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Comparison of brook trout reproductive success and recruitment in an acidic adirondack lake following whole lake liming and watershed liming

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Abstract. Limestone applications to the catchment of one tributary to Woods Lake were highly effective in reducing stream acidity and stabilizing seasonal fluctuations in pH. The resulting improvement in stream water quality also led to a dramatic shift in reproductive strategy of the Woods Lake brook trout population. Prior to catchment liming, brook trout in Woods Lake were restricted to spawning on poor quality near shore substrate with limited ground water seepage. Reproductive success was limited by high mortality of eggs and larvae and recruitment from in lake spawning was not successful. Spawning brook trout did not utilize the tributary for spawning prior to watershed liming. Mitigation of acidity in the tributary, by catchment liming, effectively extended the spawning habitat available to the Woods Lake brook trout population and one year following treatment brook trout spawned successfully in the tributary for the first time in 6 years of observation. Significant recruitment of young trout into the lake population occurred from 1991 through 1993, although the absolute number of fish captured was relatively small. In the fall of 1993, four year classes of naturally spawned brook trout were present in the lake. Although reproductive success was enhanced by improving tributary spawning habitat in the Woods Lake basin, self maintenance of the population may be limited by low recruitment rates of young trout, due to high levels of summer mortality resulting from predation. Mitigation of this constraint would require substantially higher levels of fry production than were observed in Woods Lake and/or enhanced refugia for young trout. The results of this experiment suggest that re-establishment of tributary spawning populations of brook trout may be possible, with future reductions in acidic deposition, in acidic Adirondack lakes with limited in-lake spawning habitat.

Introduction

The brook trout (*Salvelinus fontinalis*) is the primary cold water sport fish indigenous to the small, headwater lakes prevalent in the Adirondack mountain region of New York State. Brook trout were captured in 579 of the 1469 lakes sampled in a recent survey of Adirondack lakes (Kretser et al. 1989). However, brook trout were notably absent from an even greater number of acidic lakes that appeared to have suitable physical habitat (e.g. cool, well oxygenated water) for brook trout survival. Woods Lake is typical of the latter class of acidic Adirondack lakes and it contained no fish species when the Lake Acidification Mitigation Program (LAMP) was initiated in 1984 (Porcella 1989), although Woods Lake did historically support brook trout (Gloss et al. 1987). One of the primary objectives of LAMP for Woods Lake was to assess the efficacy of whole lake liming as a management tool for restoring and sustaining brook trout populations in acidic Adirondack lakes.

Woods Lake was limed twice (May, 1985 and September, 1986) during the LAMP study and stocked annually with brook trout, from 1985 to 1989. The liming treatments were successful in maintaining reduced levels of acidity in the lake, except during spring snow melt periods when near shore areas were temporarily re-acidified (Driscoll et al. 1989; Gubala et al. 1991; Driscoll et al. 1996), and the stocked brook trout cohorts exhibited generally satisfactory growth and survival (Gloss et al. 1989; Schofield et al. 1989; Schofield et al. 1991). However, limited reproductive success and recruitment of young fish were not sufficient to maintain the Woods Lake brook trout population (Gloss et al. 1989; Schofield et al. 1991).

The temporal re-acidification of the near shore spawning areas in Woods Lake was initially thought to be a potential source of mortality of young brook trout and the observed low levels of recruitment. Brook trout fry, confined in cages at shallow depths in the lake during acidic snow melt episodes, experienced high mortality rates, whereas fry placed at greater depths that did not re-acidify had no mortality. However, when brook trout fry were placed in long enclosures, perpendicular to the shore line and transecting the acidity gradient, they avoided the lethally acidic near shore water by moving to depths with higher pH levels (Van Offelen et al. 1994). Gunn & Noakes (1986) also observed that young brook trout avoided acidic water in a controlled laboratory environment. Younger brook trout life stages (eggs and sac fry) confined to shallow near shore areas are not generally exposed to surface water re-acidification, because they remain in the substrate, where acidity levels are low and relatively stable (Gubala et al. 1993). Additionally, peak emergence periods (early to mid May) observed for swim up brook trout fry in Woods Lake (Gloss et al. 1989) are well past the periods of episodic re-acidification (March–April) that have been recorded in Woods Lake (Driscoll et al. 1989; Gubala et al. 1993). Based on these observations and experiments, we conclude that episodic re-acidification of Woods Lake was not a primary reason for the poor reproductive success and low recruitment rates observed for the Woods Lake brook trout population.

