in parentheses) based on visual estimates evaluated at in-stream points in July 2009 for each harvested and uncut unit for each stream.

Stream	Unit	Hemispherical Cover	Hardwood Cover	Conifer Cover	Shrub Cover	Shrub Cover Over Water
		-----------------------------	-----------------------------	%	-----------------------------	-----------------------------
Ames	180m	79 (9.4)	63 (11.5)	1 (0.7)	53 (11.0)	39 (12.5)
	Uncut1	75 (3.2)	64 (5.2)	8 (3.2)	33 (4.0)	24 (4.5)
	Up 90m	78 (7.5)	52 (19.7)	6 (3.6)	44 (19.0)	39 (20.8)
	Uncut2	75 (3.4)	73 (7.1)	4 (2.3)	8 (2.5)	4 (1.6)
	Low 90m	73 (9.3)	68 (11.3)	0 (0)	18 (13.3)	19 (17.9)
	Uncut3	73 (3.7)	62 (7.7)	2 (1.8)	19 (3.2)	9 (3.2)
Bark	180m	18 (5.7)	12 (7.5)	0 (0)	5 (2.2)	2 (1.4)
	Uncut1	68 (4.2)	60 (6.2)	2 (1.8)	5 (1.1)	1 (0.8)
	Up 90m	38 (10.9)	28 (28.3)	0 (0)	9 (4.1)	2 (0.8)
	Uncut2	75 (2.2)	58 (11.1)	0 (0)	10 (3.5)	1 (0.4)
	Low 90m	40 (2.5)	31 (18.9)	0 (0)	3 (1.5)	1 (1.0)
	Uncut3	62 (12.3)	60 (12.1)	0 (0)	9 (2.5)	2 (1.3)
Buttermilk	180m	93 (5.5)	42 (14.1)	3 (1.3)	70 (12.2)	70 (13.2)
	Uncut1	80 (2.5)	61 (6.0)	.1 (0.1)	30 (6.5)	28 (7.7)
	Up 90m	37 (12.3)	13 (4.0)	0.2 (0.2)	14 (14.1)	15 (15.0)
	Uncut2	74 (5.5)	48 (14.1)	15 (8.2)	30 (13.0)	24 (11.4)
	Low 90m	62 (12.8)	46 (22.7)	3 (2.3)	9 (8.6)	0.3 (0.2)
	Uncut3	86 (1.2)	70 (7.1)	10 (7.5)	16 (6.8)	9 (5.6)
Mosby	180m	41 (9.6)	27 (11.8)	1 (0.6)	16 (6.8)	7 (4.8)
	Uncut1	70 (2.9)	46 (10.1)	0.7 (0.2)	2 (0.5)	0.5 (0.3)
	Up 90m	58 (9.5)	18 (6.3)	0.3 (0.2)	20 (15.2)	12 (11.0)
	Uncut2	69 (7.2)	63 (12.3)	0.2 (0.1)	8 (6.3)	5 (4.2)
	Low 90m	16 (3.1)	13 (12.4)	1 (0.7)	4 (1.4)	0.6 (0.3)
	Uncut3	42 (5.8)	31 (9.9)	4 (3.4)	4 (2.4)	2 (1.5)
Cascade	Cut	74 (3.6)	47 (7.3)	9 (4.1)	39 (5.7)	29 (5.9)
Brush	Uncut	80 (3.4)	79 (2.2)	0.5 (0.3)	13 (4.3)	8 (4.2)
North Mill	Cut	67 (4.6)	54 (7.9)	6 (3.6)	15 (4.4)	11 (3.0)
	Uncut	55 (9.7)	49 (13.3)	0.5 (0.5)	14 (2.7)	7 (1.8)
Scheele	Cut	84 (1.7)	78 (5.3)	0.9 (0.3)	27 (4.9)	15 (4.5)
	Uncut	79 (3.8)	67 (9.6)	5 (4.5)	12 (4.2)	7 (4.0)

Table 5. Basal area in m^2 ha^{-1} and standard errors (in parentheses) in 2009 for land points 4.6 m from each side of the stream for partial buffer streams. Number of sample points for each side was 34 for Cascade Brush, 35 for North Mill, and 51 for Scheele.

