Title: Carnation Creek – Forestry impacts and watershed recovery processes in a small coastal drainage.

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Abstract
Carnation Creek is a long-term, basin-scale case study of the effects of forestry practices on a small coastal watershed. The broad objectives of this on-going project are to determine the mechanisms, rates, and levels of forestry-related alterations and natural resource recovery in a harvested coastal drainage by describing long-term changes in biological and physical watershed processes as the second forest grows. Studies of hillslope, stream channel, floodplain, and riparian processes are integrated to describe their functional linkages and determine the ultimate consequences for channel morphology, aquatic habitats, and fish populations. Empirical data covering a comprehensive suite of parameters including climate, streamflow, water temperatures, channel morphology, and fish populations were collected, analyzed, summarized in separate component reports, and archived in the project database. These data support the descriptions of the status of biological and physical attributes of the watershed 26 years after forest harvesting concluded. The data are used for the on-going development and refinement of basin-scale models for hydrology, landslide prediction, sediment and debris budgets, channel changes, and fish habitat capability. The information gained is relevant for validating current forest practices and supporting forest policy, regulatory, and guideline development to ensure the sustainable use of forest resources, and protect watershed processes and aquatic values. This report summarizes research progress for all study components in the 2007-2008 project year.
Introduction

The effects of forest harvesting on watershed processes and fish populations has been studied for 37 years at the Carnation Creek Experimental Watershed in south-western Vancouver Island about 20 km northeast of Bamfield. Initiated in 1970, this intensive, single-watershed case study has generated the longest continuous datasets on fish-forestry interactions available anywhere (Tschaplinski et al. 2004). Currently, the broad objectives of the project are to determine the mechanisms, rates, and levels of forestry-related alterations natural resources recovery in a harvested coastal drainage by quantifying long-term changes in biological and physical watershed processes as the second forest grows.

The study uses an intensive, pre-treatment versus post-treatment design that presently consists of five years of pre-harvest baseline data (1970/71-1975), six years of observations from 1976 - 1981 when 41 % of the basin was harvested, and 26 years of post-harvest studies (1982 – present). Another 25 % of the basin was harvested in headwater areas remote from the main stream channel in the 1990s. The study features both clear-cut and largely unharvested “control” sub-basins. Riparian forestry treatments tested along the main channel vary from intensive clear-cutting to variable-width riparian buffers. Details of the project history, study design, and the methods employed for monitoring physical variables, fish populations, and biological processes before, during, and after forest harvesting were thoroughly described by Hartman & Scrivener (1990) and summarized by Tschaplinski (2000).

Current research is focused on determining the mid-term (23 – 28 years) post-harvest responses to logging practices from the condition and attributes of the hydrologic regime, hillslopes, stream channel network, riparian forest (canopy closure), aquatic habitats (mainstream, tributary, and off-channel network), water temperatures, and salmonid populations. Fish population responses examined include long-term trends in abundance, growth, age structure, survival, and smolt production.

The project’s 37-year datasets provide the framework required to address difficult forestry management questions: what is the cumulative effect of harvesting beyond specific levels (i.e., 65% basin harvest); what is the effect on both large and small stream
channels when the riparian vegetation is removed or modified; what biological changes result from altered stream habitats; and, how long do these changes persist?

These questions are addressed from a two-tiered research approach. The first tier (funded primarily by FIA-FSP) is the collection of core physical and biological data. Annually, we collect, analyze, and summarize primary data on climate (from six stations), hydrology (four streamflow weirs), stream channel morphology and fish habitat (standard ground-based and aerial-photographic surveys), and fish populations. Fish fences are used to study salmonid migrations, and multi-pass, ground-based surveys are used to study rearing populations of both juvenile anadromous salmonids and resident trout. The specific objectives of this first level of analysis are to:

(i) Determine current channel and aquatic habitat conditions in clear-cut and buffered riparian areas; relate these conditions to the ecological implications of past and current forestry practices within the watershed; and, quantify the state of recovery;

(ii) Determine and explain annual and seasonal trends in fish abundance, growth, distribution, and habitat use;

(iii) Compare the relative effects on stream channels and fish habitats made by alternative riparian forestry treatments versus those delivered to the stream network by hillslope processes (landslides and debris flows), i.e., the “downstream cumulative effects”.

The second tier of activities are performed through in-kind support by our team members and partners. Empirical data are provided as required from the above-listed activities to support process studies and model development/refinement to describe and/or predict post-harvest alterations or recovery to the hydrologic regime, hillslopes, stream channels, aquatic habitats, and fish populations. Not all of these derivative studies performed by project associates are active each year, but over the long-term, these components include:

(a) rainfall interception and runoff;
(b) water quantity and quality of surface flows;

(c) landslide frequency and location;

(d) hillslope/channel sediment-and-debris budgets (sediment storage and transport models) and channel condition;

(e) in-channel sediment mobilization (tracking and recovery of painted, magnetically-coded rocks by research team members from the Universities of British Columbia and Texas – performed for 2007 - 2008);

(f) dissolved organic carbon (DOC) shielding of UV light vs. fish survival; and

(g) export of water, DOC, particulate organic carbon, and N to the ocean and effects on coastal marine alga blooms and juvenile salmon survival.

**Objectives**

The 2007-2008 work plan included the following field research, monitoring, and extension components:

(A) Research and monitoring.

(1) Hydrological and meteorological data: routine collection at weirs and climate stations; routine station maintenance; hydrology weir discharge calibrations (ratings); hydrological recovery data (canopy rainfall interception, peak flows, annual water yield);

(2) On-going hydrology-climate data verification (focusing primarily on air and water temperatures);

(3) Channel geomorphology and fish habitats: seasonal surveys to determine changes in channel morphology, large woody debris (LWD) abundance, distribution, and orientation; channel sediment budgets and bedload movements, and streambed textures;
(4) Aerial photographic surveys: documenting hillslope disturbances, riparian canopy closure, and channel structural change (relates to fish habitat quality and quantity) in both the main stream and tributaries;

(5) Riparian canopy studies – fourth year of ground-based surveys of angular and overhead canopy density: this component is linked to work on the relationship of canopy closure and effects on water temperatures main-channel and tributary habitats;

(6) Juvenile and adult fish migrations: weir operations for enumeration, identification, and biological parameters of juvenile salmon emigrating seaward in spring, juvenile coho salmon (*Oncorhynchus kisutch*) and cutthroat trout (*O. clarki*) migrating between main-channel habitats and tributary winter habitats in spring and autumn, and adult salmonids returning to spawn in autumn;

(7) Salmonid rearing populations: three seasonal population surveys to determine the abundance, distribution, age structure, growth, and seasonal survival of juvenile salmonids;

(B) Extension.

(1) Distribution of the project brochure to client audience.

(2) Presentation of the recently updated project poster as required.

(3) Updated Carnation Creek component on the Research Branch Fish-Forestry Interaction Program website.

(4) Field workshops (1 – 2 planned).

(5) Lectures and Seminars (3 planned).

(6) Study component reports (annual progress / technical reports) for principal research components.

**Methods**

The Carnation Creek research program is a continuation and expansion of a rigorously peer-reviewed program in place since 1991. All methodologies employed are standard or have been successfully tested. Procedures and protocols are in accordance with
established, peer-reviewed work plans. The study design and the methods for monitoring physical variables, fish populations, and biological processes before, during, and after forest harvesting have been previously detailed by Hartman and Scrivener (1990) and summarized by Tschaplinski (2000).

(1) Hydrology and Meteorology Data Collection
Routine collections of stream hydrology and meteorological data were made at streamflow weirs (4) and climate stations (6) established throughout the Carnation Creek basin. Continuously-recorded, electronically-archived data were obtained from Campbell CR10X (2Mb) data loggers. Water temperature and stream depth were recorded at hydrology weirs located across the main Carnation Creek channel about 250 m upstream from the mouth (B-weir) and near the headwaters (E-weir). Similar data were collected from the two major tributaries to Carnation Creek: Tributary C (at C-weir) and Tributary H (at H-weir). Tributary C is a major sub-basin at Carnation Creek that has remained unlogged as an internal control for hydrology comparisons with the fully harvested Tributary H basin and with Carnation Creek. Stream discharge for the main channel of Carnation Creek was monitored by Water Survey of Canada (Environment Canada).

Water depth recordings for all weir sites are converted to stream discharge in the laboratory by using rating curves derived from salt-dilution techniques for tributary weirs (see methods in Schnorbus 2005b), and channel cross-section profiles of depth and velocity for main-channel weirs (Water Survey of Canada). Discharge ratings at B-weir are performed by Water Survey of Canada.