Most of the acidic, headwater Adirondack lakes (including Woods Lake) are classified as thin till basins that receive predominantly surface water inflow and relatively little ground water input (Newton et al. 1987). Lake spawning brook trout populations require near shore spawning habitat with suitable substrate (gravel and sand) and adequate (flow and water quality) ground water seepage to sustain developing eggs and larvae (Benson 1953; Webster 1962; Carline 1980; Schofield 1993). The near shore spawning habitat in Woods Lake consists primarily of sand and silt deposits with limited ground water seepage (Staubitz & Zarriello 1989; Gloss et al. 1989). Although these near shore seepage areas in Woods Lake were utilized annually by spawning brook trout, egg and larval survival was very low, based on the absence of emergent fry in traps placed over brook trout redds each spring (Gloss et al. 1989; Schofield et al. 1991). Low ground water seepage velocities and poor substrate quality were the most likely causes of the poor survival of these brook trout early life stages in Woods Lake. Installation of artificial spawning boxes, with gravel substrate and simulated ground water seepage from gravity fed tributary water, resulted in successful spawning and fry emergence the first year after installation (Gloss et al. 1989). Although brook trout continued to utilize both the spawning boxes and the natural seepage areas in subsequent years, siltation of the boxes resulted in a lack of successful fry emergence (Schofield et al. 1991). These observations suggested that physical limitation of the spawning habitat in Woods Lake (inadequate ground water seepage and poor substrate quality) was the primary reason for the lack of successful reproduction.

Two perennial tributaries to Woods Lake have potentially better physical spawning habitat than the in lake areas used for spawning, but these streams are highly acidic and were never utilized by spawning brook trout during the period of the LAMP study. Self sustaining brook trout populations in other Adirondack lakes utilize both near shore seepage zones and tributaries with circumneutral water quality for spawning (Webster 1962; Schofield 1993). We hypothesized that if liming the catchments of the tributaries to Woods Lake resulted in reduced tributary acidity, then the resident brook trout population should exhibit a shift in reproductive strategy from unsuccessful in lake spawning to utilization of higher quality habitat in the tributaries for spawning. In this paper we present observations of the effects of aerial limestone applications to the tributary sub catchments of Woods Lake in the fall of 1989 on brook trout spawning behavior and reproductive success.

Methods

Study sites

The two perennial tributaries of Woods Lake that were limed in the fall of 1989 (Driscoll et al. 1996) are identified in Fig. 1. Also shown are the locations of the downstream outlet trap, lake trap net sites, and the near shore seepage zone

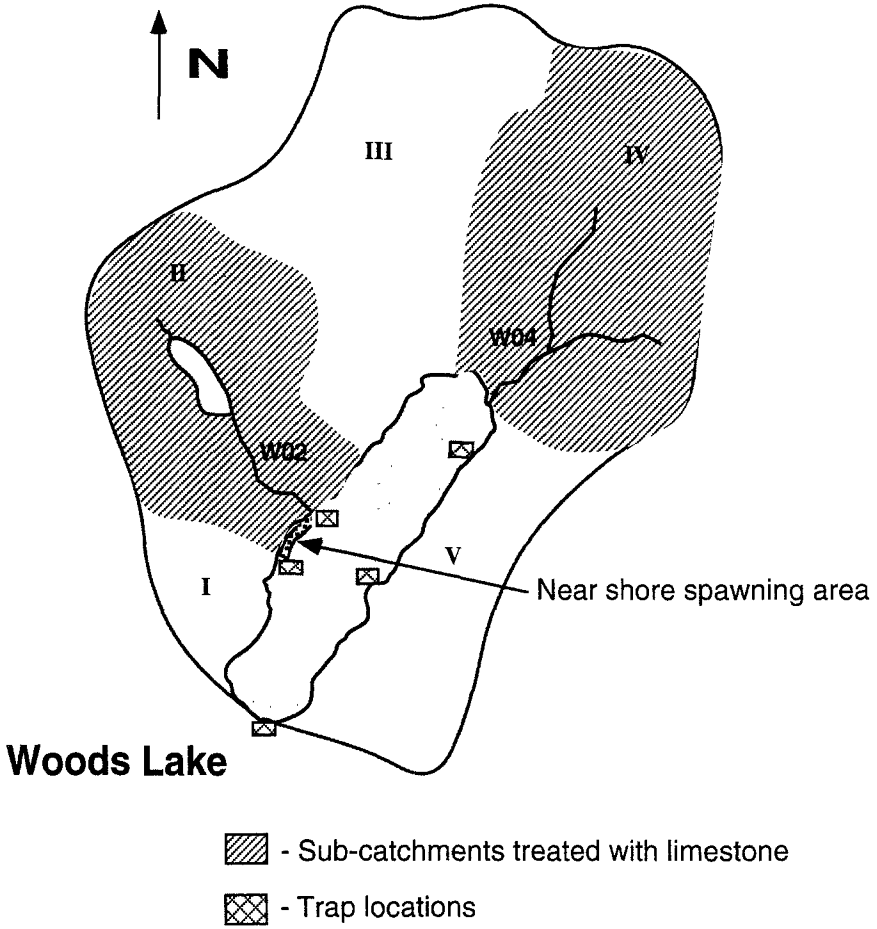

Fig. 1. Woods Lake basin showing locations of treated catchments, near shore spawning area, and trap locations.

utilized by spawning brook trout. The near shore spawning area substrate is predominantly sand and fine silt with mean ground water seepage velocities < 2 cm hr^{-1} (Gloss et al. 1989). Substrate in the two tributaries consists of coarse gravel and cobble upstream of sandy deltas at the confluence of each stream with the lake.

