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A Comparison of the Ecological Integrity of Headwater Streams Draining Harvested and Un-Harvested Watersheds in the Western Mountains of Maine, U.S.A.

Darlene Siegel

A COMPARISON OF THE ECOLOGICAL INTEGRITY OF HEADWATER STREAMS DRAINING HARVESTED AND UN-HARVESTED WATERSHEDS IN THE WESTERN MOUNTAINS OF MAINE, U.S.A.

By

Darlene Siegel

B.S. The Ohio State University, 1996

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Thesis Advisor: Dr. Christopher Cronan

An Abstract of the Thesis Presented
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Physical, chemical, and biological characteristics of four headwater streams draining forested watersheds were compared to determine the effectiveness of Riparian Management Zones (RMZs) in protecting aquatic ecological integrity from the effects of forest harvesting. Two of the watersheds were harvested with a 30% shelterwood cut and a 75 foot buffer was left adjacent to the streams. The other two watersheds were un-harvested and were used as reference conditions for comparison with the harvested watersheds.

General environmental conditions in these four headwater streams during the study period were characterized as follows. Each stream was located within a mixed-wood forest dominated by paper birch, balsam fir, and red spruce. Stream bankfull widths averaged 2.3 m to 4.2 m, mean dissolved oxygen (DO) concentrations were 9

to 10 mg/L, mean pH values ranged from 7.0 to 7.2, mean nitrate (NO_3^-) concentrations were <0.5 mg/L, mean turbidity concentrations were <0.6 NTU, mean temperatures were 11 to 12 °C, mean conductivity ranged from 24 to 32 µS/cm, and TSS values were generally below detection limits. Densities of brook trout ranged from 2 to 47 individuals per 200 m reach, macroinvertebrate densities ranged from 20 to 235 individuals per 0.1 m^2, and pieces of Large Woody Debris (LWD) per 200 m reach ranged from 42 to 100.

In general, few clear, strong differences were found when comparing the Reference and Harvest streams. The physical habitat data were within the range of normal variation. However, the high variability of LWD, macroinvertebrate, and fish data analyzed between streams made it difficult to differentiate treatment effects.

Overall, more data are required in order to determine the effects of harvesting within headwater watersheds. Further research is recommended that will increase the duration, replication, and range of treatments found in this study, as well as include a focus on baseline data collection and storm-water monitoring.

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INTRODUCTION

The management of forest resources in Maine has become a major public policy issue that has drawn landowners, citizens, policy makers, and special interest groups into ongoing debates. The issues concern acceptable harvesting practices that will maintain ecological integrity in forested landscapes, while also producing economic opportunities for the forest products sector. One area of concern is the impact of forest management activities on aquatic ecosystems, a topic that has been the subject of scientific investigation for decades. The US Environmental Protection Agency (USEPA) (1990) has identified forestry practices as potential nonpoint sources (NPS) of pollution. Nonpoint pollution sources are now regarded as the primary cause of degraded water quality in the US. The reality is that NPS pollution caused by silviculture operations is low compared to other land-uses; on a national level, silviculture contributes NPS pollution to only about 1% of the river and stream miles with major degradation, and about 9% of all impaired miles (USEPA 1995). However, on the regional or local scale the impacts of logging can be substantial. Forested watersheds receive intense scrutiny because of this potential magnitude of disturbance associated with forest harvesting.

The potential adverse effects of forest harvesting on NPS pollution have been examined by a number of investigations (Brown & Binkley 1993, Brown 1980, Kahl 1996, NCASI 1994). These studies illustrate that chemical, physical, and biological characteristics of stream quality can be degraded by forest practices. Indicators that have received significant attention include sedimentation, temperature, dissolved

oxygen (DO), nutrient cycling, and physical habitat characteristics. Much research also has been conducted on how changes in these variables influence benthic macroinvertebrate and salmonid populations.

Sediment is one of the primary water quality concerns regarding forest practices. Practices that disturb the soil and remove vegetation can increase sediment delivery to streams and impair beneficial uses of streams. Large accumulations of fine sediments can smother invertebrates, reduce permeability of streambed gravels and fish-egg nests, and impede emergence of fish fry (Kattelmann 1995). However, the response of suspended sediment concentrations to forest practices depends strongly on the location and nature of the forest operations (Brown and Binkley 1993). Stream turbidity and concentration of total suspended solids are measures that are used to quantify suspended sediment in the water; the national drinking water turbidity standard is 10 NTU (USEPA 2001). At Weymouth Point, ME, effects of whole-tree clearcutting produced an increase in turbidity units (12 to 17 JTU) as compared to the maximum turbidity for the control stream (3 JTU) (Pierce et al 1993). Furthermore, in Ontario, Canada, Kreutzweiser and Capell (2001) found that inorganic sediment load increased up to 1900 g/m^2, compared to pre-harvest means as low as 300 g/m^2, as a result of site disturbance for selective forest harvesting activities in riparian areas.

Temperature is another variable of concern because it controls the saturation concentrations of dissolved gases and metabolic rates of organisms (Hauer and Lamberti 1996). Forest practices that change temperature more than 2°C from natural levels may alter the development and success of fish populations (Brown and Binkley 1994). Pierce et al. (1993) found that a stream within a whole-tree clearcut in Maine

frequently had stream temperatures 4°C higher than the stream in the uncut control. In addition, a study in western Newfoundland showed that clearcut harvesting caused an alteration and overall warming of the thermal regimes in brook trout incubation habitats (Curry et al 2002).

Water temperature is a biological concern as it directly affects dissolved oxygen (DO) concentrations. As temperature increases, the concentration of DO decreases, because the oxygen solubility decreases (Brown and Binkley 1994). Furthermore, forestry practices may indirectly influence the dissolved oxygen concentration in small streams by adding nutrients to the system, or causing the accumulation of logging debris in the stream channel (Brown 1980). The DO concentration in small, forested streams significantly influences the character and productivity of the aquatic ecosystem. Fish and other aquatic organisms depend on a stream's oxygen content for survival, growth, and development (Brown 1980). Streams containing spawning salmonids should not drop below 8 mg/L of DO for one day, or below 9.5 mg/L for a 7-day mean; concentrations of 5 to 6.5 mg/L may be sufficient for adults (MacDonald et al 1991). Although few studies have examined changes in oxygen concentrations following forest harvesting, investigations in Oregon and California measured summer DO concentrations as low as 3 mg/L and 5 mg/L respectively (Binkley and Brown 1993).

As a result of forest harvesting, the removal of the large volume of biomass has been found to effect nutrient cycling and cation exchange processes resulting in potential impacts on the nutrient balance of the ecosystem and acidification. Forest harvesting can have a substantial impact on nutrient cycling in the first years after

harvest. The more severe the harvesting operation, the greater the potential for nitrification and loss of nitrate will be. Nitrate is a very mobile anion; the increase in soil moisture and runoff after the canopy is removed or reduced may be sufficient to leach nitrate that normally would remain in the upper soil zone (Kahl 1996). The USEPA Maximum Contaminant Level for nitrate in drinking water is 10 mg/L as N. The eggs of some salmonid species have shown sensitivity at these levels (Binkley and Brown 1993). The treatment stream in the northern hardwood forest at Hubbard Brook in central New Hampshire showed substantial nitrate increases after harvesting (Binkley and Brown 1993). Although the annual averages of nitrate did not exceed the drinking water standard, there were pulses that exceeded this limit. Studies in Maine found that concentrations of nitrate in streams after a whole-tree harvest rose to peak levels of 3 to 4 mg /L (Hornbeck and Martin 1986).

Forest harvesting also influences soil pH and subsequently influences the pH of stream water. Acidification may result because of increased nitrification and because of removal of base cations in biomass that would otherwise become components of the forest floor (Pierce et al.1993). During nitrification ammonium ions (NH_4^+) are oxidized producing two hydrogen ions (H^+) for every nitrate ion (NO_3^-). The release of these extra hydrogen ions creates a pH imbalance. In addition, the hydrogen ions will replace base cations (Na^+, K^+, Ca^{2+}, Mg^{2+}) on soil surfaces which increases the permanent loss of these nutrients to groundwater and streamwater (Kahl 1996). At the Hubbard Brook Experimental Forest, NH, increases in average stream water concentrations of Ca^{2+}, Mg^{2+}, K^+, and Na^+ were observed after deforestation along with a 5 fold reduction of pH (from 5.1 to 4.3) (Likens et al.

1970). Other studies show that changes in pH depend on the forest type and the severity of harvest. Martin et al. (1984) found an average decrease in pH of 0.8 in coniferous forests in Maine subjected to clearcutting of more than 30% of the watershed. Yet in one entirely clearcut watershed in the northern hardwoods of Vermont, pH was only 0.5 units lower than the reference (Binkley and Brown 1993). Time after harvest also displays different effects on pH. Another study at Hubbard Brook shows that 1-2 years after block cutting, pH was reduced from 5.0 to 4.8. However, pH began to rise so that during the 4^{th} through 10^{th} years pH averaged a half unit higher than pre-cut values (Hornbeck et al 1987).

Stream channel characteristics often are altered by forestry operations through direct inputs of sediments in run-off and landslides, direct encroachment, alteration of long-term large woody debris recruitment into the stream channel, reduction in streambank integrity, and alteration of hydrologic patterns (NCASI 1994). Increases in stream flow normally follow forest harvesting and these increases can influence stream quality by accelerating biogeochemical cycling of nutrients and increasing erosion rates (Lynch and Corbett 1990). Hornbeck et al (1997) found that logging <25% of the total basal area of a given watershed will alter summer flow regimes. Aquatic organisms may be adversely affected by loss of channel structure and habitat diversity and complexity in logged watersheds (Allan 1995).

Benthic macroinvertebrates and fish respond to integrated stream quality and can be sensitive indicators of degradation caused by forest practices. Freshwater macroinvertebrates are ubiquitous; even the most polluted or environmentally extreme lotic environments usually contain some representatives of this diverse and

ecologically important group of organisms (Hauer and Lamberti 1996). Forest management operations that impinge on the stream channel directly, leading to increased sediment input and subsequent declines in water quality and stream habitat integrity, cause declines in macroinvertebrate abundance (Davies and Nelson 1994) and changes in community structure (Lenat et al 1981, Garman 1984, and Noel et al 1986).

Management Solutions to Nonpoint Source Pollution

In order to control NPS pollution, Section 208 of The Clean Water Act requires states to implement area-wide water-quality management plans to prevent pollution. The US EPA has adopted Best Management Practices (BMPs) as the NPS control tool of choice (Lynch and Corbett 1990). A BMP has been defined as a practice or combination of practices that are determined by a state or area-wide planning agency to be the most effective, practical means of preventing or reducing the amount of pollution generated by nonpoint sources to a level compatible with water quality goals (Ice et al 1997). The Maine Department of Conservation recommends the use of BMPs when implementing forest practices in order comply with Section 208 of The Clean Water Act.

Riparian management zones (RMZs) were chosen as the BMP to emphasize in this study because they have proven to be the most effective in minimizing adverse impacts to stream quality. RMZs have high ecological importance because they consist of the interface between terrestrial and aquatic ecosystems (Gregory et al 1991). Riparian ecosystems influence the structure of both aquatic and upland

terrestrial communities and affect important functional processes in the stream channel (Osborne and Kovacic 1993). Riparian zones can modify, incorporate, dilute, or concentrate substances before they enter a stream system. For these reasons, RMZs have been adopted as a viable and useful tool for restoring and managing streams (Osborne and Kovacic 1993). Intact, naturally vegetated RMZs will: (1) promote bank stabilization; (2) deter streambank erosion and subsequent sedimentation; (3) provide natural shading and protection from wide fluctuations in water temperature; (4) provide for continued inputs of terrestrial food and organic material; (5) serve as a continued source of large woody debris inputs that contribute to pool formation and habitat; (6) reduce the transport of waterborne pollutants; and (7) contribute to regional ecosystem diversity (Verry et al 2000, Halliwell 1997).