Some climate stations have historically been located with the hydrology weirs. Climate data include air temperature, precipitation (tipping buckets backed up with Sacramento gauges), relative humidity, wind speed and direction, and solar radiation. Presently, one “full” climate station – station A, located at low elevation near the mouth of Carnation Creek, is used to monitor all climate variables. Station N located above 600 m elevation near the north-eastern headwaters of the stream monitors all parameters except for solar radiation. Four other stations (at B, C, H, and E-weirs) monitor air temperatures and precipitation.
All collected hydrology and climate data were assembled and archived in the project hydrology-climate database and are accessible in Microsoft Excel spreadsheet format to project partners and other users.

The dynamics of rainfall interception by the re-establishing forest canopy, and changing runoff patterns have been determined for the second-growth forest by Dr. David Spittlehouse for several years. These studies continued in 2007-2008. Data were obtained from a network of 25 rain gauges, meteorological instruments, and a series of runoff troughs in young stands of Sitka Spruce. Rain gauges and troughs are used to determine percentages of precipitation intercepted by the canopy versus percentages falling to the ground. Interception, weather, and canopy-structure data were collected and employed to calibrate and test various rainfall interception models for regenerating forests. Details of design, objectives, methods are provided by Spittlehouse (1998a, 1998b).

(2) Hydrology and Meteorology Data Verification

Electronically archived data from all Carnation Creek hydrology and meteorology stations have been assembled into the 37-year project database extractable as MS Excel spreadsheets. The quality of water temperature data recorded by continuous automated equipment from 2000-2006 was verified during the current project year. In addition, a specific program was developed in MS Excel which will allow future water temperature data to be quickly assessed for quality assurance as it becomes available. With this procedure accomplished, spatial and temporal trends in water temperature at Stations B, C, E, and H were then compared. Multiple copies of the project database are available on compact discs for distribution to project team members, partners, and other users upon request.

(3) Stream Channel Geomorphology and Fish Habitat Studies

Channel morphology changes were determined in nine survey reaches of the stream (which incorporate the same sections used to determine fish population abundance, distribution, and habitat attributes) (Bird 2008). Although some fish habitat attributes are collected during fish population surveys (area of riffle and pool habitats by discharge stage), structural habitat variables including sediment textures, water depths, LWD and
logjams, overhanging banks, and other relevant features are collected during geomorphology surveys each year. Standard survey/mapping techniques were employed to obtain channel cross-sectional and longitudinal profiles (from determinations of elevations, distances, and morphologic features at transects fixed by permanent survey hubs). Reach mapping was based upon survey-hub triangulations.

Within each survey section, all pieces of large woody debris (LWD) were mapped and identified with numbered, metal tags in order to observe changes in LWD distribution and abundance. Within each study section, textural distributions of surface sediments were described visually by using grid samplers. Data on cross-sectional and longitudinal profiles, and LWD distributions were analyzed on electronic spreadsheets and plotted to describe the geomorphic characters of each study section. Data on the relative amount and distribution of fine sediments were also mapped. Details of all procedures are provided collectively by Bird (2007, 2008), Bird and Dicken (2005), and Blocka (2004).

The ground-based survey data were used to (1) generate variability indices for channel depth, width, and large woody debris (LWD), (2) map three-dimensional LWD orientations (horizontal and vertical arrangements), and (3) summarize annual channel cross-sectional changes required to determine net streambed erosion and deposition volumes.

Channel geomorphic cross-section and longitudinal-section data are available to our research team members for on-going studies of sediment dynamics. Net changes in the volumes of stored and eroded sediments are determined annually and are available for use in a high-resolution, large-scale, digital terrain model developed at UBC and used with GIS to (1) estimate substrate (bedload) movements for all study sites, and (2) determine net changes in the volumes of both stored and eroded sediments.

Within the current phase of this project (2004 – 2008), this innovative methodology has been applied to analyze the inter-annual series of cross-sectional and longitudinal stream profiles available for Carnation Creek to determine pre-logging, during-logging, and post-logging patterns in bedload sediment transport interpreted from channel scour and deposition. From the stream-channel survey data collected annually at Carnation Creek (a) substrate (bedload) movements for all study sections have been estimated, (b) net
changes in the volumes of stored and eroded sediments were determined, and (c) channel
morphology changes determined from cross-sectional and longitudinal profiles were
linked to changes in channel structural units (e.g., pools, riffles, glides, bank types). All
data have been digitally summarized and stream channel maps have been generated.
These maps demonstrate the inter-annual changes in distribution of bedload (e.g.,
downstream movement of gravel bars) and the effects of LWD (logjams) on sediment
distribution and channel structural features.

(4) Aerial Photographic Survey
Ground-based surveys were supplemented with an aerial photographic survey of the
entire creek channel. Stereo aerial photographs (200-mm aperture) were obtained at both
the 1:3000-scale and 1:10,000 scale and used to (1) determine changes in channel
structure in areas between reaches surveyed on the ground fish habitats throughout the
stream. Aerial photographs will be used in the future to compare riparian canopy closure
in recent years with historic (pre-1975) photographs monitor the rates of canopy closure
over the creek as the new riparian forest grows. Future canopy closure and forest growth
will be monitored to confirm predicted long-term declines in Carnation Creek water
temperatures.

(5) Riparian Canopy Study
This study component was initiated as a pilot program in 2004-2005 (Tschaplinski 2005)
and has now obtained observations spanning four years. The ultimate objective is to
determine current fish habitat conditions as influenced by degree of riparian canopy
closure in the both main-channel and the three principal fish-bearing tributaries in
Carnation Creek. Research emphasis is on the link between riparian canopy closure and
possible effects on local stream temperatures. Temperature effects on rearing populations
of juvenile coho salmon and cutthroat trout in both tributaries and the main channel will
be investigated over several years relative to habitat use (local abundance and
distribution) and seasonal growth and survival of juvenile salmonids in Carnation Creek.
Activities in the past project year included verification work on the Carnation Creek
water temperature database (2000-2006) to identify outliers and otherwise suspect data
points by comparisons among stations and years. This was completed and a specialized
program was developed in Microsoft Excel which will allow future water temperature data to be quickly assessed for quality assurance as it becomes available. The quality assurance of water temperature data collected from 1989 to 1999 was completed in 2005 (Schnorbus 2005a). Water temperature data collected from 1989-2006 was used primarily to compare the spatial and temporal temperature regime of one basin subjected to clear-cut harvesting (Tributary H) and one used as a control (Tributary C). Water temperatures collected at B-weir located about 250 m upstream of the stream mouth is representative of cumulative effects upon this variable. The water temperature regime was also determined for Tributary E in the headwaters where some clear-cut harvesting has also occurred.

Water temperatures in main-channel and tributary habitats will ultimately be correlated with measures of riparian canopy closure taken in the same locations. An outcome of the analysis of the water temperature data was the recommendation that supplemental canopy cover (shade) measurements be also collected at locations where water temperature is recorded (B-weir, E-weir, H-weir, and C-weir) during the next project year. In 2007, measurements of riparian canopy closure were obtained by spherical angular canopy density measurement techniques (Teti 2001) in the same study sections and cross-channel transects covered previously. Canopy densities were determined from areas in Carnation Creek that received different historic riparian management treatments ranging from variable-width riparian buffers to clear-cuts with no riparian tree retention including small conifers and deciduous trees.

This study was performed in early September under virtually full riparian foliar coverage in order to (1) compare results with the findings of the previous years, (2) obtain additional information on within-site and between-site variation in post-harvest riparian canopy closure, and (3) confirm from goal (2) whether additional in-stream water temperature monitoring should be established (e.g., in individual tributaries) to examine whether significant differences in canopy cover result in measurable differences in local water temperatures, especially in mid-summer.

Measurements of riparian canopy cover were made in main-channel study sections VIII (careful clear-cutting), V and VI (intensive clear-cutting), and II, III, and IV (variable-
width riparian buffer) as well as in three fish-bearing tributaries important for both summer rearing and overwinter shelter habitats. Tributary sites included 2600 Tributary (careful clear-cutting) near section VIII, 1600 Tributary (intensive clear-cutting) which enters Carnation Creek at the lower end of section V, and 750 Tributary located between sections III and IV (variable-width riparian buffer). Three types of canopy density measurements were taken according to methods detailed by Teti (2001) at each observation point in all study sites: (1) 45° angular canopy density (the most relevant measure for stream shading and heating) taken facing true south and including quadrants spanning 180° azimuth from east to west; (2) canopy density at 60 – 80° elevation taken facing both due south and due north (360° coverage), and (3) direct overhead canopy density (80 - 90° elevation) which could be taken facing any direction. Details of all procedures and analyses are provided by Tschaplinski (2005, 2006) and Russo (2008b). Mean canopy density measurements for the three types of canopy measurements, and all measurements combined were compared statistically (single factor ANOVA, Tukey’s test for pair-wise comparisons, and Student’s t-tests) between individual sites, between main-channel and tributary sites within riparian management categories, and between sites representing the different riparian treatment categories within main-channel and tributary environments.