Population assessment

The Woods Lake brook trout population was inventoried each spring and fall from 1985 through 1991 by trap netting, utilizing procedures described by Gloss et al. 1989. Sampling effort was approximately 126 net nights per inventory period. A limited inventory (30 net nights) was conducted in the fall of 1993 by the Adirondack Lake Survey Corporation to assess population age and size structure. Population size was estimated by the Schnabel procedure (Ricker 1975) and survival was estimated by ratio of successive seasonal estimates of population size, for inventories conducted from 1989 to 1991. Length (mm), weight (g), sex, maturity, and fin clips were recorded for all fish captured. With the exception of one cohort of young of year trout stocked in 1985, all stocked cohorts were identifiable by unique fin clips. After determination of age from scale samples to identify year class, all unmarked trout (excluding the 1985 year class) were assumed to have originated from natural reproduction. Brook trout were stocked annually in Woods Lake from 1985 to 1989 (Schofield et al. 1991). An inclined screen outlet trap was used to assess potential emigration loss from the population (Gloss et al. 1989). Adult trout captured in the outlet trap were tagged and returned to the lake.

Spawning success

Visual observations of the tributaries and shoreline of Woods Lake were made at twice weekly intervals from mid October through November each year to monitor spawning activity and inventory redd locations. Fry emergence traps (Stauffer 1981) were placed over identifiable redds (5 to 15) each spring, immediately after ice out, to assess recruitment of swim up brook trout fry. Tributaries were electrofished during June of 1991 to assess brook trout fry abundance and distribution. A downstream barrier was deployed at the mouth of tributary W02 in May 1991 to prevent emigration and immigration of newly hatched fry, prior to the stream electrofishing inventory. Eyed egg survival in the nearshore spawning area and the two tributaries was assessed by placing 5 Plexiglas incubators, containing 50 eyed eggs each, on the substrate in each location during February. Incubators were retrieved in late April after ice out and live and dead eggs were counted to estimate survival.

Results and discussion

Movement and spawning behavior before and after watershed liming

Based on observations from 1985 through 1991, spawning activity, redd construction, and inshore movement of adult brook trout begins in mid October, peaks in late October or early November, and continues until ice up in late November. In most years, outlet trap catches of mature trout have also peaked in association with the increased movement of adult fish during this period (Gloss et al. 1989; Schofield et al. 1991). Total outlet trap catches of mature

Table 1. Estimated number of mature brook trout in Woods Lake during fall trap net inventories, total outlet trap catch, and percent of mature population emigrating, 1985–1991.

Year	Mature fish in lake	Outlet catch	% of mature fish emigrating
1985	447	154	34.4
1986	248	6	2.4
1987	286	79	27.6
1988	182	57	31.3
1989	252	3	1.2
1990	342	230	67.2
1991	217	45	20.7

brook trout from October through November constituted 21 to 68% of the estimated population of mature fish present in the lake, except for 1986 and 1989 (Table 1) when only 2.4% and 1.2% of the mature fish in the lake attempted to emigrate. There was no significant relationship ($P>0.05$) between the number of mature fish in the lake population and the number emigrating. Additionally, there was no apparent relationship between the proportion of the population emigrating and outlet discharge (Gloss et al. 1989; Schofield et al. 1991). However, in both 1986 and 1989 when emigration rates were extremely low, limestone treatments were made just before or during the fall spawning season. These treatments resulted in trends of increasing pH and acid neutralizing capacity (ANC) in the lake and outlet during October and November of each year , whereas in all other years these parameters were decreasing during this period (Driscoll et al. 1989; Cirmo & Driscoll 1996; Driscoll et al. 1996). It is possible that the reversed seasonal trends in pH and related water quality parameters during the fall of 1986 and 1989 inhibited the normal tendency of mature fish to emigrate during the spawning period. Laboratory studies have demonstrated that mature brook trout are attracted to higher pH water and will avoid low pH water when selecting spawning sites (Johnson & Webster 1977; Webster & Eriksdottir 1976).

During the period 1985 to 1989, brook trout were observed spawning only in the nearshore seepage zone, just south of tributary W02 or on the artificial spawning boxes located in the same area (Fig. 1). No adult brook trout were observed in either tributary during this period. In the fall of 1989, brook trout had already initiated spawning and redd construction in the nearshore seepage zone by the time the watershed liming treatments were conducted in mid to late October and no movement of adult trout into the tributaries

Table 2. Winter mortality of eyed brook trout eggs incubated in tributary W02, tributary W04, and the near shore spawning area of Woods Lake.