As water passes through a riparian zone the chemical and sediment loads carried by the water can be reduced. This reduction is possible through both the biological and physical action of the plant community in the riparian zone as well as the chemical, physical, and biological action of the soil (NCASI 1992). The ability to reduce the transport of waterborne pollutants is a function of: (1) the physio-chemical conditions of the soil in the buffer area; (2) the physio-chemical conditions that exist in the water column; (3) the types of plant, animal, and microbiological communities present; and (4) the residence time of the water in the buffer area (NCASI 1992). For example, nitrogen (N) in the form of a solute can be removed from flowing water through abiotic and biotic processes. The abiotic processes involve the volatilization as ammonia and sorption on the soil solid phase. Biotic processes include dissimilatory and assimilatory mechanisms. Biological

denitrification is a dissimilatory process. Assimilatory processes involve the incorporation of N into biomass, either as uptake by plants or assimilation by microorganisms (NCASI 1992).

Riparian zones act as a filter for the removal of sediment and suspended solids. The solids will either settle out as flow is reduced, or they will be filtered out by soil structure, vegetation, and organic litter (Welsch 1991). Factors that determine the effectiveness of riparian zones in trapping sediments are runoff velocity, size distribution of incoming sediments, slope and length of travel, and vegetation characteristics (NCASI 1992).

Stream temperature can also be protected by RMZs in small streams, because streamside forest canopies moderate and stabilize stream temperature by providing shade. This shade helps optimize the survivorship, growth, and reproductive needs of fish and aquatic macroinvertebrates (Welsch 1991).

Research that specifically examines the function of RMZs in protecting aquatic environments is sparse (NCASI 1992) and most studies involve agricultural systems. However, available evidence supports the effectiveness of RMZs. These studies illustrate that RMZs reduce nutrient leaching, sediment erosion, and stream warming.

A few studies have been conducted in the Northeast regarding the efficacy of RMZs in conserving stream water quality. In an experiment conducted in the White Mountains of New Hampshire, RMZs were shown to reduce the magnitude and duration of increases in nitrate concentrations in streams that were clearcut, in comparison to those without RMZs (Martin and Pierce 1980). Another experiment in New Hampshire illustrated that streams protected with RMZs were able to maintain

normal water temperature; the streams were never more than 2°C warmer than the uncut control (Pierce et al. 1993). A study in Quebec illustrated that streams protected by RMZs within a harvest area had lower suspended sediments and temperatures than unprotected streams (Plamondon et al 1982).

Research Needs

Further research is required to gain a greater understanding of the efficacy of RMZs as a tool for conserving stream quality. Current stream and riparian management methods are not always effective, because significant degradation of protected streams often occurs when inputs from small-unprotected tributaries enter the main stream (Kahl 1996) and because water BMPs are often ignored or poorly constructed (Briggs et al 1996).

Furthermore, the appropriate size for RMZs is continuously under debate. Recommendations are often made for RMZ widths that provide protection for one specific parameter. For example, the typical recommended RMZ width for protecting water quality is between 7 and 12 meters (NCASI 1992). However, the recommended width for protecting macroinvertebrates and fish is greater than 30 meters (Davies and Nelson 1994, Huryn 2000) or two tree lengths (Verry 1992). Compton (1999) proposed that RMZs of ≥ 300m are needed to protect wood turtles in Maine. In reality, the appropriate width varies as a function of management objectives, local conditions and the parameter in need of protection.

Research studies routinely determine that the success of RMZs depends on site-specific factors such as climate, soil type, slope, topography, vegetation,

management practices, and the nature of the surface water being protected (NCASI 1992). Much of the research examining the effects of forest harvesting on riparian and in-stream biota has been conducted in northwestern and southern North America; similar research in northeastern North America has been limited (Loftin et al 2000). Consequently, there is considerable need for additional research in this region to investigate the relationships between RMZ design and specific site conditions to facilitate development of improved BMP guidelines (NCASI 1992).

In Maine, riparian and water quality policy is regulated by two agencies: the Land Use Regulation Commission (LURC) and the Maine Department of Environmental Protection (DEP). LURC governs forest practices in the unorganized townships. Headwater streams, as defined by LURC, are streams that drain less than 50 square miles and are protected under P-SL2 (Protection-Shoreland) regulations. The following rules apply:

(1) Sufficient vegetation must be retained along streams to "maintain shading of surface waters".

(2) Harvesting operations must not cause sedimentation of water in excess of 25 Jackson Turbidity Units (JTUs) at the point at which a stream drains 1 square mile or more.

(3) Streams that drain less than 300 acres are exempt from these requirements, however, forestry operations must not produce sedimentation in excess of 25 JTUs downstream at the 1 square milage drainage point (LURC 1999)

The DEP regulates timber harvesting in organized townships under the Mandatory Shoreland Zoning Act (Maine Forest Service 1999a). Headwater streams are defined

by the DEP as streams that drain less than 25 square miles and are subject to the following rules:

(1) A 75' riparian management zone is required above the normal high water mark.

(2) No more than 40% of the basal area may be removed within the 75' zone within a 10 year period.

(3) No clear-cut openings are allowed within 75' of the water body.

(4) No scarification (disturbance of the soil down to the mineral layer) is permitted within the 75' zone.

In March, 2002, the Maine Forest Service presented a report to the Maine legislature based on the 118th legislature's (Public Law 648, 1998) instructions for recommendations on the development of a single set of statewide standards to minimize the impact of timber harvesting on non-point source pollution. This report consolidated the regulations now under the separate jurisdiction of LURC and DEP. The new statewide standards for forestry would be administered and enforced by the Maine Forest Service. In the report, the Maine Forest Service recommended "additional measurable harvesting restrictions adjacent to smaller streams that previously had only minimal or no protection" (Maine Forest Service 1999b). These recommendations received much opposition from public and private interests. This opposition illustrates the need for current and local scientific research to support the more stringent recommended harvesting policies.

OBJECTIVE

The intent of this study was to provide preliminary data required for resolving these debates and facilitating scientifically based management decisions. The objective of this study was to determine if differences can be distinguished between the ecological integrity of headwater streams that drain harvested watersheds with a 75 foot Riparian Management Zone and those that drain unharvested watersheds. In this study, the concept of ecological integrity encompasses the biotic elements and the processes and habitat conditions that generate and maintain those elements (Angermeier and Karr 1994). An aquatic system that possesses ecological integrity is one that has the capability of supporting and maintaining a balanced, integrated, adaptive community of organisms having a species composition, diversity, and functional organization comparable to that of natural habitat of the region (Frey 1975; Karr and Dudley 1981). Biological integrity can be assessed through diagnostic attributes or indicators, which ideally are sensitive to a range of stresses, able to distinguish stress-induced variation from natural variation relevant to societal concerns, and easy to measure and interpret (Amgermeier and Karr 1994).

SITE DESCRIPTION

The study was conducted in Hayestown Township (T5R6), an unorganized township in Somerset County located in the western mountains region of Maine. This township is privately owned by International Paper and is managed for timber. The forests of the area are composed of hardwoods and conifers. The dominant hardwoods consist of paper birch (*Betula papyrifera*), yellow birch (*Betula alleghaniensis*), red maple (*Acer rubrum*), and sugar maple (*Acer saccharum*). The dominant conifers consist of balsam fir (*Abies balsamea*) and red spruce (*Picea rubens*). Soils in the study area are somewhat excessively drained soils to somewhat poorly drained soils of the Colonel, Dixfield, and Lyman series, formed in glacial till. The soils overlay Precambrian gneisses of the Chain Lakes Massif bedrock.

Sites are located on the U.S.G.S. 7.5 minute quadrangle map for Tumbledown Mountain (Figure 1). Four separate streams were selected within the headwaters of the West Branch Spencer Stream watershed (Table 1). Two of the streams drain uncut watersheds and were selected to serve as reference conditions. The two other streams drain watersheds that were subjected to forest harvesting during the winter and spring of 1997-1998 and were selected to assess the influence of forest harvesting (Figure 2).

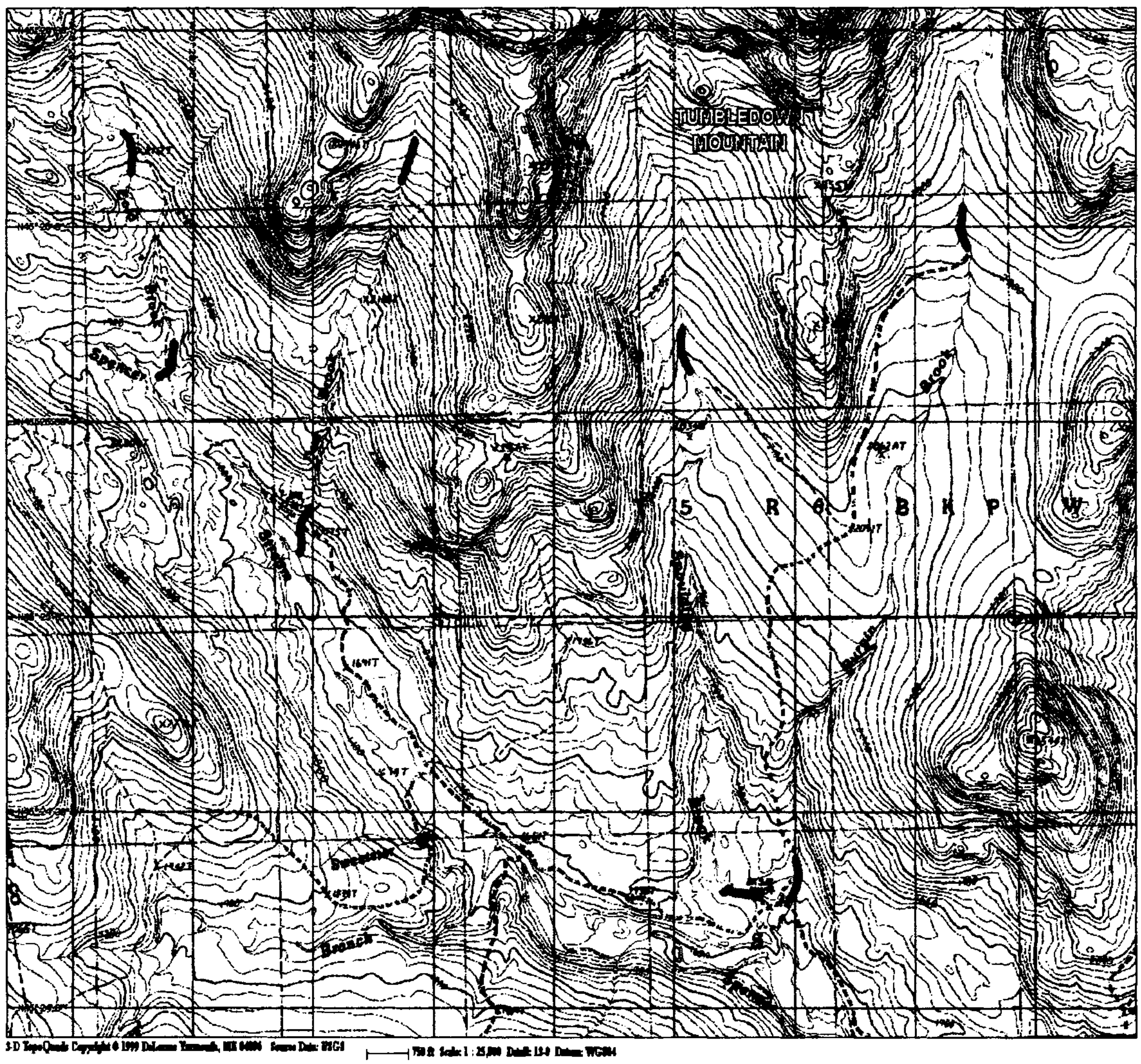
The watersheds are located in the Dead River sub-basin of the Kennebec River basin. The streams are classified as 1st and 2nd order perennial streams. The watershed sizes range from 2.56 – 5.68 km^2 (256 – 568 ha). The elevations of the study sites range between 495 and 555 meters for the lower reaches and 610 – 720

meters for the upper reaches. The streams are also classified and regulated as P-SL2 under Maine's Land Use Regulation Commission (LURC) jurisdiction.