(6) Fish Populations

(i) Salmonid Migrations at Carnation Creek:

Juveniles
Between 15 February and 17 June 2007, the numbers of seaward migrating coho salmon fry and smolts, chum salmon (O. keta) fry, the smolts of steelhead (O. mykiss) and cutthroat trout, and two species of sculpins were monitored daily at tributary weirs and at the main fish fence on Carnation Creek. Large samples of salmonid fry and smolts (up to 50 individuals per species per day) were measured for length and weighed. Scale samples for age determination were also taken from up to 50 smolts of each species per day. All data, including the results of the age analyses, were entered into the project electronic database for summarization of long-term inter-annual trends.
The numbers of juvenile salmonids (primarily coho salmon and cutthroat) moving between main-channel habitats in Carnation Creek and valley-bottom tributaries and ponds (so-called “off-channel” habitats) were determined by monitoring tributary weirs. In general, young salmonids move out of the main-channel in autumn to take shelter from winter storm flows, then return to the main channel in spring for either summer rearing or as part of the seaward smolt migration.

The 2600 Tributary was the main off-channel site monitored to assess the post-harvest use of overwinter habitats and determine their relative importance for salmon survival and production. The net difference between movements into and out from these tributaries are used as an approximate indication of overwinter survival in “off-channel” habitats.

**Adults**

Adult salmonids (coho and chum salmon, steelhead and cutthroat trout) returning to spawn in Carnation Creek were enumerated at the main fish fence located near the mouth of the stream between 15 September and 15 December (standard survey period). The abundance of the spawning run was the cumulative seasonal count of all adults migrating through the weir plus regular counts of spawners distributed downstream of the weir. Some coho and most chum salmon spawned downstream of the weir. Fish distributed downstream of the weir were enumerated visually at daily intervals by observers on foot (whenever streamflows permitted counts to be made). Both live spawners and fresh carcasses were enumerated. The abundance of fish remaining downstream of the fence were determined by area-under-the curve techniques combined with calculations of spawner residence time on the spawning grounds (Tschaplinski and Hyatt 1990, 1991). Spawners were identified to species and sex, and lengths were taken. Scale samples were taken for age determination in the laboratory.

Age and size data for the migrants, together with data on spawner fecundity and abundance of females, provide part of the information necessary to determine cohort-specific survival and growth rates for the different life stages of each species produced in fresh water. Age analyses are performed on fish scales and otoliths by a contracted laboratory. Derivative data include numbers of smolts produced per spawner and the
numbers of spawners produced per smolt for comparisons among pre-logging, during-logging and post-logging periods, and for examining linkages between survival and production between freshwater and marine environments.

(ii) Salmonid Populations Rearing in Carnation Creek During Summer

The abundance, habitat distribution, growth, and survival of populations of juvenile salmonids and sculpins rearing in Carnation Creek from spring to autumn were determined from three seasonal surveys conducted between 15 June and 19 September. During each survey, the Seber-LeCren (1967) two-catch removal method was used to assess abundance within eight representative study sections within Carnation Creek. Fish were captured by electrofishing and seining in each of two fishing trials of equal effort. Barrier nets were employed to ensure no fish moved between the surveyed section and adjacent portions of the stream.

Fish captured were identified to species and measured for length. Large samples were weighed, and scales were taken from most of the larger individuals to determine the ages of fish older than one year. These measurements were used to determine size distributions and growth rates for all age classes throughout the "summer" rearing period. Growth and survival of different age classes of juveniles for each species were determined by standard methods referenced in Ricker (1975) separately for each survey section, for the areas of Carnation Creek receiving different riparian harvesting treatments (clear-cutting vs. riparian buffers), and for all study sections combined.

The total abundance of fish rearing in Carnation Creek in 2007 was determined by extending the numbers of fish captured in the survey sections to the total length of stream inhabited by each species. Within each surveyed section, the total wetted surface area of the stream and its component pool, glide, and riffle areas were measured by using meter tapes in order to describe the distribution of species and life stages in terms of fish densities (number of fish per unit area) by habitat unit. Fish habitat is classified according to methods adapted from Bisson et al. (1982) and Hankin and Reeves (1988). Fish population status and trends were summarized by Russo (2008a).
Results and Discussion

All core research and extension objectives of the 2007-2008 project work plan were achieved. The primary products of the Carnation Creek project are the generation of empirical datasets on local climate, watershed hydrology, channel morphology, and fish populations and habitats. Annually collected data are archived into the long-term project database for provision to our research associates as requested for derivative studies which include empirical models for hydrology and geomorphology in support of several broad objectives: (1) improving our understanding of watershed functions, particularly the sequential linkages among hillslopes, stream channels, and fish habitats, (2) determining the long-term ecological implications of past and current logging within a coastal BC watershed, and (3) quantifying the mechanisms, rates, and level of post-harvest recovery as the second forest grows.

Specific datasets were compiled for (1) hydrology and meteorology, (2) microclimatology (rainfall interception and hydrologic recovery); (3) stream channel morphology and fish habitat structural changes including partial sediment budgets derived from channel bedload movements and scour-fill processes (see Bird and Dicken 2005); and (4) juvenile and adult fish populations including (a) annual abundance and biological characteristics of adult salmonid species returning to spawn, and juveniles emigrating seaward, and (b) seasonal abundance, distribution, age structure, growth, survival, and habitat ecology of juvenile salmonids rearing in Carnation Creek (see Russo 2008a).

The Carnation Creek project continues to advance our knowledge of fish-forestry interactions by virtue of its longevity and data continuity. These features are essential to interpret long-term variations in fish population abundance and productivity, and interpret these variations with respect to forestry practices and other determining factors such as climate change and shifts in ocean conditions (Tschaplinski 2000).

Fish populations in Carnation Creek in 2007-2008 reflected recent trends in both adult and juvenile populations with some exceptions. The return of 120 adult chum salmon in 2007 was the sixth lowest return since the project was initiated. This return was similar to the previous year’s return of 105, yet much reduced from the 2,053 spawners enumerated
in 2004 (Fig. 1). Chum salmon have faced the greatest post-logging declines in abundance at Carnation Creek relative to other salmon species. Only a part of this decline from pre-logging and during-logging means of 2,188 and 2,024 adults respectively have been explained by harvest-related effects (about 26%), mainly through reductions in egg survival in chum spawning beds near the mouth of the stream due to accumulations of fine sediments (sand) (Hartman and Scrivener 1990, Holtby and Scrivener 1989, Tschaplinski 2000, Tschaplinski et al. 2004). These fine sediments originated from both (1) the clear-cut riparian areas of Carnation Creek due to reduced bank integrity resulting from riparian harvesting, and (2) landslides and debris flows origination in steep, unstable gullies 1 km upstream of anadromous fish habitats (Hartman and Scrivener 1990, Hogan and Bird 1998). Ocean productivity variations and long-term climate shifts have accounted for most of the long-term effects on chum numbers (see Tschaplinski 1998, 2000). The most recent declines (2004-2007) coincided initially with a moderate El Niño event, an event that is known to reduce marine survivals in Pacific salmon through declines in ocean productivity and increases in predation. Coho salmon from the southwest coast of BC appear to have been strongly affected by this particular EL Niño cycle, with marine survivals of smolts declining to about 0.5% (DFO 2006). However, Chum salmon are among the most far-ranging of all Pacific salmon species during their period of ocean residence, and may enter Asian waters from North America. The exact locations in the north Pacific Ocean inhabited by Carnation Creek chum are not known; however, conditions for ocean survival are assumed to have been less favorable for the survival of their cohorts (consisting primarily of four-year-old spawners) than they were in 2004.

Adult coho returns (“escapements”) in 2007 were more encouraging than in 2006 when only 10 adults including 4 females and 6 males, together with 57 jacks (precocious young males) returned to spawn in Carnation Creek. From 30 September to 1 December, field staff enumerated 62 females, 77 males, and 73 jacks (Fig. 2). Four of the five largest adult returns to Carnation Creek have been observed since 1998 when Fisheries and Oceans Canada first implemented fishery restrictions to conserve west coast coho stocks. Fishery restrictions are still in place; however, it is clear that factors in the marine environment other than fishing pressure, such as El Niño events and longer-term climate
shifts, can alone impose a powerful influence on coho marine survival. Despite the low adult coho returns in 2006 and 2007, strong returns since 1998 maintain the post-logging mean escapement at 147 which is not significantly different from pre-logging levels (Student’s t, p > 0.05). The value of long-term studies such as Carnation Creek continues to be emphasized as the study continues. Prior to 2006, the strong increase in adult coho returns coincidental with fishery reductions in 1998 suggested that fisheries management can have a dominant influence on the strength of the coho salmon spawner abundance at Carnation Creek. However, observations in recent years clearly demonstrate that ocean survival factors other than fisheries management can depress west coast coho stocks to minimum levels.