Year	Near shore area	Trib W02	Trib W04
1989	69.5%	100.0%	100.0%
1990	82.0%	18.0%	70.0%

was observed. However, in the fall of 1990 four mature brook trout were first observed in tributary W02 on October 25. On November 1, seven brook trout were observed spawning in the lower reaches of tributary W02, above the sandy delta at the mouth and a school of approximately 50 adult trout were observed just off the mouth of the stream. Additional spawning trout were observed in tributary W02 until November 5. As noted by Cirmo & Driscoll (1994), tributary W02 had maintained circumneutral water quality since the watershed treatment in 1989. However, no adult fish were observed in tributary W04, which had already re acidified by this time (Cirmo & Driscoll 1996; Driscoll et al. 1996). During this period, spawning activity was also observed in the traditional spawning area in the near shore seepage zone. No further observations of spawning activity were obtained after the fall of 1990, so the extent of tributary utilization for spawning in subsequent years is unknown.

Reproductive success before and after watershed liming

Comparisons of eyed egg survival rates in the nearshore seepage spawning area, tributary W02, and tributary W04 were obtained during the late winter of 1989 and 1990. Eyed eggs placed in tributaries W02 and W04 experienced 100% mortality (Table 2) during the winter of 1989 and all eggs were still in the early eyed stage of development when recovered. Eyed egg mortality in the near shore spawning area during the same period in 1989 was 69.5% and only 9.5% of the eggs had died before hatching. Survivors had hatched and were still in the yolk sac stage of development. Stream and near shore pH levels fluctuated considerably during episodes of snow melt in 1989 and were below pH 5 for extended periods (Cirmo & Driscoll 1996). During the winter of 1990 mortality of eyed eggs in tributary W02 was only 18%, but mortality in W04 was 70% and the eggs in the near shore seepage area experienced 82% mortality (Table 2). Following the watershed liming treatment in the fall of 1989, stream pH levels remained above 6 in W02 and did not decline during high flow periods (Cirmo & Driscoll 1996; Driscoll et al. 1996). Egg survival was dramatically improved in tributary W02 as a result of improved water quality following the watershed liming. However, only a slight improvement in survival of eyed eggs in W04 was observed and egg survival remained low in the near shore spawning area.

As indicated in previous publications (Gloss et al. 1989; Schofield 1991), no emergent fry were ever captured in traps deployed over redds in the near shore seepage zone from 1985 through 1989. Following the watershed liming treatments in the fall of 1989, surficial water quality in the near shore spawning area was improved in comparison to previous years (Gubala et al. 1991; Driscoll et al. 1996). However, there was still no evidence that this change in near shore water quality significantly affected reproductive success in this area, based on a continued absence of emergent fry in spring trapping during 1990 and 1991.

The first evidence of successful reproduction, following the spawning observed in tributary W02 during the fall of 1990, was obtained in the spring of 1991. On may 8 several emergent brook trout fry were observed in the lower reaches of tributary W02 and by May 13 several hundred fry were observed throughout the stream from the mouth to the beaver dam near the headwater pond. No fry were observed around the shoreline of the lake in the nearshore spawning area or in tributary W04. On June 18, tributary W02 was divided into four sections and each section was electrofished to sample the young of year trout. Quantitative population estimates were not possible due to difficulties in sampling the small fish and equipment malfunctions after the first run through each section was completed. A total of 192 brook trout were captured and the distribution of these fish is shown in Fig. 2.

Recruitment of brook trout to the Woods Lake population from lake and tributary spawning

As noted previously, the only successful in lake spawning occurred in Woods Lake during the fall of 1985 on artificial spawning boxes. Gloss et al. 1989 estimated a recruitment of 700 emergent fry to the Woods Lake population, based on fry trap catches on the artificial spawning box in the spring of 1986. Only 10 fish from this year class were captured at age 0+ during the fall trap net inventory of 1986 and 1 fish at age 3+ was captured in the fall of 1989 (Fig. 3). No additional fish from natural reproduction in Woods Lake were captured in any of the intensive netting inventories conducted from 1985 to 1989.

The first year following the watershed liming treatment of 1989, 1 age 0+ fish from the 1990 year class was captured during the fall netting inventory and subsequently 13 fish from this year class were captured at age 1+ in the fall of 1991 and 21 at age 3+ in the fall of 1993 (Fig. 3). The origin