Table 1. Coordinates for the lower most sampling points on each stream.

	Reference 1 Cold Brook	**Reference 2 Dud Brook**	**Harvest 1 Spaulding Brook**	**Harvest 2 Durgin Brook**
Latitude	N45°25'35.5"	N45°25'6.6"	N45°24'16.6"	N45°24'15.8"
Longitude	W70°28'39.6"	W70°28'2.2"	W70°26'8.4"	W70°26'0.8"

Figure 1. Location of the four study sites on the USGS Tumbledown Mountain quadrangle. The downstream reaches on each stream are highlighted in red. The upstream reaches for each stream are highlighted in blue.



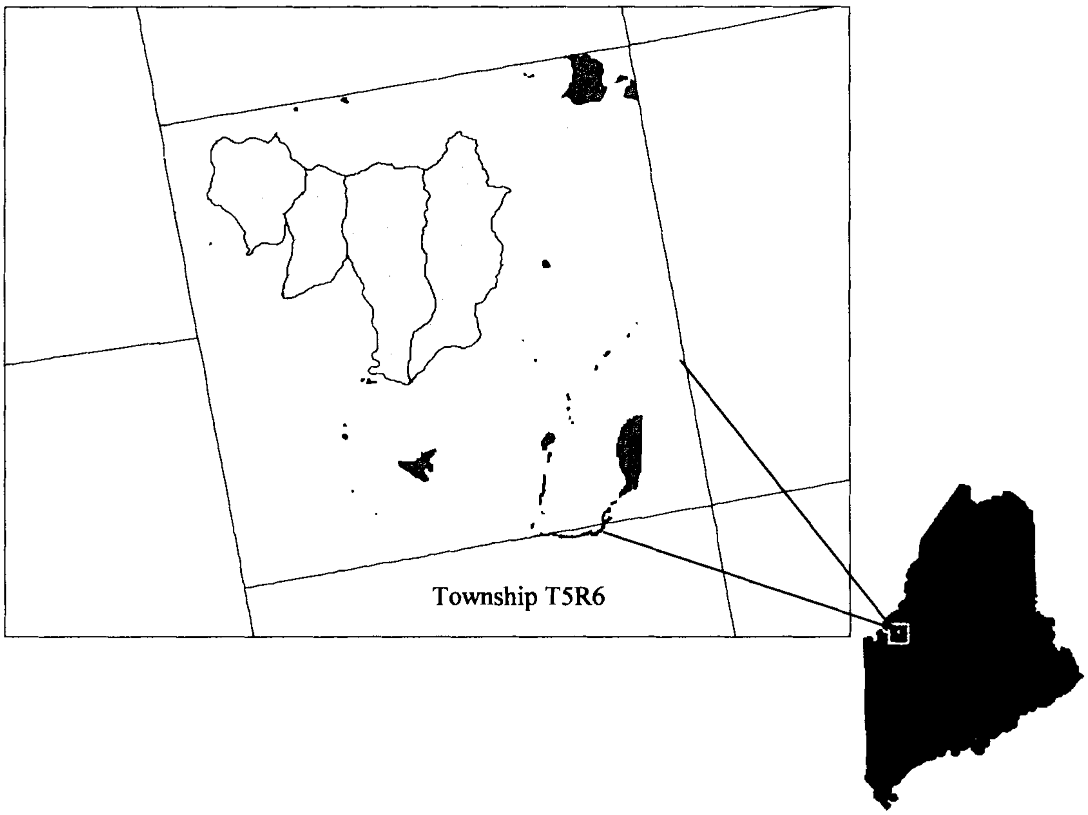


Figure 2. Boundaries of the four watersheds selected for the study. The two watersheds on the left are reference watersheds. The two watersheds on the right are the harvested watersheds.

METHODS

Site Selection

Perennial headwater streams (1st and 2nd order) in Township T5R6 were located within areas to be harvested in 1997-1998. Sites selected for the study were chosen based on: harvest plans, timing of harvest, and accessibility. Sites also were selected with the intention of normalizing physical characteristics in order to reduce variations among sites including: aspect, elevation, gradient, forest type, and watershed area.

Four separate streams were selected within the headwaters of the Spencer Stream watershed. Two of the streams drain uncut watersheds and were selected to represent reference conditions. The two remaining streams drain watersheds that were harvested during the winter and spring of 1997-1998 just prior to this study. These treatment streams were selected to assess the influence of forest harvesting. The harvests on these two streams involved a shelter-wood cut in which ~30% of the total watershed area was harvested. Cutting was non-continuous down both sides of the streams. Within the harvested areas, a riparian buffer was left adjacent to the stream that averaged 75 feet (22.9 meters) in width. These forest management practices satisfied Maine's Land Use Regulation Commission (LURC) rules that require that sufficient vegetation is retained along streams to "maintain shading of surface waters" (LURC 1999). This harvest scheme was also a realistic representation of forest management practices that currently are being implemented by the forest industry in the western Maine region in interpretation of these rules.

Study Design

Two separate reaches, each 200 meters in length, were established on each stream. For the harvested catchments, the downstream 200-meter reach was located within the harvested area just above a road crossing, and the other 200-meter reach was upstream from any harvesting activity (Figure 3). For the reference catchments, the downstream 200-meter reach was located just above the confluence with another stream, and the other 200-meter reach was approximately 0.5 km upstream from the downstream reach. The investigation was conducted for a total of five months from July 1998 through November 1998. The study incorporated the measurement of physical, chemical, and biological parameters.

Water Quality

Dissolved oxygen (DO), pH, specific conductance, turbidity, nitrogen (NO_3-N), and total suspended solids (TSS) were measured on a monthly basis throughout the duration of the study (July 1998 through November 1998). DO, pH, specific conductance, and turbidity were measured *in situ* due to variability in chemical and physical parameters when removed from the source (Environment Canada 1983; Hauer and Lamberti 1996). These parameters were measured using appropriate hand-held meters manufactured by: YSI, Hanna, and Orbeco-Hellige. Each meter was

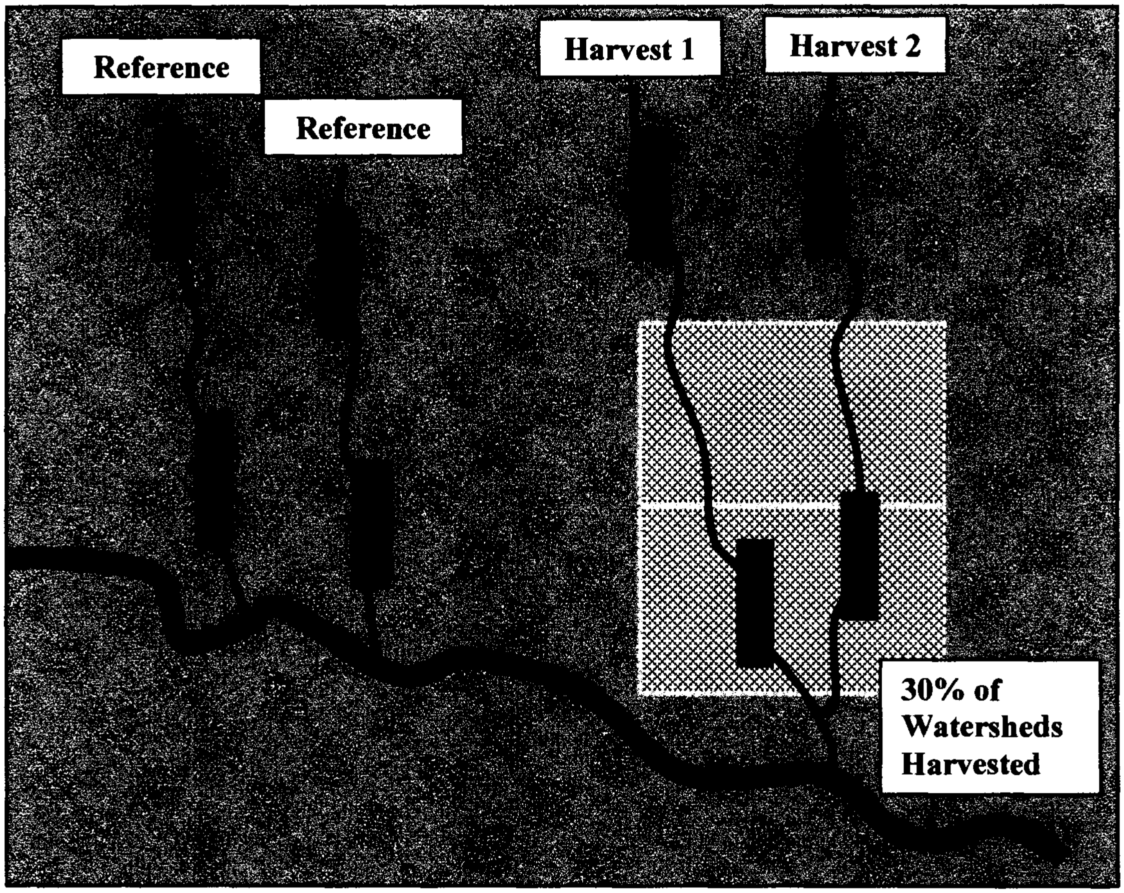


Figure 3. Experimental design, showing 200-meter reaches upstream and downstream on each stream. The upstream reaches are highlighted in blue and the downstream reaches are highlighted in red. On the harvested sites, the upstream reaches are above harvesting activities, and downstream reaches are within the harvested areas. The harvest is a shelterwood cut where 30% of the total watershed was cut. 75 foot Riparian Management Zones were left adjacent to the stream.

calibrated according to manufacturer's instructions and was tested for quality assurance throughout the duration of the study. Measurements for each of these parameters were taken in triplicate at the 50, 100, and 150 meter transects within each upstream and downstream reach. All values collected for each reach were averaged in order to minimize within site and within reach variability. Total Suspended Solids (TSS) was determined in the laboratory from 500 mL grab samples collected at the 50, 100 and 150 meter transects within each upstream and downstream reach. Each grab sample was mixed and vacuum filtered through a previously weighed Whatman 1.5 micron, 41mm glass microfibre filter into a glass flask. The filters were oven-dried at 103-105°C for one hour and reweighed to nearest 0.1 mg/L on an analytical balance (APHA 1992). The change in filter weight (mg) was divided by the total volume (L) providing the value of suspended solids in mg/L. (Brown 1980). The filtrate from the TSS procedure was frozen and was sent to the Water Research Institute (Sawyer Environmental Research Center, University of Maine, Orono, Maine 04469) for NO_3^- analysis using Ion Chromatography, EPA method 300 (USEPA 1999).

Temperature

Onset Hobo Data Loggers were anchored within the stream using metal rebar at the 50 meter transect of the upstream and downstream reaches on each stream. Each logger was placed in a white plastic submersible case to minimize the effects of ambient light. The temperature loggers were programmed to take a temperature reading each hour continuously from early July through late October. The data were downloaded once during the deployment in August and for a final time in October.

The downloading procedure required removing the units from the field, connecting each to a laptop computer for downloading, and returning them to the field the next day.