Historic analyses have shown that forestry effects on coho can explain only 6% of the long-term variation in coho abundance at Carnation Creek (Holtby and Scrivener 1989). Most of the variation has been explained by long-term climatic shifts, reductions in marine productivity, and other conditions (e.g., predation) that contribute to determining marine survival. Some impacts in fresh water are nevertheless apparent as shown by the annual channel morphology and fish habitat surveys, and by the abundance of juvenile coho which the stream can sustain during summer (Fig. 3). For most post-logging years prior to fishery restrictions and closures between 1998 and the present, Carnation Creek could sustain only about one-half the numbers of juvenile coho compared to pre-logging years. High returns of spawners have recently resulted in large numbers of coho fry emerging from the streambed in spring to inhabit the stream during summer in several years. Unlike past years when summer freshets displaced many of these fry downstream and out of freshwater habitats, benign summers since 1998 have allowed these fish to remain in fresh water. However, due to density dependent reductions in growth resulting from these larger numbers, many of these additional fry are growing slowly and not surviving the winter due to their small size and continuing declines in main-stream winter habitats. These observations demonstrate that the rearing capacity of Carnation Creek has been exceeded in recent years, and that the current capacity remains at roughly one-half of the pre-harvest condition (Tchaplinski 2000). Late-summer coho population abundance in 2007 was among the lowest levels observed since the project was initiated in 1970 (Fig. 3). These results were not surprising given the correspondingly record low
numbers of adults returning to spawn in 2006. The estimated number of coho rearing in the stream in September was only 3,485. This results in a post-harvest mean of 8,561, between 30 and 38% lower compared to the pre-logging and during-logging averages of 11,994 and 13,656 respectively (Fig.3).

Reductions in coho habitat have been due partly to riparian harvesting in both the intensively and carefully clear-cut areas that reduced bank integrity, increased rates of bank erosion and collapse, and resulted in destabilized LWD and less-abundant functional LWD pieces in main-channel habitats (sections V to VIII; Hartman and Scrivener 1990). However, the effects of riparian harvesting have been overwhelmed by the long-term effects of landslides and debris flow which occurred in 1984. Large volumes of sediment and debris quickly entered section VIII near the head of anadromous fish habitat, caused massive logjams and sediment wedges, and have progressed downstream in association with major freshets for decades. These features have caused the Carnation Creek channel to widen by 2.5 to 3 fold in the clear-cut areas of the stream. Other changes include channel aggradation with excessive bedload, destabilized LWD, fewer and shallower pools. Habitat quantity and complexity for coho salmon and andromous rainbow and cutthroat trout was reduced with less cover for both summer and winter habitat needs, e.g., fewer overhanging banks, less functional wood, and shallower and fewer pools. The sequential and continual breaking, downstream displacement, and re-forming of logjams and sediment wedges since 1984 have resulted in these geomorphology and habitat impacts to progress downstream to degrade much of the available salmon habitat in the main channel.

The additional coho fry inhabiting the system due to elevated spawner returns in most years since 1998 have not resulted in a proportional increase in smolt production because many of these fish are growing slowly and not surviving winter conditions and the associated limitations in main-channel habitats (fewer mature, stable logjams, tree root masses, undercut banks, and deep pools). These main channel habitats are continuing to deteriorate to the point where the entire length of the riparian buffered portion of the channel has now been substantially altered with excessive sediment bedload (see Bird 2007, 2008). This deterioration in available habitat may be contributing to recent declines in coho smolt abundance. The number of coho smolts produced in 2007 is the
second lowest observed in the post-logging period again primarily a result of the record low number of adult spawners during the fall of 2006. The lowest number of smolts counted at the fence was in 1996 when only 891 were observed. In 2007, 1 112 coho smolts were enumerated which is approximately one-half of the pre-harvest mean of 2 213 (Fig. 4). The smolt output for the last three years represents an important down-turn. Habitat limitations appear to be starting to counter the general post-logging trend of higher smolt production caused by the effects of elevated stream temperatures on salmonid growth, age structure, and survival determined by Holtby (1988) and Holtby and Scrivener (1989). Warmer stream temperatures after riparian clear-cutting occurred in all seasons, but the relatively subtle (~1°C) increase in winter accelerated salmon egg development rates, caused fry to emerge up to six week earlier in spring (Hartman and Scrivener 1990). This process substantially lengthened the summer growing period available to juvenile coho, allowing fry to increase in mean length by 11 mm over their pre-harvest counterparts (Hartman and Scrivener 1990). Larger body size was strongly correlated with increased rates of overwinter survival and consequently elevated smolt production. Forestry-associated reductions in main channel habitat had apparently not resulted in a reduction of coho smolt production from the watershed for most of the post-logging period. Recent declines in smolt production are beginning to suggest a reversal in these patterns for which habitat quantity and quality may be playing an increasingly important role in determining the numbers of smolts produced annually.

Rainbow and cutthroat trout smolts are still being produced in small numbers 26 years after harvest (Fig. 5). Historically, anadromous trout populations in Carnation Creek have always formed a relatively minor part of its fish fauna. Fewer than 10 adults of each species are known to have returned to spawn in any year since the project was initiated (Hartman and Scrivener 1990). Because of these low numbers, interpretation of population trends relative to the effects of forest harvesting are difficult. Only 8 cutthroat trout smolts and 10 rainbow trout smolts were counted in 2007 (Fig. 5).

In spite of these modest numbers, the long-term trends in the abundance of trout smolts demonstrate that both species continue to inhabit the lower 3.1 km of the stream regardless of the sensitivity that these small populations might have to habitat alterations
Fig. 5). No statistically significant changes in the numbers cutthroat trout smolts produced from Carnation Creek are apparent after logging (single factor ANOVA, \( p > 0.05 \)). However, the mean number of rainbow trout smolts produced after logging (100) has declined significantly (by approximately 60 \%) from the mean number observed in the pre-logging period (246) in spite of high variability among years (single factor ANOVA, \( F= 3.28, p = 0.02 \)).

Rainbow trout may be more susceptible to main-channel habitat loss than either juvenile coho or cutthroat trout, especially in winter when freshets are common. Rainbow in Carnation Creek are restricted to main-channel habitats in contrast with coho and cutthroat trout which also occupy tributaries, especially in winter (Brown and Hartman 1988; Tschaplinski and Hartman 1983). During winter, many young coho and cutthroat seek shelter from scouring freshets by inhabiting "off-channel" sites including tributaries (Brown and Hartman 1988, Tschaplinski and Hartman 1983). On the other hand, rainbow must find shelter in main-channel substrates, pools, and undercut banks associated with logs and tree roots (Bustard and Narver 1975).

In some years after logging (e.g., 1984), low abundance of rainbow smolts in spring occurred after winters with frequent severe freshets. With the loss of main-channel shelter habitats in clear-cut sections of Carnation Creek (Hartman and Scrivener 1990; Tschaplinski 2000), salmonid mortality associated with freshets was likely more pronounced in post-logging years. By comparison, winters without strong freshets were sometimes associated with high numbers rainbow smolts in the following spring, even after logging (e.g., 1993, 1998, and 1999).

Not only have elevated post-logging water temperatures affected coho salmon growth and smolt production, the positive effects on fish growth continue to affect the age composition of the coho smolt run. On average in the post-logging period, more than 90\% of coho fry have been able to grow to smolt size in just one year compared with the 50:50 ratio of 1-year-old vs. 2-year-old smolts typical during the pre-harvest phase of this study (Fig. 6; see Tschaplinski 2000). In 2007, 95 \% of all coho smolts were one-year-olds.
The coho salmon populations of Carnation Creek thus continue to demonstrate growth and survival patterns generally consistent with the thermal increases in their environment first observed in 1976 when riparian harvesting began. However, lack of summer freshets and consequent high summer abundances of fry in some recent years are showing density-dependent depression in growth rates in rearing populations (Russo 2007a). Many fry are entering the winter at small sizes. The decline in smolt production toward pre-logging levels since 2004 indicates that these small individuals are not surviving the winter.

Trout growth in post-harvest years has also responded strongly to higher water temperatures. Trout have grown in length up to 18 mm more during their first summer than in the pre-logging period (Hartman and Scrivener 1990, Tschaplinski 2000). Fish population characteristics at Carnation Creek are thus consistent with those expected from a thermal regime that continues to be elevated as a long-term result of riparian harvesting.