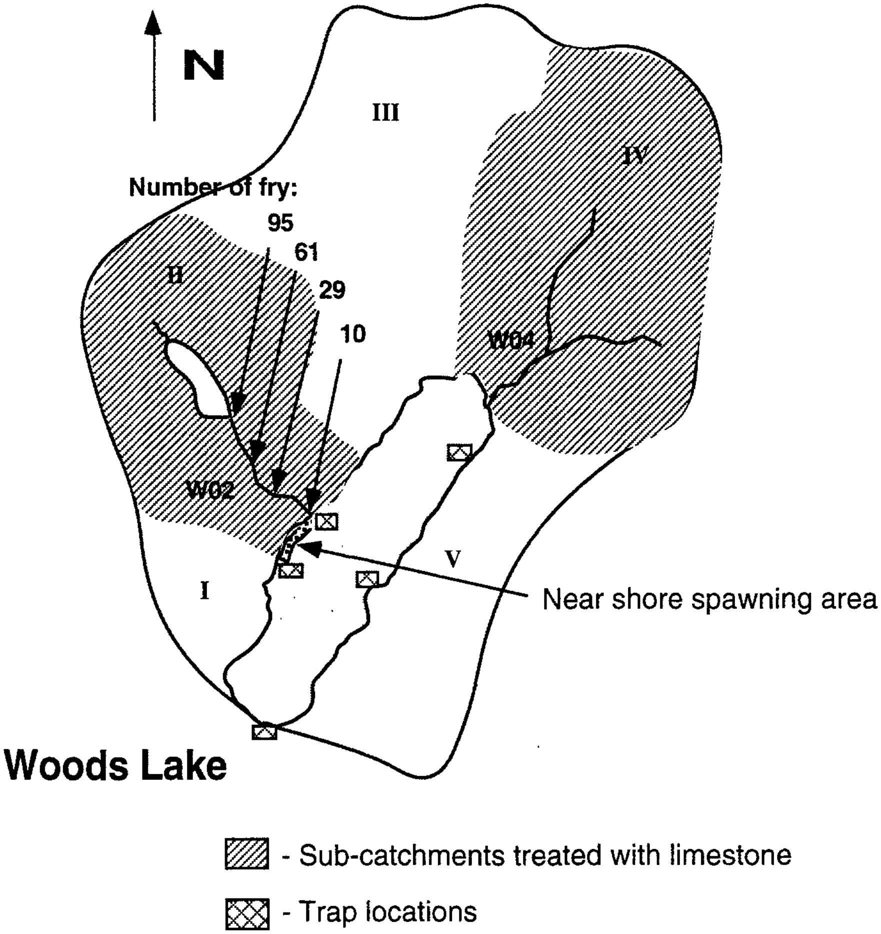

Fig. 2. Number and distribution of brook trout fry captured in tributary W02 in June, 1991.

of these fish is uncertain, as no spawning was observed in either tributary during the fall of 1989. The first evidence of recruitment from the fall 1990 spawning and fry emergence observed in tributary W02 during the spring of 1991 was obtained in the last quantitative inventory conducted in Woods Lake during the fall of 1991, when 4 age 0+ fish from the 1991 year class were captured. The limited inventory conducted by the Adirondack Lake Survey Corporation in the fall of 1993 captured 15 age 2+ fish from the 1991 year class. The 1993 inventory also captured 6 age 0+ fish (in tributary W02) and 9 age 1+ fish that were produced either from spawning in the lake or tributaries in 1992 and 1993 (Fig. 3). The total 1993 catch of 51 fish originating from natural reproduction in the Woods Lake system represents the largest fall catch of naturally reproduced fish in the past 9 years of

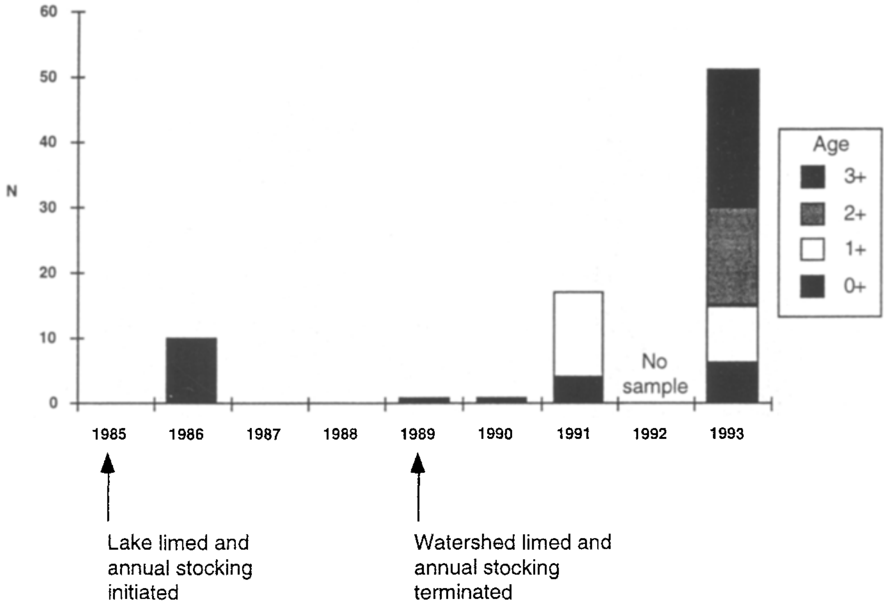

Fig. 3. Number and age of unmarked brook trout from natural reproduction captured in Woods Lake during fall trap net inventories, 1985 to 1993.

inventory. Since the 1993 inventory was a limited effort, compared to previous years, actual catch per unit effort for naturally reproduced brook trout in 1993 was 4 to 20 times greater than any of the previous inventories. The increased numbers of naturally reproduced brook trout captured in Woods Lake following the watershed liming treatment in 1989 may be indicative of improved spawning habitat and reproductive success in the tributary system. However, the relatively low numbers of fish captured suggest that other factors limit survival and recruitment of young brook trout in Woods Lake.