Physical Habitat

On all eight reaches, stream habitat was characterized using the U.S. Geological Survey's NAWQA protocols (Meador et al 1993). Six transects oriented perpendicular to the stream flow were established within each 200-meter reach. At each transect, wetted width, bank-full width, aspect, bank angle, and bank height were measured. The following parameters also were collected at three points equally spaced along the transect: depth, velocity, dominant and subdominant bed substrate, and embeddedness (the percentage of the larger substrate particles that are covered by fine sediment). Canopy angle was measured at each transect to assess the canopy cover. This angle was measured using a clinometer to determine the angle from the midpoint of the transect, at eye level above stream channel, to the tallest structure on each bank. The sum of the angles from the right bank and the left bank were subtracted from 180 degrees to obtain the canopy angle. The smaller the canopy angle value, the greater the canopy closure. Finally, the presence or absence of fish habitat features was determined within a 2-meter zone upstream and downstream of each transect. These habitat features include: woody snags, overhanging vegetation, undercut banks, boulders, macrophytes, and bank features (e.g., bank vegetation stability, bank shape, bank erosion, and bank substrate).

Large Woody Debris

Large woody debris (LWD) was measured within each 200 meter reach. For the purposes of this study, LWD was defined as any organic debris ≥10 cm in diameter and 1.0 m in length. Each piece within the active channel and within 1 meter on each side of the stream was measured (Fausch and Northcote 1992). The volume of each piece of LWD was calculated by measuring its length and average diameter. Average diameter was calculated by taking two diameter measurements, one on each end of the piece. The following equation was used to calculate the total volume of LWD Volume = π (Diameter1^2 + Diameter2^2)(Length/8) (Nakamura and Swanson 1994).

Fish

Qualitative estimates of fish communities were assessed in the upstream and downstream reaches of the harvested streams. Using a backpack electrofishing unit, one pass was taken working upstream through the reach length. Fish were collected, measured, identified to species, and returned to the stream.

Aquatic Macroinvertebrates

Aquatic macroinvertebrates were collected using a Surber sampler to achieve a quantitative measure of the benthic community composition. Samples were collected by scrubbing large rocks and agitating the substrate to a depth of 8 cm within the 0.1 m^2 area of the sampler (Newbold et al 1980). Sampling took place in November of 1998. Within every reach, three samples were collected at each of the transects using

the Surber sampler. This produced a total of nine samples per reach. Each sample was preserved separately in 90% ethyl alcohol. The macroinvertebrates were identified by professional taxonomists at EcoAnalysts, Inc. Each sample was picked completely, and a 200 count subsample was removed randomly. When possible, the macroinvertebrates in the subsample were identified to species to obtain more accuracy in assessing community composition, abundance and richness (Davies and Tsomides 1997). Analytical results provided information on species diversity, abundance, and community composition.

Riparian Zone Characterization

In order to characterize the riparian zone, a vegetation survey was conducted adjacent to each stream's upstream reach. Along each 200 meter reach, two transects were established perpendicular to the channel. These transects were located at the 50m and 150m points on both sides of the stream. At each transect and on both sides of the stream, three 10m x 10m plots were set up at 0m, 20m, and 40m (as measured perpendicular to the stream channel). Each tree within the 10m x 10m plot was measured for diameter at breast height (DBH) and identified to species.

Analyses

Comparisons were made among the upstream reaches to understand the natural variability of headwater streams and to determine the comparability of each of the four study streams. Averages for each parameter were calculated and compared among upstream reaches.

The harvested streams were then compared to the unharvested reference streams to determine the effects of forest harvesting. In most cases, upstream reaches of both the reference and harvest streams were compared to their respective downstream reaches by calculating the changes between the upstream reaches and the downstream reaches. The results of these comparisons are reported as delta values and ratios.

For parameters which were measured with sufficient replication, two sample comparison statistics were used to compare the two populations (upstream vs. downstream). Normally distributed data were compared using the two sample t-test. Data sets that were determined not to be normally distributed were compared by the Wilcoxon (Mann-Whitney) non-parametric test. Normality was determined by the Normal Quantile-Quantile test. In cases where the results of the normality test were mixed, the data were compared using the non-parametric test in order to maintain consistency. Comparing upstream to downstream data creates a pseudoreplicaton scenario where multiple measurements are taken from the same experimental unit (each stream). Caution should be used when interpreting the statistics due to the increased probability of making Type I errors (rejecting the null hypothesis when it is in fact true).

RESULTS

Characteristics of Headwater Streams

To understand how headwater streams behave under reference conditions, the upstream reaches on all four streams were compared. Harvesting activities in these upstream reaches have not occurred at least within the last 30 years.
This analysis provided a description of the natural variability and comparability among the four headwater streams.

Water Quality

Averages and ranges were calculated for the water quality data collected monthly between July and November in the upstream reaches (Table 2). Variability among streams for each water quality parameter was minimal. Average DO ranged between 9.0 mg/L and 9.8 mg/L, and average pH values for the streams ranged between 6.6 and 7.9. Average nitrate levels were very low, ranging from below detection limit to 1.3 mg/L NO_3^-. Conductivity was low ranging from 24.1 µS/cm to 32.4 µS/cm, although Reference 1 showed an upper limit of 59.4 µS/cm. Turbidity averages were under 1 NTU, except for Reference 2, which had an upper limit of 1.3 NTU. Average total suspended solids were below detection limits (0.01 mg/L). Average temperatures for the season were calculated for each stream and ranged between 11.0 °C and 11.9 °C. The maximum temperatures at each stream never reached 21 °C.

Table 2. Mean monthly water quality characteristics for the upstream reaches. Ranges are in parentheses.

Parameter	Reference 1 (Cold Brook)	Reference 2 (Dud Brook)	Harvest 1 (Spencer Brook)	Harvest 2 (Durgin Brook)
DO (mg/L)	9.2 (7.7 – 10.4)	9.7 (6.8 – 10.6)	9.8 (8.7 – 10.8)	9.0 (7.8 – 11.0)
Field pH[1]	7.1 (6.7 – 7.3)	7.0 (6.8 – 7.2)	7.0 (6.6 – 7.3)	7.2 (6.8 – 7.9)
NO_3^- (mg/L)	0.44 (0.21 – 0.80)	0.30 (0.00 – 0.65)	0.45 (0.00 – 1.31)	0.33 (0.16 – 0.65)
Conductivity (μS/cm)	32.4 (21.0 – 59.4)	26.3 (16.1 – 37.3)	25.1 (14.3 – 36.3)	24.1 (17.7 – 32.2)
Turbidity (NTU)	0.6 (0.4 – 0.9)	0.4 (0.1 – 1.3)	0.3 (0.2 – 0.8)	0.5 (0.3 – 0.8)
Temperature (°C)	11.9 (4.1 – 20.9)	11.2 (3.7 – 19.8)	11.1 (4.1 – 19.8)	11.5 (2.8 – 20.5)

[1] pH measurements made directly in stream and therefore included the variability imparted by supersaturation of CO_2.

Fish

Only the upstream reaches of Harvest 1 (Spencer Brook) and Harvest 2 (Durgin Brook) were sampled for fish due to limited funds and resources. The results of the sampling of the upstream reaches show that the numbers of fish collected varied considerably between streams (Figure 4). The only fish captured in both streams were brook trout, *Salvelinus fontinalis.* Harvest 2 had twice as many individuals (47) as Harvest 1 (23). Both streams had the same number of individuals collected in size Class 2 (2), yet Harvest 2 had nearly 5 times as many individuals in size Class 1, (19 versus 4) and still more in size Class 0 (26 versus 17).

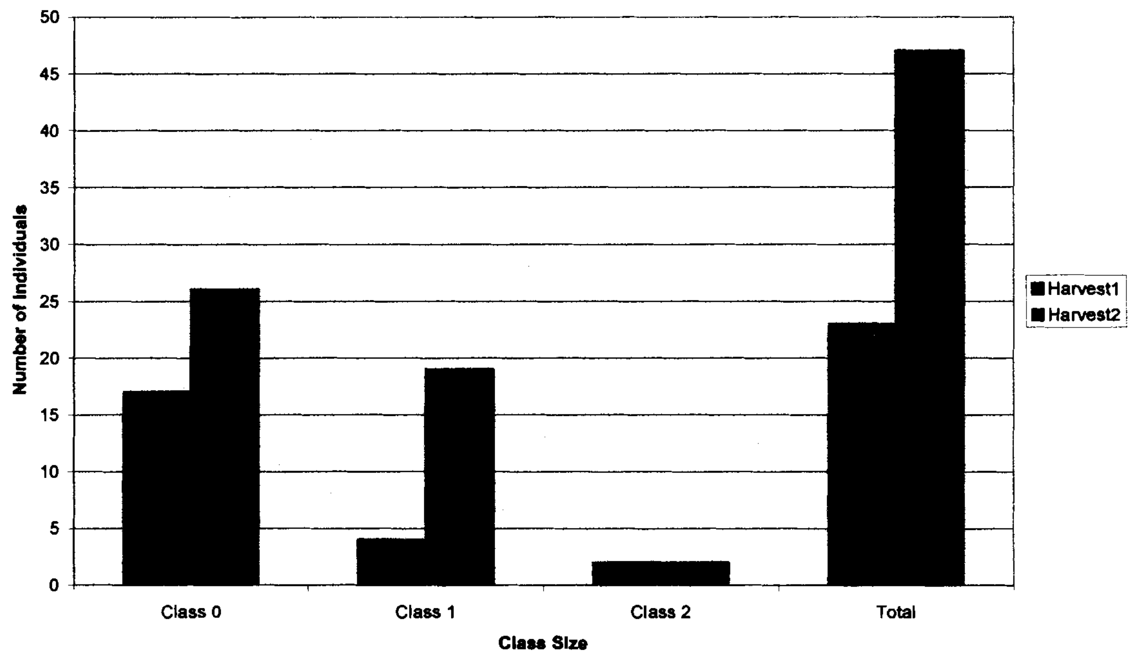


Figure 4. Number of individuals of brook trout, *Salvelinus fontinalis* captured in the upstream reaches of Harvest 1 and Harvest 2. (Number per 200-meter reach). Fish were not sampled in Reference streams. Size Class 0 is < 89 mm. Size Class 1 is 90 – 134 mm. Size Class 2 is >135 mm.

Macroinvertebrates

Nine samples were taken at each upstream reach and the results displayed in Table 3 are the calculated averages of these samples. Individuals were identified down to species in most cases, and these data were used to calculate biotic indices. Macroinvertebrate Density is the number of individuals collected in a sample. Taxonomic Richness is the number of taxa in the sample. The EPT Index is the number of taxa of Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies). The Shannon-Weaver Diversity Index combines richness and abundance of taxa in a summary statistic (Merrit and Cummings 1996).

Average macroinvertebrate densities ranged from 20 individuals per sample in Harvest 2 (Durgin Brook) to >230 individuals per sample in Reference 1 (Cold Brook) and Reference 2 (Dud Brook). Average Taxonomic richness was only 7 in Harvest 2 but was ≥26 in the other three upstream reaches. Average EPT Index values were ≥12 in Reference 1, Reference 2, and Harvest 1 (Spaulding Brook), but Harvest 2 exhibited an EPT Index of 0, which indicates there were no individuals representing the Ephemeroptera, Plecoptera, and Tricoptera orders. Finally, Shannon-Weaver Diversity Indices were similar for Reference 1, Reference 2, and Harvest 1.

Due to the extreme variability of macroinvertebrate data collected among the four streams, the results from a separate study conducted by International Paper (IP) were used as an additional source of comparison between streams. The IP study collected data on the same streams during the same season as those of this study excluding Reference 2 (Table 4). Macroinvertebrates were collected following the EPA's Rapid Bioassessment Protocol III (Plafkin et al., 1989). Although the

Table 3. Averages of macroinvertebrate index values calculated for each upstream reach. Surber samples (0.1 $m^{2)}$ were collected in November. N=9 for each upstream and downstream reach.