A riparian canopy study, initiated in 2004 continued in 2007. This research component examined post-harvest riparian shade with an angular canopy density (ACD) meter (Teti 2001) (see details in Russo 2008b, Tschaplinski 2006, Tschaplinski and Russo 2008b). Measurements of angular canopy density (ACD), canopy density above 60°, and canopy density above 80° were measured using the ACD meter from locations in the main channel and tributaries of Carnation Creek. ACD, which measures the portion of the sky occupied by canopy along the sun’s path between 10 am and 2 pm is the most important factor regulating summertime stream temperature.

Twenty-six years after harvesting was completed along the lower reaches of the Carnation Creek watershed, a trend toward higher levels of shade as measured by ACD at 45° was observed along the main-channel where a riparian buffer strip was maintained compared to other areas (Fig. 7, Table 1). With the large samples now available from four years of observations, differences between ACD measurements grouped by riparian management treatment for all years (2004 - 2007) were statistically significant (single factor ANOVA, $F_{0.05, 2, 21} = 5.79, p < 0.001$). The mean ACD for the grouped riparian buffer treatment sections (2, 3, and 4) was significantly different than the means for the
two clearcut treatment groups (Tukey’s multiple comparison method, \( Q_{0.05, 3, 69} = 5.15 \)). However, by the same test, there were no statistically significant differences between the carefully clearcut treatment area (section 8) and the intensively clearcut areas (sections 5 and 6).

Mean ACD measured in the main channel ranged from 50 % in section 5 to 79 % in section 2 in 2007 (Fig. 8, Table 1). In comparison, mean ACD values ranged from 76.2 % in 2600 Tributary to 87.1 % in 1600 Tributary (Fig. 9). These differences are consistent with observations made in previous years where ACD in the tributaries were higher on average than those observed in the main channel. Comparisons of mean ACD for data pooled for all years showed that these differences between the main channel and tributaries were statistically significant (Fig. 10; Student’s t, \( p < 0.0001 \)). Although each tributary is located within one of the three different harvest treatments, the higher ACD observed in the tributaries reflect the narrower channel widths of these reaches (1-4 m) compared with the main channel where widths ranged up to 20 m or more. The tributaries have not been subjected to the post-harvest channel widening that has occurred in Carnation Creek mainly as a consequence of landslides in 1984 that have introduced large volumes of sediment and woody debris into the lower 3 km of the main channel (Hogan et al. 1998a, 1998b; Tschaplinski et al. 2004).

Analysis of the mean ACD among individual study sections and tributaries for all years combined revealed that significant differences occurred among sites within riparian treatments (Fig.11; single factor ANOVA, \( F_{0.05, 9, 27} = 23, p < 0.001 \)). Notably, the amount of shade reaching sections 5 (intensively clearcut) and 8 (careful clearcut) do not differ statistically from one another but are different than means observed in all other main-channel sections and tributaries (Tukey’s multiple comparison test for pair-wise differences, \( Q_{0.05, 9, 27} = 4.04 \)). Sections 5 and 8 were characterized by the lowest ACD percentages, and therefore, currently have the greatest potential for mid-summer solar heating. Mean differences between sections 3, 4 (riparian buffer) and 6 (intensively clearcut) were not statistically significant but differed significantly from all other sections and tributaries. More shade occurred in sections 3, 4, and 6 than in either sections 5 and 8, but less than section 2 in the riparian buffer treatment. The mean ACD in 750
Tributary and 1600 Tributary did not differ statistically from one another but were higher in these narrow, densely-treed streams than that determined for any other site. A pairwise contrast between section 2 (riparian buffer) and 2600 Tributary 2600 (careful clearcut) showed no significant differences in shade.

As observed in 2004, the variation among study sections was not primarily related to differences in riparian harvesting. Rather, they reflected differences in channel width among the sections. Channel width has increased in all main-channel sections of Carnation Creek, but the increases in sections 5 and 8 have been greater than in other study site such as section 6 due to the presence of logjams originating from landslides and debris flows (Hogan et al. 1998a, 1998b; Tschaplinski et al. 2004). Both sections 5 and 8 have increased in width by 2.5 to 3 fold as a result of forestry-related logjams which caused channel widening through increased lateral erosion due to the channel blockage and the subsequent formation of sediment wedges upstream of the blockages. Similar logjams did not form in section 6 although large volumes of landslide-associated woody debris and sediments moved through this section. Riparian vegetation is less effective in shading the channel in the wider study reaches (5 and 8) compared with other sites, although the degree of difference may vary between years. The highest interannual variation was observed in section 8 where the mean ACD ranged from 44 % (2004) to 67 % (2006). A partial explanation for this is that riparian shade in this part of the stream is particularly dominated by deciduous species, especially Red Alder, which may experience variations in leaf drop from year to year depending on differences in seasonal drought.

The differences in shade among the different sections within the riparian buffer treatment management area also reflect the nature and history of the riparian buffer treatment. The width of the buffer varied from about 70 m in the downstream part of section 3 but was as narrow as a single conifer in other locations such as the majority of the length of section 4 (Tschaplinski 2000). Riparian shading has thus been greatly reduced from the pre-logging condition in much of the buffered length of stream. Post-harvest windthrow has since reduced available shade yet further to the point that a relatively open canopy presently exists throughout the riparian buffer.
In 2007, mean canopy densities measured at azimuths over $60^\circ$ ranged from 42% in sections 4 and 5 to 74% in 750 Tributary 750 (Fig. 12, Tables 2 and 4). As expected, the variation from year to year for this type of canopy density measurement was greater than that observed for ACD measurements. This difference in variation is due in part because this measurement is more affected by the time of year when assessments are performed and by associated annual climate conditions (effects on deciduous foliage) than are ACD measurements. For example, the results for mean canopy density in section 2 were as high as 81% in 2006 and as low as 56% in 2004 (Table 4).

Similarly, overhead canopy density measurements were more variable annually than were ACD measurements (Fig. 13, Tables 3 and 5). In 2007, mean canopy density measured at azimuths over $80^\circ$ ranged from 38% in section 3 to 87% in 750m tributary (Table 3). Inter-annual variation was again high; the overhead canopy density in 750 Tributary ranged from 47% in 2004 to 87% in 2007 (Table 5).

Canopy densities measured at azimuths over $80^\circ$ correspond closely to the shade parameter canopy cover which is a useful criterion for classifying stand structure. Therefore, mean differences in canopy density over $80^\circ$ were also investigated among individual study sections of Carnation Creek and its principal tributaries for all years of record combined (Table 5). Results indicate several statistically significant differences (single factor ANOVA, $F_{0.05, 9, 27} = 3.84$, $p = 0.00039$). Similar to results for mean ACD, the highest percent canopy densities were observed in 750 Tributary (riparian buffer treatment), section 2 (riparian buffer treatment), and 1600 Tributary (intensive clearcut) (Table 5). Percent canopy densities among these sites did not show pair-wise differences but were significantly different from other main-channel sections and tributaries (Tukey’s test, $Q_{0.05, 9, 27} = 9.32$). The lowest percent canopy cover was observed in sections 5 (intensive clearcut), 3 (riparian buffer), 8 (careful clearcut), and 4 (riparian buffer) respectively. Pair-wise comparisons among sections 5, 3, 8, and 4 were not significant yet these sections are significantly different from all other sections and tributaries. Pair-wise contrasts were not significant among section 4, 6, and 2600 Tributary. Overall, the overhead canopy appears to be relatively open throughout the main channel except for section 2 (riparian buffer treatment) which is the most downstream study site.
These results confirm pilot observations made in 2004 that a substantial amount of direct solar radiation still falls on the Carnation Creek main channel two and one-half decades after logging despite a general but variable trend for higher mean ACD and total shade in the riparian-buffered portion of the creek relative to the second-growth riparian stands which currently border the channel in the clearcut areas. High variances are associated with all mean values for riparian shade indicating that the riparian vegetation at Carnation Creek more than 25 years after harvesting provides an open and variable canopy adjacent to the channel. Windthrow and narrow buffers in parts of sections 2, 3, and 4 have reduced the amount of shade in the buffer strip relative to pre-harvest old-growth conditions. Given the variety of canopy conditions occurring throughout the main channel regardless of riparian management history, it is unlikely that local differences in water temperatures occur among sites in the lower 3 km of Carnation Creek used by anadromous salmonids.