	Partial buffer side		No buffer side	
	Hardwood	Conifer	Hardwood	Conifer
	------------------------------m^2 ha^{-1}		------------------------------	
Cascade Brush	6.5 (0.9)	8.0 (1.0)	8.1 (1.0)	4.7 (0.6)
North Mill	10.3 (1.8)	2.3 (0.5)	10.4 (1.4)	2.0 (0.4)
Scheele	16.0 (1.0)	2.0 (0.3)	14.9 (1.4)	2.6 (0.4)

[a] 1 m^2 ha^{-1} is approximately 4.36 ft^2 ac^{-1}.

Figure 1

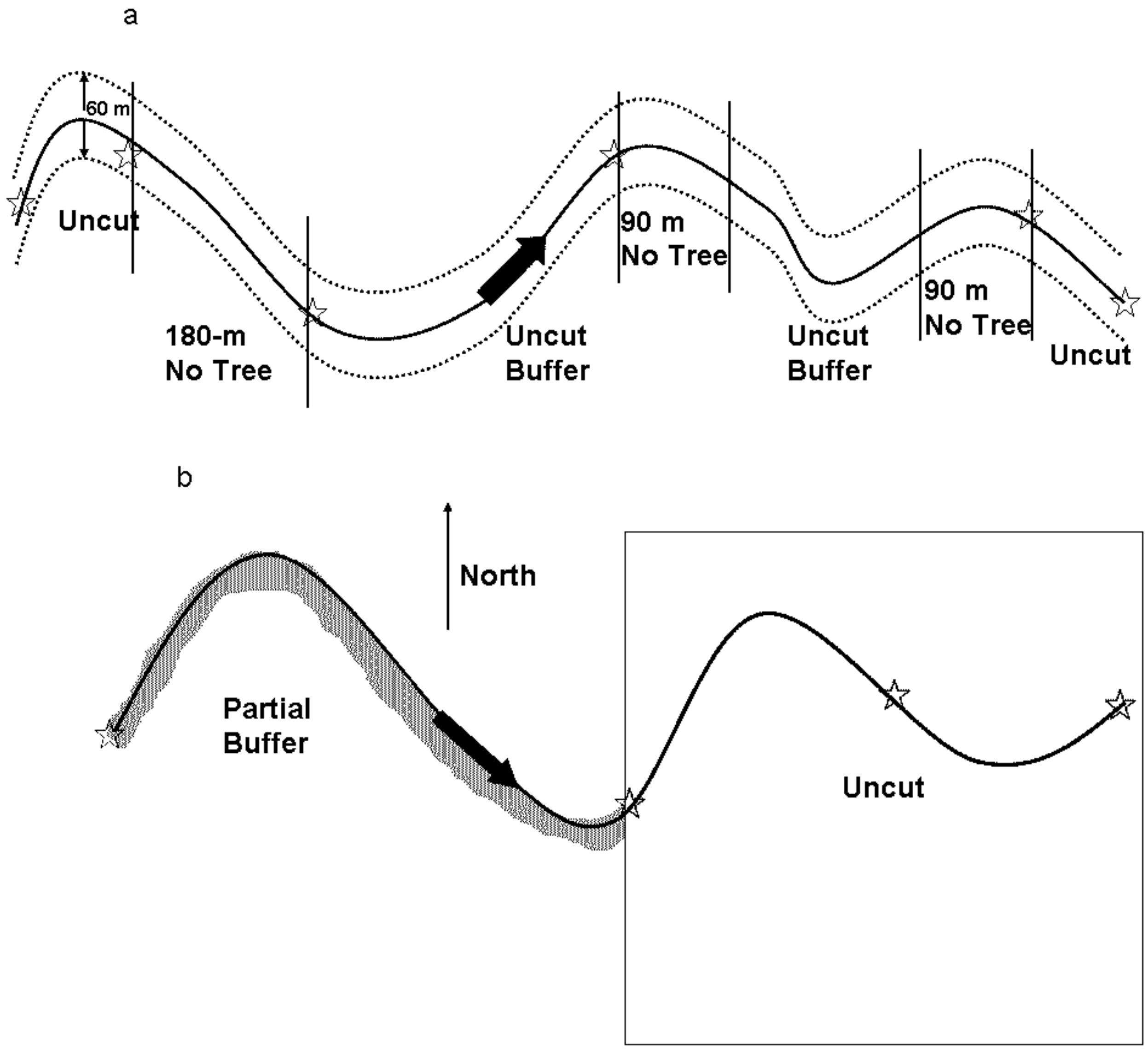

a
60 m
Uncut
180-m
No Tree
Uncut
Buffer
90 m
No Tree
Uncut
Buffer
90 m
No Tree
Uncut
b
North
Partial
Buffer
Uncut