Survival of young brook trout in Woods Lake

Sample sizes of naturally reproduced brook trout captured during trap net inventories were insufficient to make reliable estimates of population size and survival. However, large numbers of brook trout stocked as spring fingerlings in 1985, 1988, and 1989 provided adequate recapture samples for estimation of population size and survival as a function of age and season (Gloss et al. 1989; Schofield et al. 1991). The estimated summer and winter survival rates of these three cohorts of stocked brook trout from age 0 to age 2+ are shown in Fig. 4. The annual survival rates of all stocked cohorts of brook trout from

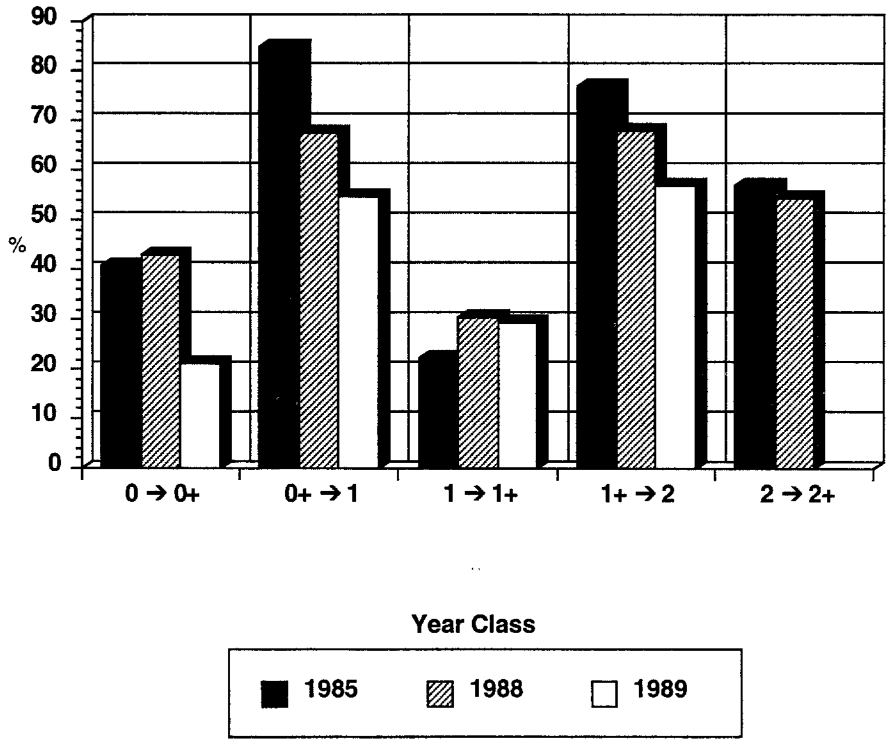

Fig. 4. Summer and winter survival rates, from age 0 to age 2+, for three year classes of brook trout stocked in Woods Lake as spring fingerlings.

Table 3. Estimated first and second year annual survival rates for stocked brook trout stocked in Woods Lake and mean weights at age.

	% Survival		Mean Weight (g)				
Year class	0+ to 1+	1+ to 2+	0+	1	1+	2	2+
1985	18.9	43.6	32	96	193	480	607
1986	24.2	50.6	27	112	250	444	634
1987	20.0	44.2	22	96	200	281	284
1988	20.7	37.0	38	89	152	216	276
1989	16.0	56.9	31	72	171		384

age 0+ to 1+ and age 1+ to age 2+ and mean weights at age are presented in Table 3.

Inspection of seasonal survival rates for brook trout stocked as spring fingerlings (Fig. 4) indicates that survival rates were lowest in the first and particularly during the second summer after stocking and that winter survival