Index	Reference 1	Reference 2	Harvest 1	Harvest 2
Macroinvertebrate Density Abundance	231	235	122	20
Taxonomic Richness	28	26	26	7
EPT Index Value	16	15	12	0
Shannon-Weaver Diversity Index (H log e)	2.6	2.4	2.6	1.6

Table 4. Macroinvertebrate index values for International Paper's study. Samples were collected in early November. N=9 for each upstream and downstream reach.

Index	Reference 1	Harvest 1	Harvest 2
Macroinvertebrate Density Abundance	185	207	154
Taxonomic Richness	32	33	28
Shannon-Weaver Diversity Index	4.2	4.0	3.8

methodologies for the IP study and this study differed, it was interesting to compare the findings of each, particularly regarding Harvest 2 (Figure 5). The results of the IP study showed that for each calculated index (Taxonomic Richness, Taxonomic Abundance and the Shannon-Weaver Diversity Index) both Harvest 1 and Harvest 2 were comparable to Reference 1. For example, Harvest 2 had a Taxonomic Richness of 28 where Reference 1 and Harvest 1 had Taxonomic Richness values of 32 and 33 respectively.

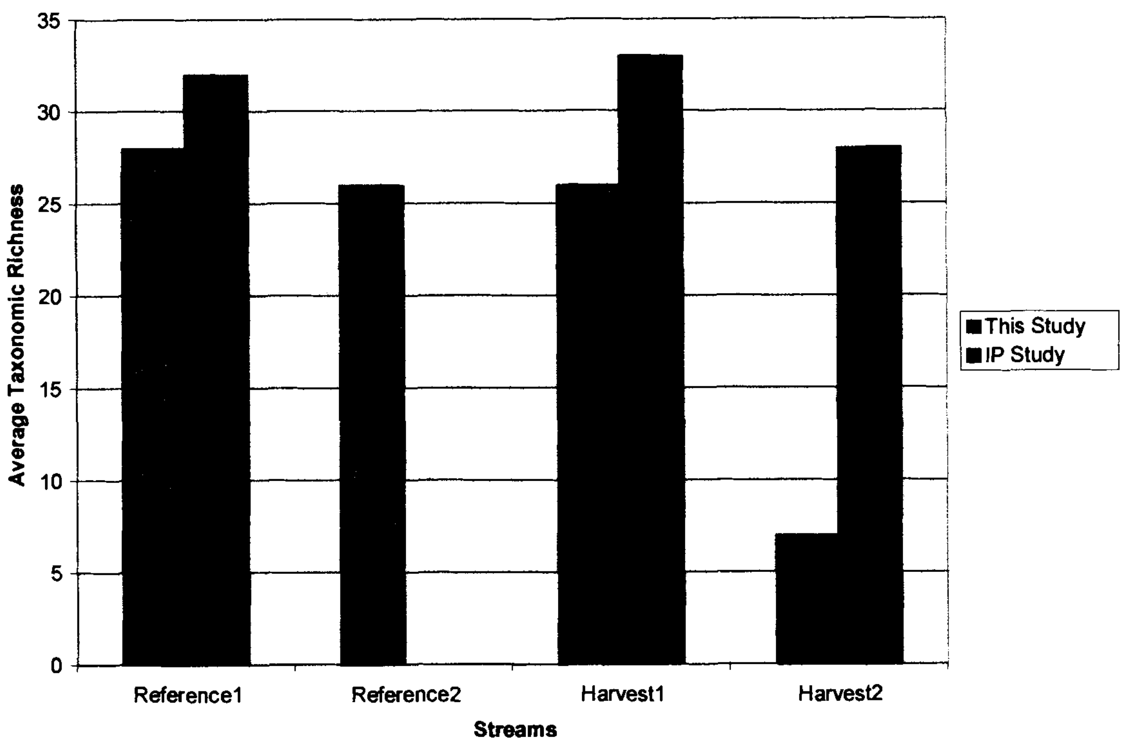


Figure 5. Comparison of macroinvertebrate taxonomic richness values obtained in the International Paper study and this study. Reference 2 was not included in the International Paper study.

Large Woody Debris

Upstream reaches of the four study streams contained variable amounts of Large Woody Debris (LWD) (Table 5). Reference 2 had the lowest number of LWD pieces of all the streams (42) and roughly half of the volume of the other streams (4.6 m^3). Reference 1 and Harvest 1 were the most similar in both volume (9.7 m^3 and 9.3 m^3) and numbers (81 and 100). Harvest 2 had fewer pieces (61) than Reference 1 (81) and Harvest 1 (100), yet the volumes were similar (8.5 m^3, 9.7 m^3, and 9.3 m^3 respectively). (See Figures 6 and 7.)

Table 5. LWD values per 200 meters of stream length for upstream reaches.

	Reference 1	**Reference 2**	**Harvest 1**	**Harvest 2**
Volume (m^3)	9.7	4.6	9.3	8.5
Abundance (# of pieces)	81	42	100	61

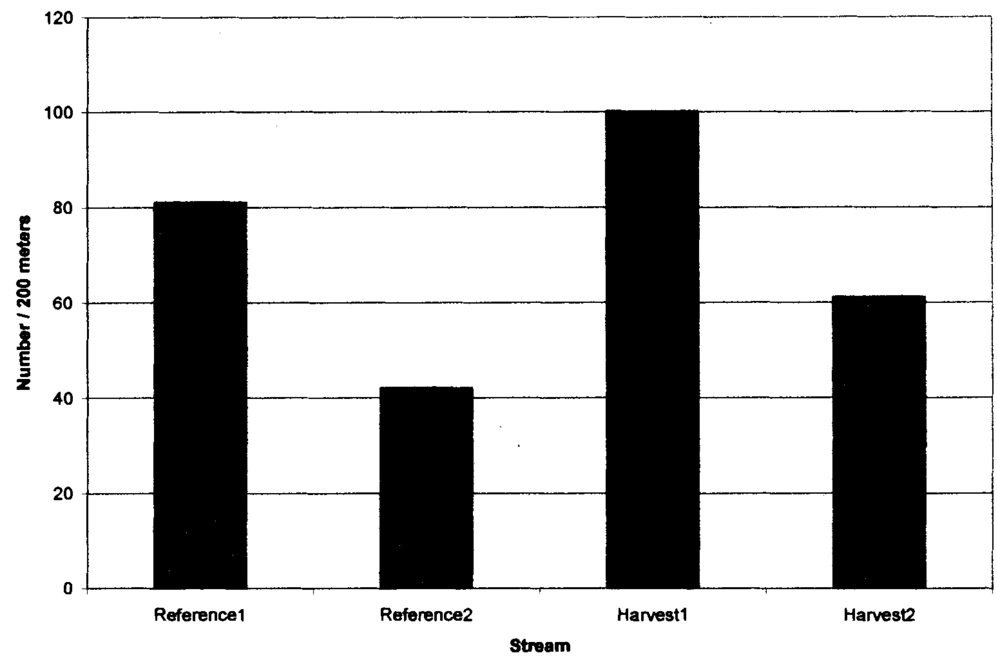


Figure 6. Number of LWD pieces per 200 meters of stream length for upstream reaches.

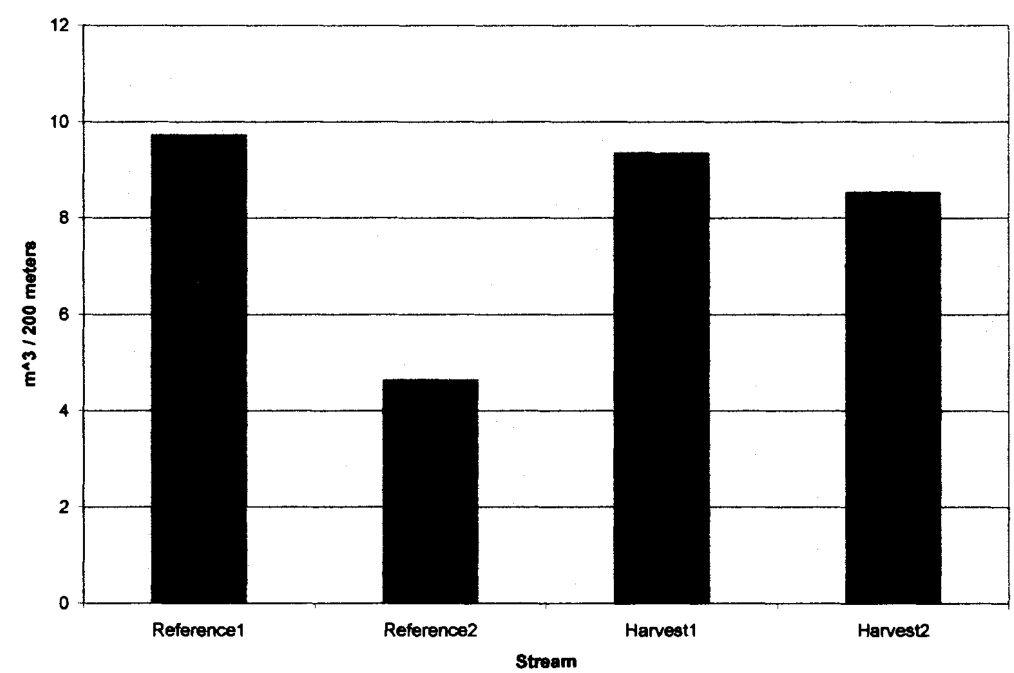


Figure 7. Volume of LWD per 200 meters of stream length for upstream reaches.

Stream Habitat

Habitat parameters were compared for the upstream reaches of all four streams (Table 6). Wetted widths ranged from 1.4 to 3.4 m, whereas bankfull widths ranged from 2.3 to 4.2 m. Canopy angles varied from 17.7° at Reference 2 to 29.2° at Reference 1. All streams had southern or southeastern exposures and were dominated by cobble-gravel substrate. Embeddedness was below 50% for both Reference streams and below 25% for both Harvest streams. Each stream provided a variety of available fish habitats.

Table 6. Average stream habitat characteristics for upstream reaches of both Reference and Harvest streams.

	Reference 1	**Reference 2**	**Harvest 1**	**Harvest 2**
Wetted Width (m)	3.4	1.4	1.7	2.2
Bankfull Width (m)	4.2	2.3	2.3	2.9
Canopy Angle (°)	29.2	17.7	22.8	21.3
Aspect (°)	175	219	159	191
Dominant Substrate	Cobble - Gravel	Cobble - Gravel	Cobble - Gravel	Cobble - Gravel
Embeddedness (%)	<50	<50	<25	<25
Fish Habitat	Undercut Banks-Boulders-Macrophytes-Woody Debris	Undercut Banks	Undercut Banks-Boulders-Macrophytes-Woody Debris	Undercut Banks-Boulders-Macrophytes

Vegetation

Riparian vegetation was analyzed adjacent to each upstream reach. Dominant species are listed in Table 7. Average densities and average basal areas were compared among streams (Table 8), and it was found that all sites had similar basal areas of 13 to 14 m^2/ha. Overall, species composition and species diversity among sites were very similar, with Reference 2 having the most species at 15. Harvest 1 had the lowest density (2100 stems / ha), yet had the greatest basal area (14.0 m^2/ha).

Table 7. Dominant tree species found adjacent to each upstream reach.

Reference 1	**Reference 2**	**Harvest 1**	**Harvest 2**
Paper Birch	Paper Birch	Red Spruce	Balsam Fir
Balsam Fir	Balsam Fir	Balsam Fir	Red Spruce
Red Spruce	Red Spruce	Paper Birch	Sugar Maple
Red Maple	Yellow Birch	Red Maple	Paper Birch
Yellow Birch			Yellow Birch

Table 8. Average density and basal area for riparian stands along upstream reaches of both Reference and Harvest streams.