Figure 2

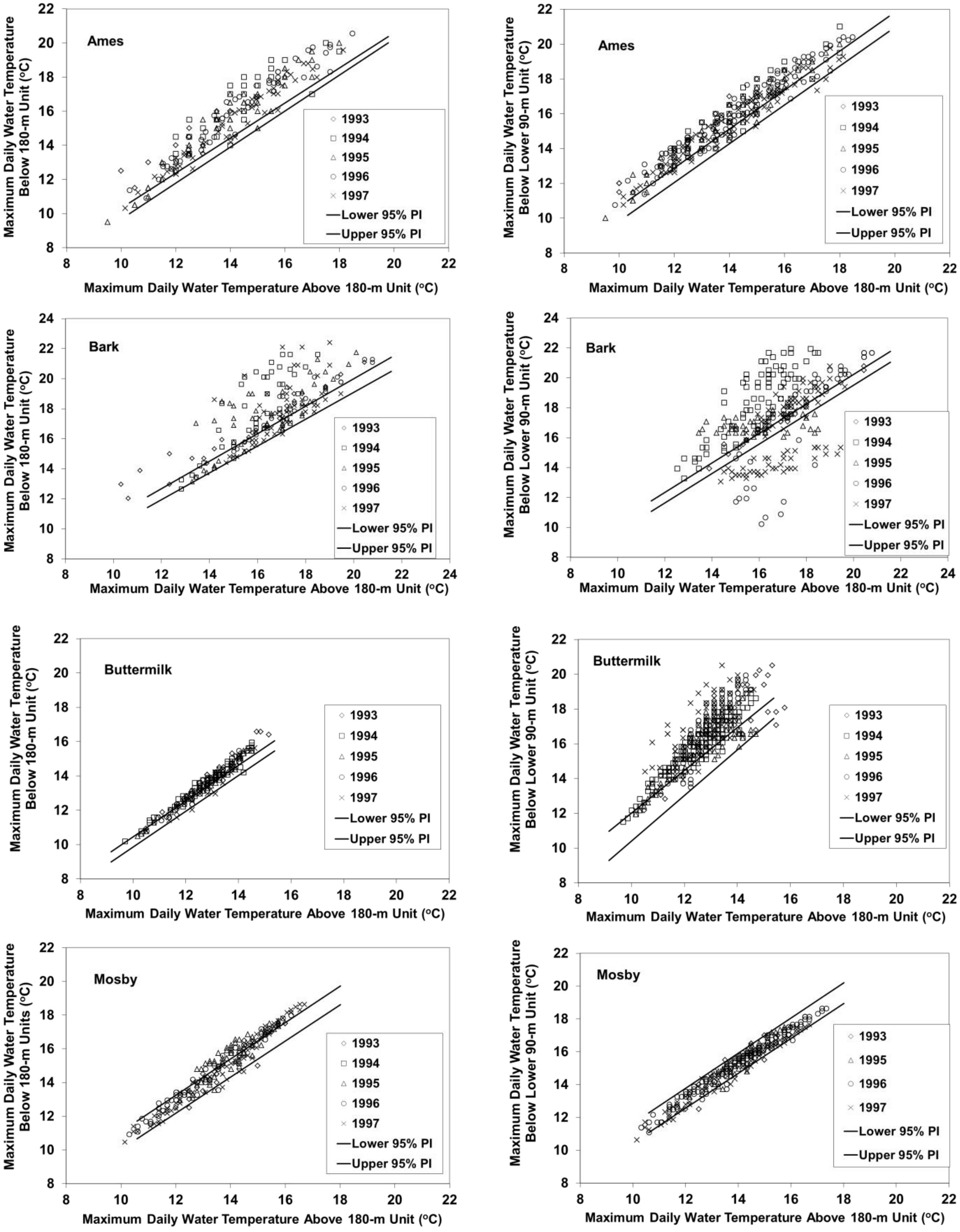

Ames
Maximum Daily Water Temperature Below 180-m Unit (°C)
Maximum Daily Water Temperature Above 180-m Unit (°C)
1993
1994
1995
1996
1997
Lower 95% PI
Upper 95% PI
Ames
Maximum Daily Water Temperature Below Lower 90-m Unit (°C)
Maximum Daily Water Temperature Above 180-m Unit (°C)
1993
1994
1995
1996
1997
Lower 95% PI
Upper 95% PI
Bark
Maximum Daily Water Temperature Below 180-m Unit (°C)
Maximum Daily Water Temperature Above 180-m Unit (°C)
1993
1994
1995
1996
1997
Lower 95% PI
Upper 95% PI
Bark
Maximum Daily Water Temperature Below Lower 90-m Unit (°C)
Maximum Daily Water Temperature Above 180-m Unit (°C)
1993
1994
1995
1996
1997
Lower 95% PI
Upper 95% PI
Buttermilk
Maximum Daily Water Temperature Below 180-m Unit (°C)
Maximum Daily Water Temperature Above 180-m Unit (°C)
1993
1994
1995
1996
1997
Lower 95% PI
Upper 95% PI
Buttermilk
Maximum Daily Water Temperature Below Lower 90-m Unit (°C)
Maximum Daily Water Temperature Above 180-m Unit (°C)
1993
1994
1995
1996
1997
Lower 95% PI
Upper 95% PI
Mosby
Maximum Daily Water Temperature Below 180-m Units (°C)
Maximum Daily Water Temperature Above 180-m Unit (°C)
1993
1994
1995
1996
1997
Lower 95% PI
Upper 95% PI
Mosby
Maximum Daily Water Temperature Below Lower 90-m Unit (°C)
Maximum Daily Water Temperature Above 180-m Unit (°C)
1993
1995
1996
1997
Lower 95% PI
Upper 95% PI