Tributary habitats at Carnation Creek are important for the survival of Carnation Creek coho, especially during winter (Brown and Hartman 1988, Tschaplinski and Hartman 1983). These habitats are now under essentially full canopy cover for much of their lengths, and may provide juvenile coho and cutthroat trout with rearing habitat and shelter in all seasons (except when channels become dry during periods of summer drought). Temperature loggers will be installed in 750, 1600, and 2600 tributaries in the near future to determine whether differences occur in the thermal regimes of these tributaries compared to the main channel. Thermal stress is unlikely in naturally cool coastal watersheds such as Carnation Creek. However, the combination of cool temperatures and available habitat cover will be investigated relative to the numbers using these tributary sites during summer compared with adjacent main channel habitats. Conversely, temperature differences during winter, as well as shelter from scouring freshets, may attract coho and cutthroat during winter. Historically, at least 25 % of all coho smolts produced from Carnation Creek used tributary habitats for overwintering (see Hartman and Scrivener 1990).

Summary statistics of water temperatures collected from Stations B, C, E, and H indicate that changes to the temperature regime in Carnation Creek as a result forest harvesting
continue to be observed. There were no obvious trends toward declining mean summertime temperatures at any of the hydrological-meteorological stations (Figs. 14 – 17, \( r^2 \) range: 0.03 – 0.30). Therefore, there is as yet no evidence of recovery from harvest-related elevations in water temperatures at Carnation Creek. The warmest temperatures were recorded at climate stations E and H which are located in the upper and easternmost part of the watershed. At station E (upper main channel), mean summertime temperatures ranged from 10.4 °C (1997) to 14.3 °C (1990) (Fig. 16). Temperatures were slightly cooler at tributary Station H (located downstream from Station E) where the means ranged from 9.8 °C (1989) to 13.1 °C (1992). A large area (12 ha) was clear-cut in Tributary H during the late 1970s and early 1980s (Hartman et al. 1996). Following logging, alterations in natural hydrological pathways were observed as well as increases in water yield, groundwater levels, peak runoffs, and summer flows. These changes will no doubt influence the temperature profile recorded at this site.

The coolest temperatures were recorded at Station C ranging from 7.4 °C (1990) to 12.6 °C (1992) (Fig. 15). This site is located near the mouth of Tributary C which serves as the unharvested control sub-basin of Carnation Creek. Station B, upstream of the mouth, recorded mean summertime temperatures ranging from 8.9 °C (1998) to 13.6 °C (1991) (Fig. 14). The results indicate that there are no significant differences in mean summertime temperatures between these hydrological-meteorological stations (single factor ANOVA, \( F_{0.05,3,53} = 2.8 \)).

At all climate stations, except B, mean daily summertime “extremes” appear to be steadily declining (Fig. 18-21, \( r^2 \) range: 0.3 - 0.8). Station H showed the most extreme daily fluctuations when in 1989 the mean summertime temperature fluctuation was over 3 °C (Figure 21). Since this time, a steady trend towards reduced daily extremes has been observed. At Station B, declines in mean daily summertime temperature ranges were observed from 1993 to 1997; however, since that time daily extremes appear to be increasing. In 2006, the average summertime daily range was the widest of all stations at 2.8 °C.

Daily fluctuations in summertime stream temperatures appear to be decreasing despite no apparent reduction in mean summertime temperatures, except possibly at Station H. It is
well known that removal of the riparian vegetation will cause increases in stream temperature and may also shift the timing of observed maximum temperatures (Jones and Johnson, 2000). A study of changes to stream temperatures affected by removal of riparian vegetation found that after 15 years, the thermal regime recovered to pre-harvesting levels. Therefore, it is not surprising that there has been a reduction in daily fluctuations in Carnation Creek during the past 29 years. It would also be reasonable to expect that summertime stream temperatures would also show a reduction during the time period of this analysis (1989-2006). This was not the case and may be partially explained by the general trend for increased air temperatures experienced due to climate warming. Future studies will explore techniques to factor out this general warming trend in order to assess changes in mean stream temperature which are attributable to canopy recovery. Alternatively, channel widening at Carnation Creek due to historic harvest-related disturbances may be maintaining high levels of stream channel exposure to direct solar radiation in spite of the growth of riparian vegetation after harvesting. The channel remains over twice as wide compared with pre-logging conditions; therefore, the second-growth riparian canopy may not yet provide sufficient shade over the stream to begin moderating temperatures.

An objective of the riparian canopy studies is to determine how fish habitat conditions are influenced by the amount of riparian canopy closure in both the main channel and the three principal fish-bearing tributaries. This study component emphasizes the links between riparian canopy closure (shade) and local stream temperatures. Measurements of both shade (2004-2007) and stream temperatures (1989-2006) are now available for the vicinity of Station B. Given that stream temperature data is also available for Stations E, H, and C, consideration will be given to obtain shade measurements collected at these stations as well in order to compare with results from Station B. Similarly, stream temperatures in 750, 1600 and 2600 tributaries may be collected in the near future to examine local temperature responses to shade.

The quality of main-channel habitats at Carnation Creek is continuing to degrade as shown by both ground-based surveys and aerial photography (see Bird and Dicken 2005 for details of procedures and results). Tributary habitats are consequently becoming
more important for coho rearing, overwintering, and smolt production. Evidence suggests that these tributary areas which were not physically altered by forestry practices may now account for up to 75% of the smolt production from Carnation Creek in some years (Tschaplinski 2000, Tschaplinski et al. 2004).

Ground-based geomorphology surveys supplemented by aerial stereo photographs confirmed the increasing effects of sediment and debris movement from upstream sites (where clear-cut riparian treatments were applied in 1976-1981) into the riparian-buffered portion of the stream (see Bird and Dicken 2005; Bird 2007, 2008). Presently, large volumes of bedload sediments originating from a major logjam in section V (intensive clear-cut) which broke in winter 1995 have reached section II immediately upstream the fish fence near the mouth of the stream. Severe channel aggradation is evident in sections II, III, and IV which comprise the riparian buffer experimental treatment, and this aggradation has increased from 2005 (Bird 2007, 2008). Large mid-channel gravel bars, in-filled pools, and lateral erosion accelerated in the past several years are causing major channel and fish habitat alterations in this area which until recently contained the last good-quality fish habitats in the lower 3 km of Carnation Creek. These habitats contained within the riparian buffer treatment have historically been much less affected by forestry-related impacts than clear-cut areas elsewhere in the watershed. These progressive changes are now beginning to affect the numbers of coho fry the stream can support and the numbers of coho smolts produced from this watershed.

These results continue to demonstrate the importance of prudent management around steep, unstable hillslopes because sediment and debris introduced to the channel network by landslides and debris flows may defeat the purpose of riparian buffers and cause increasing impact to channels and salmon habitat several decades after the conclusion of harvesting. Work at Carnation Creek will continue to emphasize studies of channel morphology, riparian canopy closure, and fish population response given their potential future effects on physical and thermal fish habitat components and salmon abundance.

The results generated by Carnation Creek research have been extended to our diverse client groups by several mechanisms and products in 2007-2008. Although only one of two field-based workshops were conducted, the presentation of Carnation Creek project
information continued by other means such as lectures provided to both graduate and senior undergraduate students at the University of British Columbia (Faculty of Forestry). In all oral presentations, ample opportunity was provided to the participants to discuss current issues and techniques relevant to (1) riparian zone, hillslope, and forestry management, (2) the restoration of watersheds, stream channels, and fish habitats, and (3) provisions to reduce the harmful effects of forest harvesting on streams and fish. The following were highlighted in all presentations:

1. Carnation Creek project objectives, experimental design, history, and study methods;

2. Watershed physical and biological processes and effects of forestry on these processes (e.g., watershed hydrology and stream channel morphology including the effects of large woody debris (LWD) recruitment/loss, and stream channel scour/deposition patterns);

3. Long-term patterns in research findings such as impacts to fish populations attributed to forestry, commercial and sport fishing, and climatic shifts;

4. How Carnation Creek results have been applied for the purposes of integrated natural resource management (Forest Practices Code, Forest and Range Practices Act); and,

5. The importance of long-term process studies such as Carnation Creek for understanding the complex relationships among land use practices, fish populations, habitat, and watershed processes.

In addition, the Carnation Creek project brochure updated in 2004-2005 as Research Branch Brochure 80 was distributed to participants during extension events. This brochure remains fully relevant at present; therefore, updates were deemed a relatively low priority for 2007-2008. This product is also posted electronically at http://www.for.gov.bc.ca/hfd/pubs/Docs/Bro/Bro80.htm. Similarly, our four-panel project poster developed in 2004-2005 and made electronically available at http://www.for.gov.bc.ca/hfd/pubs/Docs/P/P076.htm remains relevant to current activities at Carnation Creek. Carnation Creek project summaries and both the poster and brochure are included on the Research Branch, BC Ministry of Forests website for the Fish-Forestry Interaction Program and this project
(http://www.for.gov.bc.ca/hre/ffip/CarnationCrk.htm). The website which was first activated in April 2006 has been improved during 2007-2008 with interactive watershed maps and expanded references available in PDF format in both the Carnation Creek web page and the linked Fish-Forestry Interactions Page.