Reference 1

Common Name	**Species**	**Density (#/ha)**	**Basal Area (m^2/ha)**
Paper Birch	*Betula papyrifera*	450	3.4
Balsam Fir	*Abies balsamea*	425	3.4
Red Spruce	*Picea rubens*	258	1.0
Red Maple	*Acer rubrum*	242	3.6
Yellow Birch	*Betula alleghaniensis*	242	1.3
Speckled Alder	*Alnus rugosa*	217	0.1
Black Spruce	*Picea mariana*	183	0.3
Striped Maple	*Acer pensylvanicum*	50	0.0
Pin Cherry	*Prunus virginiana*	42	0.0
Sugar Maple	*Acer saccharum*	25	0.0
Black Ash	*Fraxinus nigra*	17	0.0
Mountain Ash	*Pyrus americana*	17	0.0
Northern White Cedar	*Thuja occidentalis*	8	0.0
Total		**2175**	**13.1**

Reference 2

Common Name	**Species**	**Density (#/ha)**	**Basal Area (m^2/ha)**
Paper Birch	*Betula papyrifera*	655	3.0
Balsam Fir	*Abies balsamea*	455	3.0
Red Spruce	*Picea rubens*	327	1.8
Yellow Birch	*Betula alleghaniensis*	245	2.2
Red Maple	*Acer rubrum*	182	0.4
White Spruce	*Picea glauca*	127	1.7
Pin Cherry	*Prunus virginiana*	109	0.1
Striped Maple	*Acer pensylvanicum*	109	0.1
Sugar Maple	*Acer saccharum*	82	0.6
Northern White Cedar	*Thuja occidentalis*	55	0.3
Mountain Ash	*Pyrus americana*	45	0.1
Speckled Alder	*Alnus rugosa*	18	0.0
Mountain Maple	*Acer spicatum*	9	0.0
Quaking Aspen	*Populus tremulodies*	9	0.0
White Ash	*Fraxinus americana*	9	0.0
Total		**2436**	**13.2**

Harvest 1

Common Name	Species	Density (#/ha)	Basal Area (m^2/ha)
Red Spruce	*Picea rubens*	650	4.8
Balsam Fir	*Abies balsamea*	367	5.6
Paper Birch	*Betula papyrifera*	333	0.5
Red Maple	*Acer rubrum*	250	1.0
Sugar Maple	*Acer saccharum*	192	0.2
Yellow Birch	*Betula alleghaniensis*	108	1.7
Mountain Maple	*Acer spicatum*	50	0.0
Striped Maple	*Acer pensylvanicum*	42	0.0
Northern White Cedar	*Thuja occidentalis*	42	0.2
Mountain Ash	*Pyrus americana*	33	0.0
White Spruce	*Picea glauca*	25	0.0
Pin Cherry	*Prunus virginiana*	8	0.0
Total		**2100**	**14.0**

Harvest 2

Common Name	Species	Density (#/ha)	Basal Area (m^2/ha)
Balsam Fir	*Abies balsamea*	575	5.7
Red Spruce	*Picea rubens*	425	1.8
Sugar Maple	*Acer saccharum*	333	1.2
Paper Birch	*Betula papyrifera*	317	2.2
Yellow Birch	*Betula alleghaniensis*	258	2.4
Pin Cherry	*Prunus virginiana*	108	0.1
Striped Maple	*Acer pensylvanicum*	108	0.1
Red Maple	*Acer rubrum*	100	0.2
Elm	*Ulmus americana*	42	0.0
Quaking Aspen	*Populus tremulodies*	25	0.0
White Spruce	*Picea glauca*	17	0.0
Black Cherry	*Prunus serotina*	8	0.0
Total		**2317**	**13.7**

Effects of Forest Harvesting

In order to identify the effects of forest harvesting on the measured response variables, the upstream reaches were utilized as reference conditions with which to compare the downstream harvested reaches. The same comparisons were made in the Reference streams in order to identify and account for differences caused by natural variability. For multiple parameters, net changes from the upstream reaches to the downstream reaches were calculated on each stream. In some cases, delta values (downstream minus upstream) and ratios (downstream to upstream) were compared between harvested and reference sites to determine if harvesting effects could be detected. When replication was sufficient, upstream and downstream comparisons were made for the reference and harvest streams using statistical tests. When the data were identified as having a normal distribution the Two-sample t-test was used; if the data were not normally distributed the Wilcoxon (Mann-Whitney) non-parametric test was used.

Water Quality

All water quality parameters were compared using the two-sample Wilxocon (Mann-Whitney) non-parametric test (Table 10). Since not every data set was found to be normally distributed, the non-parametric test was chosen to analyze all the data to maintain comparison among streams and parameters. In addition, the average delta values (monthly downstream mean minus monthly upstream mean) of upstream reaches for water quality parameters were analyzed (Table 10).

When comparing average delta values in the reference and harvest streams, some differences were detected. There was a slight, significant increase in DO downstream in the Reference streams (0.25 mg/L) and an insignificant decrease downstream in the Harvest streams (-0.45 mg/L). There was a small significant increase in pH downstream in the Reference sites (0.3) and a minor decrease in pH downstream in the Harvest streams (-0.15). Nitrate concentrations were not significantly different between upstream and downstream reaches of the Reference and Harvest streams. There was a slight tendency for downstream decreases in conductivity for both Reference and Harvest streams (-2.75 and -0.15 μS/cm respectively) but the differences were not significant. In the Reference streams, little change was detected in turbidity (-0.05 NTU) but there was a small significant increase in the Harvest streams (0.45 NTU). Values for total suspended solids (TSS) were below detection limits and were therefore not analyzed for differences.

Table 9. Mean monthly water quality characteristics for the downstream reaches. Ranges are in parentheses.

Parameter	Reference 1 (Cold Brook)	Reference 2 (Dud Brook)	Harvest 1 (Spencer Brook)	Harvest 2 (Durgin Brook)
DO (mg/L)	9.6 (6.8 – 10.5)	10.4 (8.7 – 12.6)	9.2 (7.6 – 10.9)	9.1 (6.7 – 10.6)
Field pH[1]	7.2 (6.9 – 7.5)	7.3 (6.9 – 8.2)	7.0 (6.7 – 7.2)	7.0 (6.4 – 7.8)
NO_3^- (mg/L)	0.41 (0.08 – 0.79)	0.27 (0.00 – 0.65)	0.46 (0.00 – 1.31)	0.47 (0.15 – 3.21)
Conductivity (µS/cm)	27.7 (16.9 – 35.6)	25.7 (19.8 – 34.4)	26.4 (16.8 – 32.7)	22.5 (19.1 – 26.4)
Turbidity (NTU)	0.6 (0.3 – 0.9)	0.4 (0.3 – 0.6)	0.8 (0.3 – 1.3)	0.7 (0.5 – 1.2)
Temperature (°C)	11.7 (4.1 – 19.0)	11.7 (4.1 – 23.2)	11.8 (4.1 – 18.6)	12.4 (4.1 – 17.8)

[1] pH measurements made directly in stream and therefore included the variability imparted by supersaturation of CO_2.

Table 10. Comparison of water quality data between Reference and Harvest streams. The two sample Wilcoxon (Mann-Whitney) non-parametric test was used to determine if differences were significant between the upstream and downstream populations of the reference and harvest streams. Significance was determined by a $p < 0.05$. Delta values (downstream averages minus upstream averages) were also calculated.

	P-Values		Delta Values	
Parameter	**Reference Streams**	**Harvest Streams**	**Reference Streams**	**Harvest Streams**
DO (mg/L) n=18	0.0066*	0.1153	0.25	-0.45
Field pH n=18	0.0000*	0.0149*	0.3	-0.15
NO_3^- (mg/L) n=6	0.2619	0.2282	-0.04	0.15
Conductivity (μS/cm) n=18	0.8225	0.3105	-2.75	-0.15
Turbidity (NTU) n=18	0.0646	0.0000*	-0.05	0.45

Temperature

Temperature data for reference and harvest streams were analyzed by calculating average delta values, average temperatures, and maximum temperatures for the upstream and downstream reaches (Table 11). Although both streams had mean temperatures between 11 °C to 12 °C, there was a small, significant warming trend from upstream to downstream in both the reference and harvest streams (an increase of 0.2 °C and 0.8 °C respectively).

Table 11. Comparison of temperature data between Reference and Harvest streams. Averages, maximum values, and delta values (downstream – upstream) of seasonal data were collected for reference and harvest streams.

Parameter	**Reference Streams**	**Harvest Streams**
Average Delta Values (°C)	0.2	0.8
Upstream Maximum (°C)	20.9	20.2
Downstream Maximum (°C)	23.2	18.2
Upstream Average (°C)	11.6	11.3
Downstream Average (°C)	11.7	12.1

Fish

Delta values and ratios of fish present downstream to upstream were calculated for the Harvest streams (Table 12). Numbers of fish in Size Class 0 decreased in both sites (-13 and –17); the downstream reach of Harvest 1 had 24% of its upstream reach and the downstream reach of Harvest 2 had 35% of its upstream reach. However, increases in the other size classes (1 and 2) were observed. The total numbers of fish were greater downstream in Harvest 1, but were lower downstream in Harvest 2 (Figure 8).

Table 12. Delta values (total numbers downstream minus total numbers upstream) for brook trout captures on the harvested streams (numbers per 200 meter reach). Ratios of downstream to upstream are in parentheses.

Stream	Class 0 (<89mm)	Class 1 (90-134mm)	Class 2 (135-200mm)	Class 3 (>200mm)	Total
Harvest 1	-13 (24%)	+10 (350%)	+3 (167%)	+2	+2 (109%)
Harvest 2	-17 (35%)	+2 (111%)	+1 (150%)	0	-14 (70%)

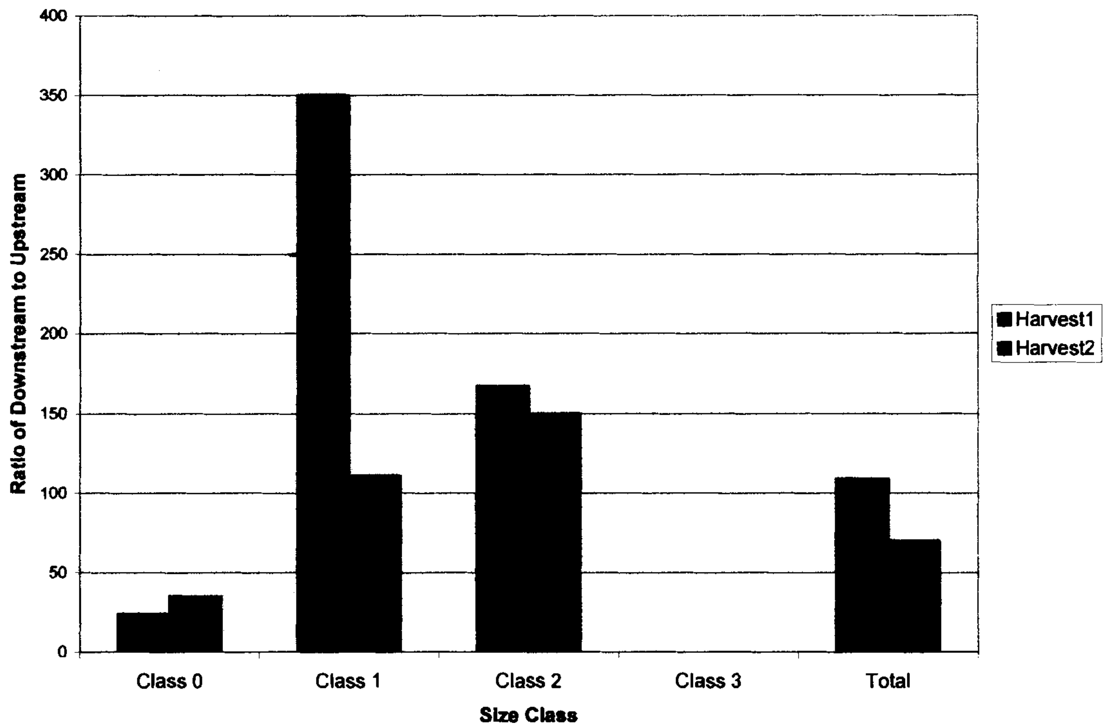


Figure 8. Ratios (downstream vs. upstream) of the number of individuals of brook trout captured in each size class in both Harvest streams.

