

# **Temporal Patterns in Breeding Success of Common Loons in Ontario, 1981-1997**

Final report

to

Canadian Wildlife Service  
Ontario Region  
49 Camelot Drive  
Nepean, Ontario K1A 0H3

By

Russ C. Weeber  
Aquatic Surveys Coordinator  
Bird Studies Canada  
P.O. Box 160  
Port Rowan, Ontario N0E 1M0



Canadian  
Wildlife  
Service



31 March 1999

Please cite as:

Weeber, R. C. 1999. Temporal patterns in breeding success of Common Loons in Ontario, 1981-1997.

Unpublished report by Bird Studies Canada to Canadian Wildlife Service, Ontario Region.

## Table of Contents

List of Tables and Figures .....	iii
Introduction .....	1
Methods.....	2
<i>Data collection</i> .....	2
<i>Data selection</i> .....	3
<i>Data coding</i> .....	4
<i>Temporal variation</i> .....	4
<i>Effects of pH</i> .....	5
<i>Effects of human disturbance</i> .....	5
<i>Geographic variation</i> .....	6
<i>Within-lake and within-year analyses</i> .....	6
<i>Power analyses</i> .....	6
Results .....	8
<i>Data summary</i> .....	8
<i>Temporal variation in loon breeding success</i> .....	9
<i>Effects of pH</i> .....	9
<i>Temporal variation in pH effects</i> .....	9
<i>Within-lake temporal variation in pH effects</i> .....	10
<i>Effects of disturbance</i> .....	10
<i>Geographic variation</i> .....	11
<i>Power to detect trends</i> .....	11
Discussion .....	12
Future Monitoring .....	15
<i>Extensive and intensive monitoring strategies</i> .....	15
<i>The CLLS as a tool for monitoring loon productivity</i> .....	16
<i>Recommendations for future survey design</i> .....	19
Acknowledgements .....	20
Literature Cited .....	21
Appendix A .....	41

## List of Tables and Figures

- Table 1. Sample sizes based on lake-years (i.e. each surveyed lake counting as one observation each year) expressed in terms of pair numbers and breeding success, before and after removal of records with missing lake area and pH.
- Table 2. Sample sizes, expressed in terms of lake-years, for variables describing lake characteristics before and after removal of records with missing lake area and pH values. Annual number of lakes in each lake descriptor class reflect sample sizes used for within-lake analyses.
- Table 3. Number of lakes used in logistic regression models, summarised for two time periods by the number of years surveyed, lake pH and area class.
- Table 4. Results of logistic regression models testing for the effects of lake area and pH on loon breeding success after controlling for annual variation.
- Table 5. Results of logistic regression models testing for varying effects of pH among years after controlling for lake area.
- Table 6. Results of logistic regression models testing for linear trends and differences in trends among pH classes, in the proportion of loon pairs with at least one large young.
- Table 7. Results of logistic regression models testing for within-lake variability in the effects of pH among years. Only lakes surveyed for two or more years between 1987 and 1997 were included in analysis.
- Table 8. Results of logistic regression models testing for within-lake linear trends in the proportion of loon pairs with at least one large young. Only lakes surveyed for two or more years between 1987 and 1997 were included in analysis.
- Table 9. Results of logistic regression models testing the contributions of shoreline development and human activity on loon breeding success after controlling for annual variation and lake area and pH.
- Table 10. Results of logistic regression models testing for the effects of latitude on loon breeding success after controlling for annual variation and lake area and pH.
- Table 11. Comparison of the change that could be detected with various sample sizes, based upon sampling the same lakes repeatedly over time, versus selecting new lakes each year. Numbers represent the percentage change in the mean proportion of pairs with at least one large young, that could be detected over a one-year interval (i.e. two survey years) with various sample sizes, assuming  $\alpha=0.05$ ,  $\beta=0.80$ . Variance estimates for the within-lake analyses were obtained from sample CLLS data from 1987-1997 considering changes between pairs of years on all lakes surveyed for two consecutive years. Variance estimates for the among-lake analyses were obtained by including all lakes from 1987-1997, and considering each lake-year as a separate sample. Estimates are back transformed from a logit scale, as described in the text.