Figure 3

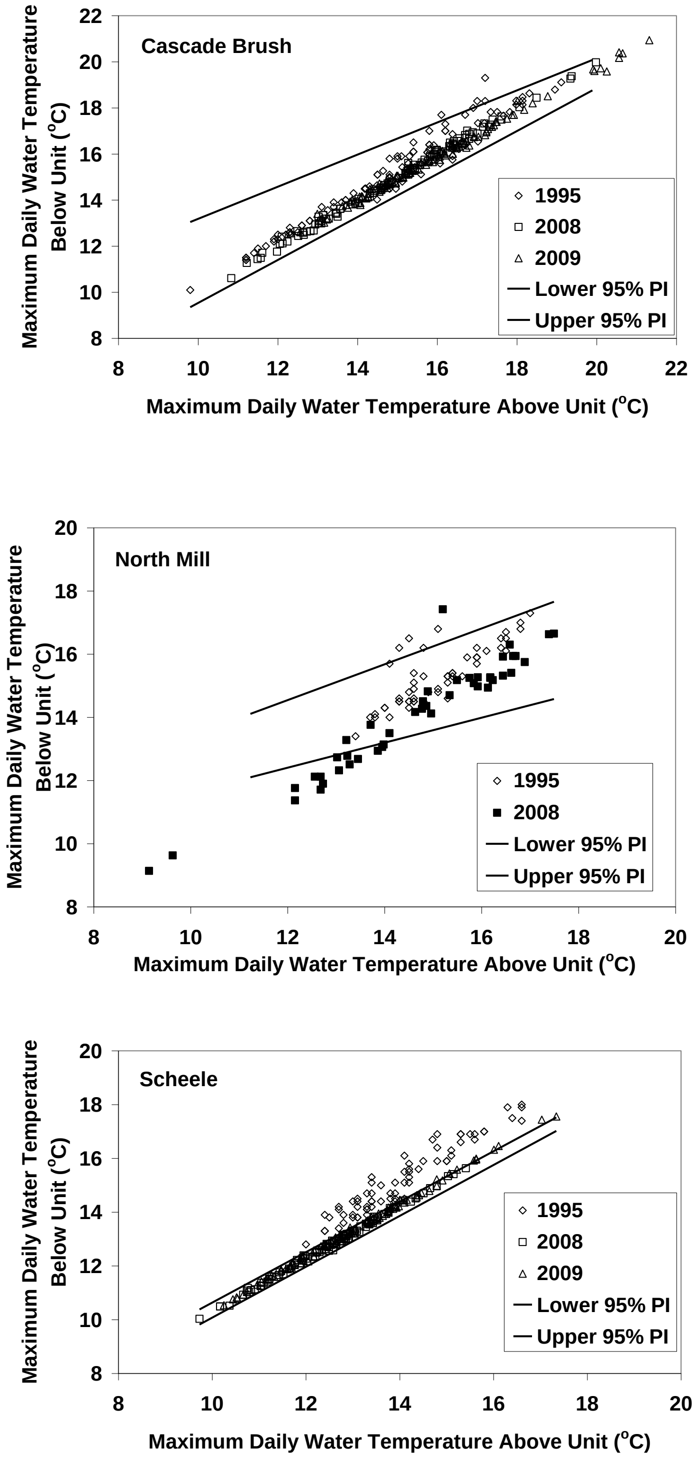
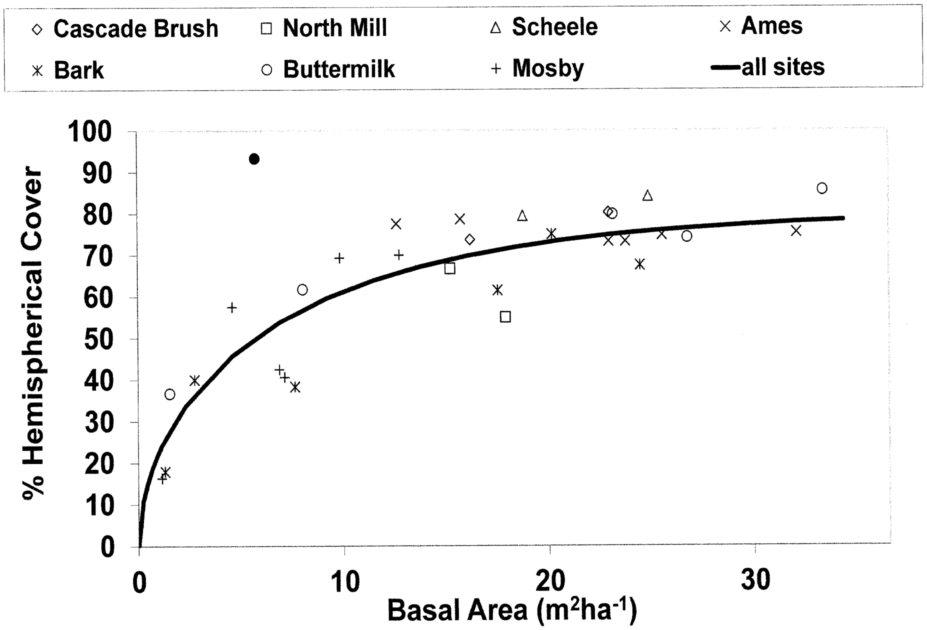

Cascade Brush
Maximum Daily Water Temperature Below Unit (°C)
Maximum Daily Water Temperature Above Unit (°C)
8
10
12
14
16
18
20
22
◇ 1995
□ 2008
△ 2009
— Lower 95% PI
— Upper 95% PI
North Mill
Maximum Daily Water Temperature Below Unit (°C)
Maximum Daily Water Temperature Above Unit (°C)
8
10
12
14
16
18
20
◇ 1995
■ 2008
— Lower 95% PI
— Upper 95% PI
Scheele
Maximum Daily Water Temperature Below Unit (°C)
Maximum Daily Water Temperature Above Unit (°C)
8
10
12
14
16
18
20
◇ 1995
□ 2008
△ 2009
— Lower 95% PI
— Upper 95% PI

Figure 4


◇ Cascade Brush
□ North Mill
△ Scheele
× Ames
⁎ Bark
○ Buttermilk
+ Mosby
all sites
% Hemispherical Cover
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
Basal Area (m^2ha^{-1})