Macroinvertebrates

Analysis of macroinvertebrate indices among the streams indicated the absence of significant effects of the harvest treatment on macroinvertebrate assemblages. As shown in Table 13, significant differences were found in the reference streams for most indices, except the Macroinvertebrate Density (p-value = 0.275). In contrast, no significant differences were found between upstream and downstream reaches of the harvest streams.

Table 13. Comparison of macroinvertebrate populations (index values) between Reference and Harvest streams. The two sample Wilcoxon (Mann-Whitney) non-parametric test was used to determine if differences were significant between the upstream and downstream populations of the reference and harvest streams. Significance was determined by a $p < 0.05$ and with a sample size (n) = 18.

Index	**Reference Streams**	**Harvest Streams**
Macroinvertebrate Density Abundance	0.2750	0.2262
EPT Index Value	0.0308*	0.5434
Shannon-Weaver Diversity Index	0.0034*	0.2231
Taxonomic Richness	0.0134*	0.7394

Large Woody Debris

The volume and abundance of LWD were compared among Reference and Harvest streams by calculating delta values (average downstream minus average upstream) and ratios (downstream : upstream). LWD volume in downstream Harvest streams was 56% of upstream, whereas Reference streams exhibited a ratio of 160% (Table 14 and Figure 9). The number of pieces in the Harvest streams also decreased (-44) whereas Reference streams showed a slight increase (+1) (Figure 10). Reference 2 and Harvest 1 reversed roles between the upstream and downstream reaches. In the upstream reaches, Reference 2 had the least LWD pieces (42) and Harvest 1 had the most (100). Downstream, Reference 2 had the most LWD pieces (71) and Harvest 1 had the least (24).

Table 14. Delta values (downstream minus upstream) for LWD measurements per 200-meter stream length for both Reference and Harvest streams. Ratios of downstream to upstream are in parentheses.

	Reference 1	Reference 2	Reference Mean	Harvest 1	Harvest 2	Harvest Mean
Volume (m^3)	-2.1 (78%)	+6.5 (241%)	+2.2 (160%)	-6.1 (35%)	-2.0 (77%)	-4.1 (56%)
Abundance (# of pieces)	-28 (65%)	+29 (169%)	+1 (117%)	-76 (24%)	-11 (82%)	-44 (53%)

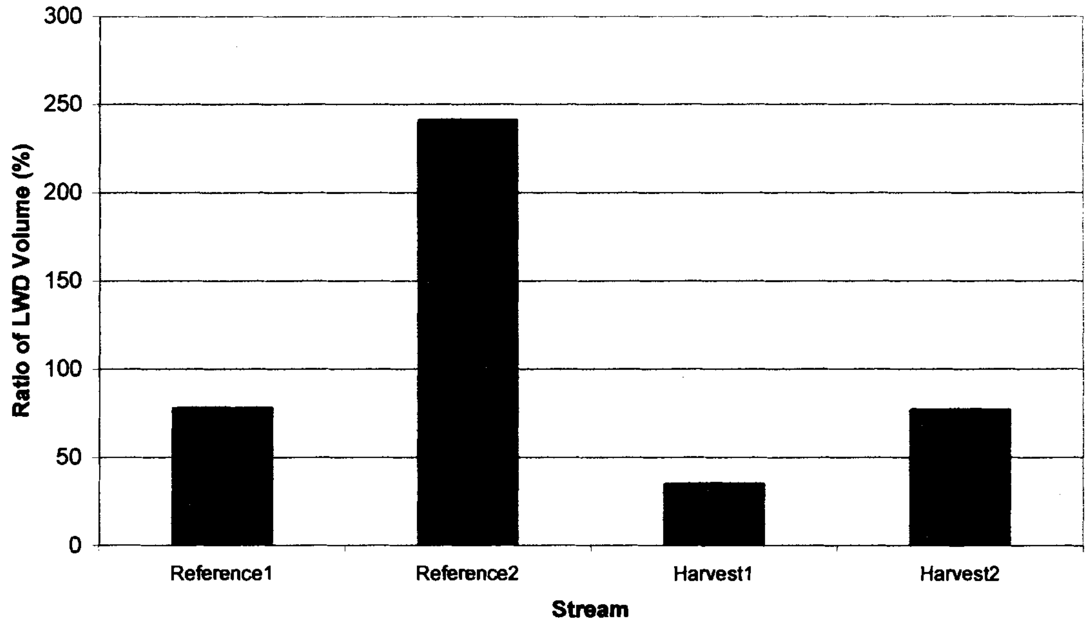


Figure 9. Ratios (downstream to upstream) of LWD volume per 200 meters of stream length for both Reference and Harvest streams.

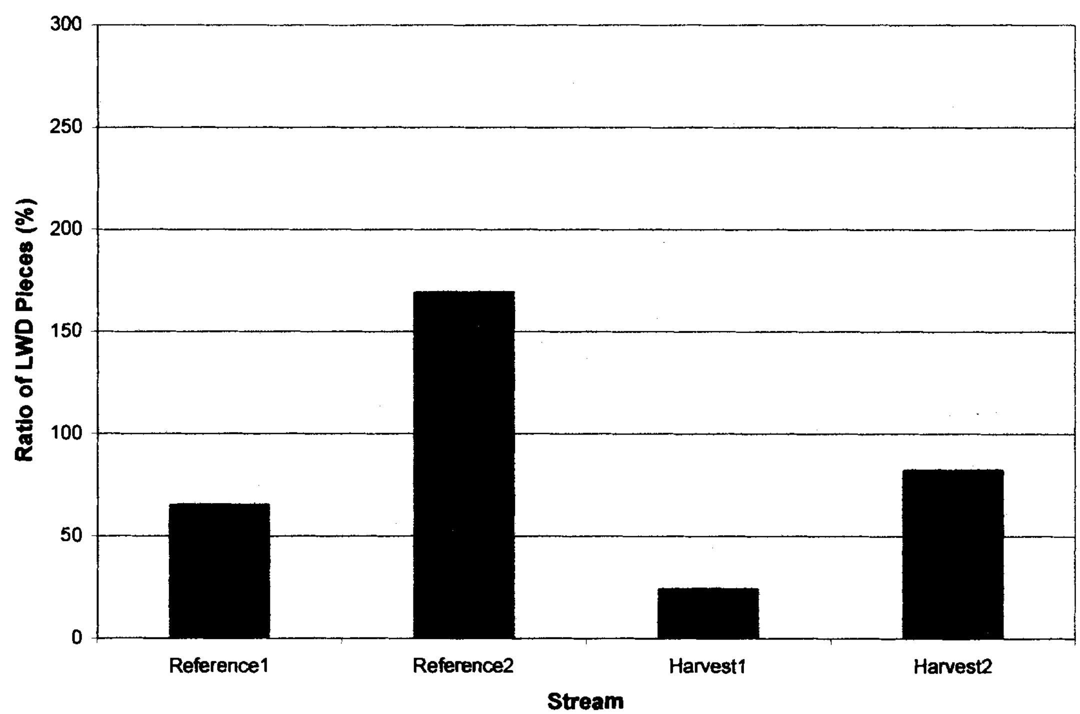


Figure 10. Ratios (downstream to upstream) of LWD numbers per 200 meters of stream length for both Reference and Harvest streams.

Stream Habitat

To compare physical habitat conditions between upstream and downstream reaches, averages and delta values (average downstream minus average upstream) were calculated. For the downstream habitat characteristics, wetted widths were similar among streams ranging from Reference 2, with 2.0 meters to Harvest 2, with 3.3 meters (Table 15). Bankfull widths were also similar among streams ranging from Reference 2, with 3.7 meters to Harvest 1 with, 5.3 meters. The canopy angle for Harvest 1 was 55.3°, where the other streams were below 30°. Each stream had a southern exposure, except for Harvest 1, which had a southeastern exposure. Dominant substrate type was, again, identical for all four streams (Cobble-Gravel). For embeddedness, only at Harvest 1 were levels detected between 25-50%, whereas the other streams were <25%. Harvest 1 was the only stream that lacked a great variety of fish habitat. All streams had boulders present to provide fish habitat; yet, Reference 1, Reference 2, and Harvest 2 had other types present including undercut banks, woody debris, overhanging vegetation, and macrophytes.

The delta values (downstream means minus upstream means) were calculated for stream habitat characteristics and, in most cases, the stream behaved as expected. For example, the bankfull width increased for every stream moving downstream. Harvest 1 increased the most by 3.0 meters (Table 16). Wetted width also increased moving downstream for all streams except Reference 1, which decreased by 0.5 meters. For Reference 1, Reference 2 and Harvest 2, canopy angle changed very little (±0.7°) between the upstream and downstream reaches. However, Harvest 1 displayed

an angle increase (a decrease in canopy cover over the stream channel) by a significant 32.5°.

Table 15. Average stream habitat characteristics for downstream reaches of both Reference and Harvest streams.

	Reference 1	**Reference 2**	**Harvest 1**	**Harvest 2**
Wetted Width (m)	2.9	2.0	3.0	3.3
Bankfull Width (m)	4.7	3.7	5.3	4.7
Canopy Angle (°)	29.8	18.3	55.3	20.7
Aspect (°)	214	217	117	207
Dominant Substrate	Cobble - Gravel	Cobble - Gravel	Cobble - Gravel	Cobble - Gravel
Embeddedness (%)	<25	<25	<50	<25
Fish Habitat	Overhanging Vegetation-Boulders-Macrophytes	Undercut Banks-Boulders-Woody Debris	Boulders	Undercut Banks-Boulders

Table 16. Delta values (downstream mean minus upstream mean) for select stream habitat characteristics of both Reference and Harvest streams.

	Reference 1	**Reference 2**	**Reference Mean**	**Harvest 1**	**Harvest 2**	**Harvest Mean**
Wetted Width (m)	-0.5	0.6	0.1	1.4	1.1	1.3
Bankfull Width (m)	0.5	1.4	1.0	3.0	1.8	2.4
Canopy Angle (°)	0.7	0.7	0.7	32.5	-0.7	15.9

DISCUSSION

Characteristics of Headwater Streams

Because streams can be highly variable ecosystems, this study began with an analysis to determine the similarity and comparability of the four study streams. Multiple parameters were measured in 200 meter reaches upstream from any disturbance or harvesting. Low variability among these measures would suggest that one can have more confidence when comparing harvested to un-harvested conditions.

The variability among the four streams was low for most parameters. Water quality, habitat, and vegetation parameters indicated high similarity among streams. In addition, the water quality data showed that the water, at times, exceeded the United States' Environmental Protection Agency Drinking Water Standards (USEPA 2001) and was well within biological tolerances. For example, the average pH level for each stream was neutral (7.0 ±0.2). DO concentrations averaged around 9.0 mg/L, which was well above brook trout preferences of 5 mg/L or greater (Spoor 1990). Nitrate levels never exceeded 1.4 mg/L, which was well below the EPA established maximum contamination level allowed in public drinking water of 10 mg/L NO_3^-. Conductivity was low ranging from 24.1 µS/cm to 32.4 µS/cm. Turbidity values were typically below the maximum contamination level for drinking water turbidity of 10 NTU (USEPA 2001). Total Suspended Solids (TSS) were often below detection limits. Seasonal temperatures were between 11 °C and 12 °C at each stream which was within the optimal zone for brook trout (11 °C – 16 °C) (McRae and Edwards 1994).