- Table 12. Estimated percent change in productivity in mean proportion of pairs with at least one large young that could be detected ( $\alpha=0.05$ ,  $\beta=0.80$ ), assuming a logit-linear decline in productivity over periods ranging from two to 11 years. Variance estimates for the power analyses were obtained from observed variances of within-lake changes in CLLS data for the relevant time periods from 1987-1997. These analyses assume that all lakes are surveyed each year, although similar results would be expected if new lakes were surveyed each year (Table 11). Percent change is expressed in two ways: the annual change that could be detected over each time period, and the aggregate change that this represents over the survey period.
- Figure 1. Locations of Canadian Lakes Loon Survey lakes used in analysis of temporal patterns in Ontario loon breeding success, 1981 - 1997.
- Figure 2. Mean proportion ( $\pm$  2 standard errors) of pairs observed with at least one large young, 1981-1997.
- Figure 3. Mean proportion ( $\pm$  2 standard errors) of successful pairs observed with at least two large young, 1981-1997.
- Figure 4. Mean proportion of pairs with at least one large young, by lake pH class, 1981-1997.
- Figure 5. Mean proportion of successful pairs observed with at least two large young, summarised by lake pH class, 1981-1997. Means differed among pH classes in two years (1993:  $X^2=6.4$ , 2df,  $p=.0407$  and 1994:  $X^2=13.22$ , 2df,  $p=.0013$ ).
- Figure 6. Predicted probabilities of at least one successful pair, by lake pH class, 1981-1997. Probabilities were generated by logistic regressions controlling for lake area and done by pH class. (Lines smoothed using spline fit and tension parameter of 70.)
- Figure 7. Predicted probabilities of at least one successful pair, by lake pH class, 1987-1997. Using data collected during this time period, probabilities were generated by logistic regressions controlling for lake area and done by pH class. (Lines smoothed using spline fit and tension parameter of 70.)
- Figure 8. Locations of lakes in each of three pH classes.
- Table A1. Spearman correlations among covariates used in modelling loon breeding success (correlation coefficient / p / sample size).
- Figure A1. Relationship between pH and area (log transformed) of Ontario CLLS lakes 1981-1997.
- Figure A2. Mean ( $\pm$  2 standard errors) pH of Ontario CLLS lakes in each year 1981-1997.
- Figure A3. Mean ( $\pm$  2 standard errors) area of Ontario CLLS lakes in each year 1981-1997.
- Figure A4. Mean ( $\pm$  2 standard errors) shoreline development class of Ontario CLLS lakes in each year 1981-1997.
- Figure A5. Mean ( $\pm$  2 standard errors) human activity class of Ontario CLLS lakes in each year 1981-1997.

## Introduction

Two decades ago, damage from acidifying inputs to lakes in eastern Canada and northeastern United States stimulated a concern for the lakes, streams, forests and wildlife of the region (Haines 1981, Longcore et al. 1993). Documentation of the impacts to aquatic systems and their wildlife during the early 1980's led to the initiation in 1987 of Environment Canada's Long Range Transport of Air Pollutants (LRTAP) Biomonitoring Program (McNicol et al. 1995a). The Common Loon (*Gavia immer*), which is strongly dependent on lake food webs during the breeding season, was recognised as a potential indicator of lake health and its breeding success was identified as an important measure for inclusion in LRTAP monitoring. The Canadian Lakes Loon Survey (CLLS) was initiated in 1981 by Bird Studies Canada (then Long Point Bird Observatory), Environment Canada (Canadian Wildlife Service – Ontario Region), the Ontario Ministry of Natural Resources and other co-operators, and the program was integrated into Environment Canada's biomonitoring in 1987. The program's objectives were to monitor Common Loon breeding productivity on Canadian lakes, through the use of volunteers, and to provide information on the effects of acid precipitation, human disturbance and other factors on breeding loons. The CLLS has served an important role in lake biomonitoring by providing information on regional patterns in loon breeding success and has contributed to an improved understanding of relationships between lake acidity and loon breeding success (McNicol et al. 1995b).

Due to broad habitat preferences, high adult survival rates, and low reproductive rate (one, two or occasionally three chicks annually), population size of Common Loons is unlikely to change rapidly, and hence may not be an ideal measure for rapidly assessing changes in lake health. However, annual reproductive rate, measured as the proportion of pairs fledging chicks each year, can be a much more sensitive and immediate indicator of the status of lakes and their food webs (Strong 1990, Belant et al. 1993). Data on the breeding success of loons thus has the potential to provide information necessary for monitoring the status of lakes and their food webs relative to acidifying inputs.