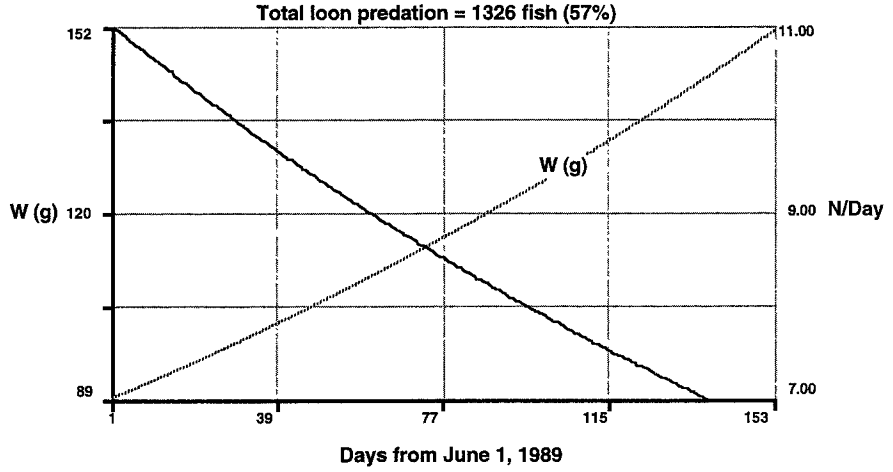

Fig. 5. Simulated daily predation rate by one loon on yearling brook trout from the 1988 year class, in relation to mean yearling weight. Assumed daily loon food requirement to be 1 kg/day. Observed initial number of trout was 2320 and over summer mortality was 69%.

rates were generally higher. Also, second year survival rates (winter and summer) were significantly higher ($P<0.05$) for all year classes of stocked brook trout (Fig. 4 and Table 3). These patterns of survival suggest that size and behavior dependent susceptibility to predation is a major source of mortality and limited recruitment of brook trout in Woods Lake. The relatively shallow, clear water and sparse cover (Particularly as a result of the decline in macrophyte density following liming treatments, Bukaveckas 1988.) are probably major contributors to heavy mortality of young brook trout from avian predators and cannibalism from larger trout. Schofield et al. 1991 noted that 5 to 6 loons from a near by nesting colony on Stillwater Reservoir were frequently observed feeding on Woods Lake during the summer. Young of the year and yearling brook trout in Woods Lake (Table 3) are within the preferred size range (10 to 200 grams) for loons (Barr 1973) and these younger fish also tend to inhabit shallower water than larger trout during the warm summer months (Schofield et al. 1993). An adult loon will consume approximately 1 kg of fish per day (Barr 1973) and assuming a predation period of 5 months, a single bird could consume enough fish to account for about 80% of the observed summer mortality of yearling brook trout in Woods Lake (Fig. 5).

Conclusions

Limestone applications to the catchment of tributary W02 of Woods Lake were highly effective in reducing stream acidity and stabilizing seasonal fluctuations in pH. The resulting improvement in stream water quality also led to a dramatic shift in reproductive strategy of the Woods Lake brook trout population. Prior to the catchment liming, brook trout in Woods Lake were restricted to spawning on poor quality near shore substrate with limited ground water seepage. Reproductive success was limited by high mortality of eggs and larvae and recruitment from in lake spawning was not successful. Mitigation of acidity in tributary W02, by the catchment liming, effectively extended the spawning habitat available to the Woods Lake brook trout population and one year following the treatment brook trout spawned successfully in the tributary for the first time in 6 years of observation. Significant recruitment of young trout into the lake population occurred from 1991 through 1993, although the absolute number of fish captured was relatively small.

The life history pattern and spawning behavior of brook trout present in Woods Lake prior to acidification (Gloss et al. 1987) is unknown. However, based on the lack of reproductive success observed in this study for the lake spawning population and the comparative success of tributary spawning following removal of stream acidity constraints by liming, it seems likely that the historical brook trout population must have been dependent on recruitment from tributary spawning. The majority of currently acidic and fishless Adirondack lakes do not have suitable in lake brook trout spawning habitat, as a result of limited ground water inflows to potential near shore spawning areas (Schofield 1993). Based on the findings of this study, restoration of self maintaining brook trout populations to these acidic lakes may also be dependent on the availability of tributaries with adequate spawning habitat.

The observation of reduced emigration by mature brook trout during years when limestone treatments were made during the spawning season suggested that treatment disturbance, perhaps resulting from a reversal in normal seasonal and spatial water quality patterns, affected the movement pattern of mature trout seeking spawning habitat. The potential loss of mature fish from the population due to emigration can be substantial, based on observations from this study (21 to 67% potential emigration loss of mature fish). Losses of this magnitude could seriously alter age and size structure of the population and perhaps reproductive potential. However, these effects were not experienced by the Woods Lake population during the study because potential emigrants were returned to the lake.

Although reproductive success was improved significantly by improving tributary spawning habitat in the Woods Lake basin, self maintenance of the population may be limited by low recruitment rates of young trout, due to high levels of summer mortality resulting from predation. Mitigation of this constraint would require substantially higher levels of fry production than observed in Woods Lake and/or enhanced refugia for young trout.