The stream habitat data show that there was a high similarity in stream habitat conditions for every stream. The differences in wetted widths and bankfull widths were small. Reference 1, however, had the largest wetted and bankfull channel width (3.42 m and 4.20 m respectively). Reference 1 also had the largest canopy angle (29.2°), which may be a direct result of its larger channel width. The dominant substrate is identical for all streams (cobble-gravel), therefore providing similar habitat conditions among the streams. Also, each stream had a southern exposure (aspect measurements between 159° and 219°). Fish habitat was available in all streams, and embeddedness for each stream was <50%. Overall, the study streams were comprised of similar characteristics that provide suitable fish habitat.

Riparian vegetation along the upstream study reaches was similar. The dominant species for each stream were some combination of the following species: red spruce, balsam fir, paper birch, yellow birch, and red maple. Densities and basal areas fell within narrow ranges (2100 stems/ha – 2436 stems/ ha and 13.1 m^2/ha – 14.0 m^2/ha, respectively).

However, notable variability was found among streams for a few parameters including, fish, LWD, and macroinvertebrates. The number of individuals of fish collected in Harvest 2 (47) was twice the number collected in Harvest 1 (23). Unfortunately, because no fish data were collected in the Reference streams, it is difficult to determine how significant this difference was.

The LWD data also exhibited some variability among streams. Reference 2 had half the volume of the other streams (4.6 m^3 versus 9.7 m^3, 9.3 m^3, and 8.5 m^3). This may be a result of past harvesting activities or may be within the range of natural

variability of LWD recruitment in 1st and 2nd order streams. However, the limited data collected in this study are not sufficient for drawing these conclusions.

For macroinvertebrates, it is difficult to draw any conclusions regarding the similarity of the streams, as Harvest 2 appears to have outlier characteristics. The results of Harvest 2 show that few individuals and few taxa were collected from this stream. The Macroinvertebrate Density Abundance for Harvest 2 was 20, compared to Reference 2 with a value of 235. Harvest 2 also had an EPT Index Value of 0.0, which indicates that there were no individuals collected in the Ephemeroptera, Plecoptera, and Trichoptera orders. These results may be, in part, due to a rain event that occurred two days prior to the beginning of our sampling. Harvest 2 was the first stream that was sampled after this event. During the sampling of this site, the flows were elevated; however, they were not perceived to be of disturbance magnitude. Nevertheless, a disturbance would explain the outlier characteristics of the data collected for Harvest 2. When the data of this study were compared to an International Paper (IP) study conducted during August 1998, it became clear that the data from this study are inaccurate. The species that were missing in the primary study are present in the IP study. Furthermore, the index values that were calculated in the IP study show that Harvest 2 has a very similar macroinvertebrate community to those found in Harvest 1 and Reference 1. Unfortunately, the results of the two studies are not directly comparable because of different methods of data collection as well as the timing (season) of collection (August versus November). The IP study is useful for understanding the species assemblage found in each stream.

Harvest 1 also showed a reduced value of Density Abundance in comparison to Reference 1 and Reference 2 (121.9 versus 230.6 and 234.8 respectively). This reduction may be due, in part, to the low numbers of individuals in the Ephemeroptera, Plecoptera, and Trichoptera orders as expressed in the EPT Index Value (11.7 versus 16.2 and 15.2 for Harvest 1, Reference 1 and Reference 2 respectively). Another reason for these decreased numbers may also be that Harvest 1 was the second stream to be sampled after the previously mentioned storm event.

Effects of Forest Harvesting

Reference and Harvest streams were compared in order to identify the effects of forest harvesting. When upstream and downstream reaches were compared for water quality parameters, it was difficult to detect differences between reference and harvested conditions. However, the data show that there were some differences for a few parameters.

For example, DO levels have been shown to decrease as a result of harvest activities (Brown and Binkley 1993). Whereas DO delta values increased in Reference streams (0.25 mg/L), DO decreased slightly in Harvest streams (-0.45 mg/L). However, this reduction in DO concentration was not significant and never reached levels below brook trout preferences of 5 mg/L (Spoor 1990). These results may be an artifact of the stream water temperature as temperature directly affects the DO concentration. It has been well documented that stream water temperatures increase due to removal of the canopy during forest harvesting (Brown and Binkley 1994, Pierce et al. 1993).

Another characteristic of the temperature data was that Reference 1 was the only stream that cooled along its profile. The source of Reference 1 is a flowage formed by abandoned beaver activity. This physical feature may partially explain the cooling effect found in this stream. Stream water that flows through a flowage slows and spreads out providing greater exposure to the warmer air temperatures and solar radiation. Therefore, when water exits a flowage, it may be warmer than if the flow was unrestricted and passed through a closed canopy. As a result, upon entering a closed canopy forest, Reference 1 was cooled by shading and groundwater inflows, as displayed in the delta values (-0.3 °C).

Although statistically significant differences in pH were found in the reference streams (p-value = 0.000) and the harvest streams (p-value = 0.0149), these small changes are somewhat equivocal from an analytical standpoint. Other studies have shown that depending on the soil chemistry of the site, forestry practices can raise or lower the soil pH, subsequently influencing the pH of streams (Stafford et al. 1996). It may be differences in soil types that negate the harvest impacts. pH is a very difficult parameter to measure in the field and the methodology utilized in this study may have been inadequate in detecting differences attributed to forest harvesting.

There was minimal change detected in nitrate concentration in the Reference streams (-0.04 mg/L) but a slight increase in nitrate was displayed in the Harvest streams (0.15 mg/L). In other studies, it has been found that nitrate levels can increase substantially after forest harvesting (Brown and Binkley 1993, Hornbeck and Martin 1986).

There was a slight significant tendency for turbidity to increase in the Harvest streams (0.45 NTU) whereas a slight decrease occurred in the Reference streams (-0.05 NTU). Although NTU levels below 1 NTU are not of biological concern, these results suggest differences that are consistent with other studies where turbidity levels increased after harvesting (Pierce et al 1993).

In general, differences in the water quality of harvested and unharvested streams in this study were slight, and the results were often not statistically or biologically significant. More studies and exploration are required to determine the extent to which harvesting activities and RMZs influence stream water quality.

The delta values and ratios for the fish population estimates show that there were decreases in brook trout numbers in the Class 0 size class for both Harvest streams (-13 and –17). However, increases in the other size occurred. Overall, the total numbers collected downstream in Harvest 1 were 109% of upstream values and the total numbers collected downstream in Harvest 2 were 70% of upstream values. This variability makes it difficult to conclude whether the differences found are a result of harvest effects.

The only statistically significant differences found in the macroinvertebrate data were between the upstream and downstream reaches of the reference streams. Significant differences were found for the following indicies: the EPT Index, the Shannon-Weaver Diversity Index and Taxonomic Richness. Unfortunately, the high variability of macroinvertebrates in the harvest streams made it difficult to discern any harvesting impacts on stream macroinvertebrate fauna.

There were no patterns of LWD that could be attributed to harvesting activities. In addition, considering other physical habitat characteristics, few significant differences were found between reference and harvest streams. However, Harvest 1 displayed the least amount of canopy cover in the downstream reach with a canopy angle of 32.5°. This may be an artifact of Harvest 1 having the widest bankfull width of all the downstream reaches that was 3.0 meters wider than the width of its upstream reach.

In general, few clear, strong differences were found when comparing the Reference and Harvest streams. Furthermore, it was difficult to conclude that the differences are the result of harvesting effects. The harvest itself was intended to represent a realistic harvesting scenario as found in the western mountains region of Maine. However, in retrospect, this harvest may be the best-case scenario in terms of protecting water quality. Since the harvest took place mostly during the winter months, on frozen ground, the disturbance to the ground was minimal. In addition, since water quality related indicators were sampled only in the drier months (July – November) many of the larger disturbance producing storm events were missed. These scenarios may have reduced the observed impact of the harvest on the measured indicators.

Recommendations for RMZs

Based upon current understanding, I expected that a 75 foot Riparian Management Zone (RMZ) would be adequate to protect some elements of ecological integrity. However, for other elements or for sites where there are high sediment loads

or steep slopes, this buffer size may be inadequate. Two comprehensive studies conducted on headwater streams in northern California (Newbold et al. 1980) and Tasmania (Davies and Nelson 1994) concluded that RMZs ≥ 30 meters or 99 feet were required to protect macroinvertebrate communities from the effects of forest harvesting and this width has been recommended for use in Maine (Huryn 2000). Based on these studies, the 75 foot RMZ evaluated in this study may be inadequate for protecting this aspect of aquatic integrity. The experimental design and data collected for this study are not expected to address this issue in a definitive way due to the complexity of natural ecosystems ant the large amount of data required to capture this complexity.

Future Research

The success of future research evaluating the effects of forest harvesting on stream integrity would depend on the ability to address the shortcomings of this study and those of the many studies that preceded it. (1) To begin with, the duration of the study should be increased. Although studies show that the greatest effects are usually detected during or shortly after harvesting, year-round and multiple season sampling would reduce natural seasonal variability and would provide statistical power. A larger study would resolve the complications that arose when variables were sampled only once (i.e. aquatic macroinvertebrates). This would in particular address the high natural variability in headwater streams found with such indicators as LWD, fish, and macroinvertebrates. (2) Increasing treatment replicates would provide the opportunity to analyze the data statistically in order to obtain more robust conclusions. This would

provide more confidence in differentiating between natural variability and treatment effects. (3) Increasing the range of treatments (different RMZ widths) would also be beneficial. For example, harvesting alongside streams without a RMZ would provide an extreme treatment condition. Also, examining narrower and wider RMZ widths would help to determine the width required to protect the different elements of aquatic integrity. Parameters that would benefit from a larger study include those that displayed little natural variability: temperature, turbidity, dissolved oxygen, pH, and nitrate. (4) There are inherent difficulties in studying headwater streams due to their unpredictability. Headwater streams are often unmapped, frequently dry during low flows, and are not accurately represented by protocols that have been designed for larger streams. The lack of research in small, headwater streams and the lack of developed methodology to address headwater characteristics pose further complications in study design. (5) Sampling of storm events for water quality parameters would provide an unique opportunity to witness pulses of runoff that may carry higher concentrations.

Recently, more interest has developed in the role of headwater streams in managed forests. Increasing numbers of studies focused on RMZ management along headwater streams are being conducted across the county including Manomet Center of Conservation Science's study in Maine and the University of British Colombia's Stream and Riparian Research Laboratory's study in British Columbia. Results from these studies should answer some of the questions raised above in the near future.

CONCLUSION

The four study streams exhibited remarkable similarity for most variables. The water quality, physical habitat and riparian vegetation data showed few differences among streams. As the fish population estimate data were only collected in the Harvest streams, it was difficult to assess the variability among the four streams for this parameter. Macroinvertebrate data were relatively similar for three of the streams but the effects of a natural disturbance from a rainfall event and outlier characteristics were evident in at least one stream. The LWD data displayed some variability among streams and it is difficult to conclude if this is within the range of natural variability of LWD recruitment in headwater streams or if the differences are artifacts of past harvesting activities.

In general, few clear, strong differences were found when comparing the Reference and Harvest streams. Furthermore, it was difficult to conclude that the differences are the result of harvesting effects. The physical habitat data were within the range of normal variation. Unfortunately, the data sets for fish and macroinvertebrates were incomplete, thus preventing a thorough test of treatment effects.

Overall, in order to determine the effects of harvesting within headwater watersheds, more data are required. Further research is needed that would provide greater replication of the treatments in order to run statistical analyses, a longer duration of study, and a more extensive examination of potential harvest treatments in headwater catchments. In addition it is important to decipher the different components

of biological integrity and the different requirements needed for their protection. It is recommended that the parameters that displayed the most promise in responding to treatment effects in this study should be focused on for future studies including temperature, turbidity, dissolved oxygen, pH, and nitrate. In addition, LWD, fish and macroinvertebrate populations could also be good indicators of harvest effects with a more intensive and longer duration sampling protocol.

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