**Conclusions and Management Implications**

This project seeks to describe the long-term effects of historic and current forestry practices on hydrologic regimes, hillslope processes, stream channels, and fish habitats, and the mechanisms and timelines of impact and recovery. Difficult management issues and questions are embedded within this overarching objective including: the cumulative effect of harvesting beyond specific levels (i.e., 65% basin harvest); the effect on both large and small stream channels when the riparian vegetation is removed or modified; the biological impacts of altered stream habitats; and, the length of time these impacts persist.

Complete answers to these questions can only be obtained through long-term, multi-year observations. However, the past several years of research activity at Carnation Creek has made important contributions to this ultimate goal by increasing our understanding of forestry-related impact and recovery processes and their implications for salmonid populations.

Empirical data covering a comprehensive suite of parameters have provided the necessary descriptions of the current condition and attributes of the watershed 26 years after the conclusion of the main period of forest harvesting. These determinations include the watershed’s hydrologic regime (peak and base flows, water temperatures, climate data), hillslopes (disturbance frequencies, stability), stream channel morphology (including bedload and LWD abundance, distribution, and function), aquatic habitats (riparian, mainstream, tributary, and off-channel habitat quantity and quality), and fish populations. These status assessments are essential to interpret the forestry component of observed inter-annual trends in salmonid abundance and production from Carnation Creek.
The same empirical data are available by request to our research associates to continue the on-going development and refinement of basin-scale models for hydrology, landslide prediction, sediment and debris budgets, channel changes, and fish habitat capability. Application of data collected in recent years confirm interpretations made in prior to the initiation of this past three-year phase of Carnation Creek study:

(1) Second-growth forest stands at Carnation Creek are demonstrating precipitation interception and runoff functions similar to unharvested stands (existing models by Dr. David Spittlehouse, Research Branch, BC Ministry of Forests) thus illustrating one component of hydrologic recovery;

(2) Water-temperature-related shifts in juvenile coho salmon (increased growth, survival, and smolt production; predominance of age-class 1 smolts) caused by riparian harvesting in 1976-1981 persist today. The channel remains over twice as wide compared with pre-logging conditions; therefore, the second-growth riparian canopy cannot yet provide sufficient shade over the stream to begin moderating temperatures. However, riparian canopy growth and water temperature response are expected in the near future. These changes need to be documented given the implications of lowered salmonid growth, survival, and smolt output due to sub-optimally lowered water temperatures and aquatic primary production at the same time that habitat quality and quantity remain degraded 25 years after harvesting.

(3) Sediment and debris delivered to the stream channel network by landslides and debris flows from unstable hillslopes over 20 years ago continue to cause impacts to the available anadromous salmon habitat in the main channel of Carnation Creek. These changes now substantial in the entire zone occupied by anadromous species. Some channel changes (widening due to lateral erosion and de-stabilization of LWD) were first initiated as a result of riparian harvesting; however, these effects have been overwhelmed by the subsequent effects of logjams and excess bedload associated with landslides which persist today.

(4) Continued impacts to channels and fish habitats are occurring due to the downstream progression of landslide-generated sediment and debris into the part of Carnation
Creek historically protected by riparian buffers and which, until recently, contained the last remaining high-quality anadromous fish habitats. This not only demonstrates the long time course of some harvest-related alterations, this also shows the vulnerability of streams to the cumulative effects of hillslope failures and debris flows regardless of riparian reserves. Our results indicate that forestry managers and practitioners need to ensure good forestry stewardship on hillslopes in addition to sound management of riparian areas.

(5) Channel morphology and fish habitats also continue to be affected in the long-term by reductions in LWD supply due to clear-cut riparian treatments. These effects will continue and increase in magnitude for several decades because new riparian sources of stable LWD may not be available for 60 years or longer.

Stream and fish habitat changes are occurring rapidly and appear to be counteracting the effects of the post-logging trend for elevated coho salmon smolt production due to increased water temperatures. The reduction in smolt production in 2005 and 2006 may signal the initiation of long-term coho declines in fresh water. Continued documentation of effects of canopy closure, subsequent reductions in water temperature, and on-going channel alterations which are continuing to reduce habitat quality will be a research priority for the next several years. After this period, the study will be evaluated to assess which components still need to be continued for longer-term study and to identify appropriate inter-annual sampling frequencies.

References Cited


Tschaplinski, P. J. 2006. Riparian canopy density in clear-cut-logged and riparian buffered areas of Carnation Creek, Vancouver Island, BC. FIA Project Progress


**Figures**

![Graph](image_url)

**Figure 1.** Adult chum salmon returns to Carnation Creek, 1970 – 2007.
Figure 2. Adult coho salmon returns to Carnation Creek, 1971 - 2007.

Figure 3. Populations of juvenile coho salmon (fry and yearlings) rearing in Carnation Creek during late summer, 1971 - 2007.
Figure 4. Coho salmon smolts produced in Carnation Creek, 1971 - 2007.

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Figure 11. Comparison of mean 45° ACD in the Carnation Creek by main-channel study sections and tributaries for all years combined, 2004 - 2007. Means are provided with ± 95 % confidence limits.

Figure 12. Comparison of canopy density measured at over 60° azimuth in Carnation Creek by main-channel study sections and tributaries in 2007. Means are provided with ± 95 % confidence limits.
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Figure 15. Mean summertime stream temperatures (Jun, Jul, and Aug) at Station C of Carnation Creek, 1990-2006. Means are provided with ± 95 % confidence limits.
Figure 16. Mean summertime stream temperatures (Jun, Jul, and Aug) at Station E of Carnation Creek, 1990-2006. Means are provided with ± 95 % confidence limits.
Figure 17. Mean summertime stream temperatures (Jun, Jul, and Aug) at Station H of Carnation Creek, 1990-2006. Means are provided with ± 95% confidence limits.
Figure 18. Average daily range of summertime stream temperatures (Jun, Jul, and Aug) at Station B of Carnation Creek, 1990-2006. Means are provided with ± 95 % confidence limits.
Figure 19. Average daily range of summertime stream temperatures (Jun, Jul, and Aug) at Station C of Carnation Creek, 1990-2006. Means are provided with ± 95% confidence limits.
Figure 20. Average daily range of summertime stream temperatures (Jun, Jul, and Aug) at Station E of Carnation Creek, 1990-2006. Means are provided with ± 95% confidence limits.
Figure 21. Average daily range of summertime stream temperatures (Jun, Jul, and Aug) at Station H of Carnation Creek, 1990-2006. Means are provided with ± 95% confidence limits.
Table 1. Mean angular canopy densities (ACD) with ± 95 % confidence limits in the main-channel study sections and tributaries of Carnation Creek for 2004 – 2007 combined.

<table>
<thead>
<tr>
<th>Section</th>
<th>Section Width (m)</th>
<th>Year</th>
<th>Mean ACD + 95 % CI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Range</td>
<td>2004</td>
</tr>
<tr>
<td>2</td>
<td>12</td>
<td>10-14</td>
<td>78</td>
</tr>
<tr>
<td>3</td>
<td>16</td>
<td>12-20</td>
<td>65</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>6-15</td>
<td>66</td>
</tr>
<tr>
<td>5</td>
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<td>56</td>
</tr>
<tr>
<td>6</td>
<td>14</td>
<td>9-20</td>
<td>64</td>
</tr>
<tr>
<td>8</td>
<td>11</td>
<td>6-20</td>
<td>44</td>
</tr>
<tr>
<td>750</td>
<td>4</td>
<td>*</td>
<td>85</td>
</tr>
<tr>
<td>1600</td>
<td>4</td>
<td>*</td>
<td>89</td>
</tr>
<tr>
<td>2600</td>
<td>4</td>
<td>*</td>
<td>83</td>
</tr>
</tbody>
</table>

* Only one transect completed for each tributary

Table 2. Mean canopy densities (> 60°) in the main-channel study sections and tributaries of Carnation Creek and by riparian harvest treatment in 2007. Means are provided with ± 95 % confidence limits.