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References

Barr JF (1973) Feeding biology of the common loon in oligotrophic lakes of the Canadian Shield. Ph.D. Thesis, University of Guelph, Ontario, 192 pp

Benson NG (1953) The importance of ground water to trout populations in the Pigeon River, Michigan. Trans. North Amer. Wildl. Conf. 18: 269–281

Bukaveckas PA (1988) Effects of calcite treatment on primary producers in acidified Adirondack lakes. I. Response of macrophyte communities. Lake Reserv. Manage. 4: 107–113

Carline RF (1980) Features of successful spawning site development for brook trout in Wisconsin ponds. Trans. Amer. Fish. Soc. 109: 453–457

Cirmo CP & Driscoll CT (1996) The role of a beaver impoundment in regulating stream chemistry after a watershed calcium carbonate treatment. Biogeochemistry 32: 265–297 (this volume)

Driscoll CT, Ayling WA, Fordham GF & Oliver LM (1989) Chemical response of lakes treated with $CaCO_3$ to re acidification. Can. J. Fish. and Aquat. Sci. 46: 258–267

Driscoll CT, Cirmo CP, Fahey TJ, Blette VL, Burns DJ, Gubala CP, Newton RM, Raynal DJ, Schofield CL, Yavitt JB & Porcella DB (1996) The experimental watershed liming study (EWLS): Comparison of lake/watershed base neutralization strategies. Biogeochemistry 32: 143–174 (this issue)

Gloss SP, Schofield CL & Spateholts RL (1987) Conditions for re-establishment of brook trout (*Salvelinus fontinalis*) populations in acidic lakes following base addition. Lake Reserv. Manage. 3: 412–420

Gloss SP, Schofield CL, Spateholts RL & Plonski BA (1989) Survival, growth, reproduction, and diet of brook trout (*Salvelinus fontinalis*) stocked into lakes after liming to mitigate acidity. Can. J. Fish. Aquat. Sci. 46: 277–286

Gubala CP, Driscoll CT, Newton RM & Schofield CL (1991) Chemistry of a near-shore lake region during spring snowmelt. Environ. Sci. Technol. 25(12): 2024–2030

Gubala CP, Driscoll CT, Newton RM & Schofield CL (1993) Device for finely resolved sampling of littoral lake regions: Design and operation. Hydrological Processes 7: 99–104

Gunn, JM & Noakes LG (1986) Avoidance of low pH and elevated Al concentrations by brook charr (*Salvelinus fontinalis*) alevins in laboratory tests. Water, Air and Soil Pollution 30: 497–503

Johnson DW & Webster DA (1977) Avoidance of low pH in selection of spawning sites by brook trout (*Salvelinus fontinalis*). J. Fish. Res. Board Can. 34: 2215–2218

Kretser W, Gallagher J & Nicollette J (1989) Adirondack lakes study, 1984-1987: An evaluation of fish communities and water chemistry, summary report, Adirondack Lakes Survey Corp., 345 pp, Ray Brook, NY

Newton RM, Weintraub J & April R (1987) The relationship between surface water chemistry and geology in the North Branch of the Moose River, Biogeochemistry 3: 163–180

Porcella DB (1989) Lake Acidification Mitigation Project (LAMP): an overview of an ecosystem perturbation experiment. Can. J. Fish. Aquat. Sci. 46: 246–248

Ricker WE (1975) Computation and interpretation of biological statistics of fish populations. Fish. Res. Bd. Can. Bull. 191. 382 pp

Schofield CL, Gloss SP, Plonski B & Spateholts RL (1989) Production and growth efficiency of brook trout (*Salvelinus fontinalis*) in two Adirondack Mountain (New York) lakes following liming. Can. J. Fish. Aquat. Sci. 46: 333–341

Schofield CL, Keleher C & VanOffelen H (1991) Population dynamics of brook trout (*Salvelinus fontinalis*) during maintenance liming of an acidic lake. Water, Air, and Soil Pollution 59: 41–53

Schofield CL (1993) Habitat suitability for brook trout (*Salvelinus fontinalis*) reproduction in Adirondack lakes. Water Resources Research, 29(4): 875–879

Schofield CL, Josephson D, Keleher C & Gloss SP (1993) Thermal stratification of dilute lakes – An evaluation of regulatory processes and biological effects before and after base addition: Effects on brook trout habitat and growth. U.S. Fish and Wildlife Serv., National Ecology Research Center-Leetown, Kearneysville, W.Va. Biological Report 9, 36 pp

Staubitz WW & Zarriello PJ (1989) Hydrology of two headwater lakes in the Adirondack Mountains of New York. Can. J. Fish. and Aquat. Sci. 46: 268–276

Stauffer TM (1981) Collecting gear for lake trout eggs and fry. Prog. Fish. Cult. 43: 186–193

Webster DA (1962) Artificial spawning facilities for brook trout, *Salvelinus fontinalis*. Trans. Amer. Fish. Soc. 91: 169–174

Webster DA & Eriksdottir G (1976) Upwelling water as a factor influencing choice of spawning sites by brook trout (*Salvelinus fontinalis*). Trans. Amer. Fish. Soc. 105: 416–421

Van Offelen HK, Krueger CC, Schofield CL & Keleher C (1994) Survival, Distribution, and Ion Composition in Two Strains of Brook Trout Fry After Exposure to Episodic pH Depressions in an Adirondack Lake. Canadian Journal of Fisheries and Aquatic Sciences 51(4): 792–799