<table>
<thead>
<tr>
<th>Section</th>
<th>(n) Transects</th>
<th>(n) CD Measurements</th>
<th>Mean Percent Cover</th>
<th>Standard Deviation</th>
<th>Lower C.L.</th>
<th>Upper C.L.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
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<td>61.1</td>
<td>29.9</td>
<td>56.5</td>
<td>65.8</td>
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<tr>
<td>3</td>
<td>3</td>
<td>160</td>
<td>50.4</td>
<td>35.6</td>
<td>44.9</td>
<td>55.9</td>
</tr>
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<td>41.8</td>
<td>31.6</td>
<td>36.7</td>
<td>47.0</td>
</tr>
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<td>42.8</td>
<td>33.6</td>
<td>37.8</td>
<td>47.9</td>
</tr>
<tr>
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<td>3</td>
<td>160</td>
<td>51.3</td>
<td>27.6</td>
<td>47.1</td>
<td>55.6</td>
</tr>
<tr>
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<td>280</td>
<td>47.5</td>
<td>33.8</td>
<td>43.5</td>
<td>51.4</td>
</tr>
<tr>
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<td>464</td>
<td>51.5</td>
<td>33.4</td>
<td>48.4</td>
<td>54.5</td>
</tr>
<tr>
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<td>47.0</td>
<td>31.1</td>
<td>43.7</td>
<td>50.3</td>
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<tr>
<td>Careful Clearcut (8)</td>
<td>6</td>
<td>280</td>
<td>47.5</td>
<td>33.8</td>
<td>43.5</td>
<td>51.4</td>
</tr>
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<td>750 Trib. (Riparian Buffer)</td>
<td>3</td>
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<td>72.4</td>
<td>25.5</td>
<td>62.2</td>
<td>82.6</td>
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<tr>
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<td>71.6</td>
<td>17.9</td>
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<td>78.7</td>
</tr>
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<td>2600 Trib. (Careful Clearcut)</td>
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<td>56</td>
<td>72.8</td>
<td>24.3</td>
<td>66.4</td>
<td>79.1</td>
</tr>
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</table>
Table 3. Mean canopy densities (> 80°) in the main-channel study sections and tributaries of Carnation Creek and by riparian harvest treatment in 2007. Means are provided with ± 95 % confidence limits.

<table>
<thead>
<tr>
<th>Section</th>
<th>(n) Transects</th>
<th>(n) ACD Measurements</th>
<th>Mean % Cover</th>
<th>Standard Deviation</th>
<th>Lower 95% C.L.</th>
<th>Upper 95% C.L.</th>
</tr>
</thead>
<tbody>
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<td>2</td>
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<td>35.5</td>
<td>43.8</td>
<td>74.9</td>
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<tr>
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<td>3</td>
<td>20</td>
<td>38.0</td>
<td>30.7</td>
<td>24.5</td>
<td>51.5</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>18</td>
<td>46.0</td>
<td>30.2</td>
<td>21.2</td>
<td>59.9</td>
</tr>
<tr>
<td>5</td>
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<td>21</td>
<td>37.4</td>
<td>34.9</td>
<td>22.4</td>
<td>52.3</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>20</td>
<td>51.3</td>
<td>27.6</td>
<td>35.7</td>
<td>63.4</td>
</tr>
<tr>
<td>8</td>
<td>6</td>
<td>35</td>
<td>45.8</td>
<td>33.2</td>
<td>24.3</td>
<td>56.8</td>
</tr>
<tr>
<td>Riparian Buffer (2, 3, 4)</td>
<td>9</td>
<td>58</td>
<td>47.8</td>
<td>33.0</td>
<td>29.8</td>
<td>56.3</td>
</tr>
<tr>
<td>Intensive Clearcut (5, 6)</td>
<td>9</td>
<td>41</td>
<td>49.7</td>
<td>28.8</td>
<td>22.9</td>
<td>58.5</td>
</tr>
<tr>
<td>Careful Clearcut (8)</td>
<td>6</td>
<td>34</td>
<td>45.8</td>
<td>33.2</td>
<td>24.5</td>
<td>57.0</td>
</tr>
<tr>
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<td>103.0</td>
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<td>55.0</td>
<td>22.9</td>
<td>29.1</td>
<td>80.9</td>
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<tr>
<td>2600 Trib. (Careful Clearcut)</td>
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<td>5</td>
<td>62.9</td>
<td>22.1</td>
<td>43.4</td>
<td>82.3</td>
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</table>

Table 4. Annual trends in canopy density > 60° in the main-channel study sections and tributaries of Carnation Creek, and by riparian harvest treatment, 2004 – 2007.

<table>
<thead>
<tr>
<th>Section</th>
<th>Mean Transect Length (m)</th>
<th>2004 CD (%)</th>
<th>2005 CD (%)</th>
<th>2006 CD (%)</th>
<th>2007 CD (%)</th>
<th>Mean CD ± 95 %CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>12</td>
<td>56</td>
<td>78</td>
<td>81</td>
<td>61</td>
<td>69 ± 12</td>
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<td>3</td>
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<td>47</td>
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<td>54</td>
<td>49</td>
<td>49 ± 4</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>50</td>
<td>44</td>
<td>60</td>
<td>42</td>
<td>49 ± 8</td>
</tr>
<tr>
<td>5</td>
<td>15</td>
<td>38</td>
<td>46</td>
<td>52</td>
<td>42</td>
<td>44 ± 6</td>
</tr>
<tr>
<td>6</td>
<td>14</td>
<td>54</td>
<td>59</td>
<td>70</td>
<td>51</td>
<td>59 ± 8</td>
</tr>
<tr>
<td>8</td>
<td>11</td>
<td>34</td>
<td>42</td>
<td>58</td>
<td>47</td>
<td>45 ± 10</td>
</tr>
<tr>
<td>Riparian Buffer (2, 3, 4)</td>
<td>12</td>
<td>51</td>
<td>57</td>
<td>65</td>
<td>51</td>
<td>56 ± 7</td>
</tr>
<tr>
<td>Intensive Clearcut (5, 6)</td>
<td>14</td>
<td>46</td>
<td>53</td>
<td>61</td>
<td>48</td>
<td>52 ± 7</td>
</tr>
<tr>
<td>Careful Clearcut (8)</td>
<td>11</td>
<td>34</td>
<td>40</td>
<td>58</td>
<td>47</td>
<td>45 ± 10</td>
</tr>
<tr>
<td>750 Trib (Riparian Buffer)</td>
<td>4</td>
<td>74</td>
<td>82</td>
<td>90</td>
<td>74</td>
<td>80 ± 8</td>
</tr>
<tr>
<td>1600 Trib (Intensive Clearcut)</td>
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<td>80</td>
<td>81</td>
<td>80</td>
<td>70</td>
<td>77 ± 5</td>
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<td>2600 Trib (Careful Clearcut)</td>
<td>4</td>
<td>79</td>
<td>71</td>
<td>78</td>
<td>72</td>
<td>75 ± 4</td>
</tr>
</tbody>
</table>

n = number of canopy density measurements
CD = canopy density (%) 
SD = standard deviation
Table 5. Annual trends in overhead canopy density (> 80°) in the main-channel study sections and tributaries of Carnation Creek, and by riparian harvest treatment, 2004 – 2007.

<table>
<thead>
<tr>
<th>Section</th>
<th>Mean Transect Length (m)</th>
<th>2004 CD (%)</th>
<th>2005 CD (%)</th>
<th>2006 CD (%)</th>
<th>2007 CD (%)</th>
<th>Mean CD ± 95 % CI</th>
</tr>
</thead>
<tbody>
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<td>66 ± 14</td>
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<tr>
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<td>16</td>
<td>35</td>
<td>34</td>
<td>47</td>
<td>38</td>
<td>39 ± 5</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>56</td>
<td>44</td>
<td>59</td>
<td>46</td>
<td>51 ± 7</td>
</tr>
<tr>
<td>5</td>
<td>15</td>
<td>29</td>
<td>39</td>
<td>42</td>
<td>37</td>
<td>37 ± 6</td>
</tr>
<tr>
<td>6</td>
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<td>35</td>
<td>40</td>
<td>55</td>
<td>46</td>
<td>44 ± 9</td>
</tr>
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<td>82</td>
<td>52</td>
<td>62</td>
<td>48</td>
<td>61 ± 15</td>
</tr>
<tr>
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<td>73</td>
<td>46</td>
<td>54</td>
<td>50</td>
<td>56 ± 12</td>
</tr>
<tr>
<td>Careful Clearcut (8)</td>
<td>11</td>
<td>65</td>
<td>40</td>
<td>55</td>
<td>46</td>
<td>51 ± 11</td>
</tr>
<tr>
<td>750 Trib. (Riparian Buffer)</td>
<td>4</td>
<td>47</td>
<td>72</td>
<td>70</td>
<td>87</td>
<td>69 ± 16</td>
</tr>
<tr>
<td>1600 Trib. (Intensive Clearcut)</td>
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<td>40</td>
<td>75</td>
<td>73</td>
<td>55</td>
<td>61 ± 16</td>
</tr>
<tr>
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<td>35</td>
<td>69</td>
<td>68</td>
<td>63</td>
<td>59 ± 16</td>
</tr>
</tbody>
</table>

n = number of canopy density measurements
CD = canopy density (%)
SD = standard deviation