Previous analyses have shown that loons are less likely to nest on very acidic ( $\text{pH} < 5.5$ ) lakes, tend to be less successful in rearing two-chick broods on acid lakes (McNicol et al. 1995b), and have higher brood mortality in general on acid lakes (Alvo et al. 1988). Direct toxicological impacts (e.g. mercury poisoning) associated with acidification of lakes have also been documented and can also lead to increased mortality of eggs, young and adults (Frank et al. 1983, Scheuhammer and Blancher 1994).

In addition to adverse effects of lake acidification and pollution, there are other documented or suspected impacts to loons associated with human activity and development. Lead poisoning due to the ingestion of fishing sinkers, entanglement in discarded fishing line, or incidental mortality from hunting may also increase loon mortality rates (McIntyre and Barr 1997, Twiss and Thomas 1998). Loss of nesting sites due to the development of lake shorelines, or disturbance to nests or chicks on lakes with intensive human activity may also affect the ability of loon pairs to successfully raise young (Titus and VanDruff 1981, Heimberger et al. 1983).

The value of the CLLS for monitoring loon productivity lies not only in demonstrating that lake acidification affects loon breeding success, but also in measuring how this relationship changes with time. An improved understanding of temporal patterns in loon breeding success, particularly with regard to lake chemical status and human disturbance, has the potential to identify how lakes are changing in their ability to support breeding loons and, by inference, other lake-dependent wildlife. Identification of these temporal patterns and the lake types most at risk can be used to call attention to reproductive problems in Ontario's loons, adjust monitoring strategies, and support alterations in lake and emissions management. The objectives of the analyses presented here were to use indices of loon breeding success from the Ontario portion of the CLLS database to:

1. estimate the magnitude of annual variation in loon breeding success;
2. re-evaluate the effects of lake acidity on loon breeding success and how this has changed over time;
3. estimate the effects of human disturbance, as measured by shoreline development and human activity, on breeding success; and
4. based on these analyses, make recommendations concerning the contribution made by surveys of breeding loons to future lake biomonitoring in Ontario.

## **Methods**

### *Data collection*

Data collection for the CLLS relies mainly on volunteers, primarily those with a cottage or home on a lake, although additional data were collected in some years by paid staff of Bird Studies Canada or CWS. Volunteers were allowed to make their own selection of a lake or portion of a lake to survey. Participants were asked to observe the loons whenever possible with, as a minimum, observations at least once during

each of three time periods corresponding to the Common Loon breeding cycle: nesting (early June to mid-July), hatching (early to late July) and when the young should be near fledging, at six weeks of age or older (mid-August to mid-September). During each survey, observers recorded the number of loon pairs and, for each pair, the number and age/size class of chicks. Survey training materials instructed volunteers to class chicks that were at least two-thirds adult size and had a full coat of light and dark grey feathers as Large Young (LY) (i.e. six weeks old or older).

Volunteers also provided measures of potential human disturbance by shoreline development (e.g. cottages, homes, marinas) and monthly (April through September) ratings of human activity on the lake (e.g. canoeing, power boating, water skiing). Shoreline development was assigned to four classes, with each class representing a 20 percent increase in the percent of lake shoreline containing human development (e.g. class 0: 0-20%, class 1: 21-40%, etc.). Human activity was classified by increasing intensity as follows:

1. No people, no boats.
2. People but no boats.
3. Occasional use of boats without motors.
4. Frequent use of boats without motors.
5. Occasional use of boats with motors.
6. Frequent use of boats with motors.
7. Occasional water skiing and/or boat racing.
8. Frequent water skiing and/or boat racing.

Further details on the survey method are described by Wayland and McNicol (1990).

Lake pH values were provided through the water chemistry component of Environment Canada's lake biomonitoring program. Lake surface area was taken from the Gazetteer of Canada (Natural Resources Canada 1997).

#### *Data selection*

Data used for this analysis were CLLS records collected on Ontario lakes from 1981 through 1997. Data quality ratings, assigned by CLLS staff prior to data entry, were used to include only those records with sufficient observations to assess reproductive success (data quality code 1 or 2) and to select the best record among duplicate observations of lakes or sections of lakes within years. Common Loon clutch size is usually one or two, rarely three, eggs (McIntyre and Barr 1997). Because records of pairs with more than three young probably represented either unusual events or errors in observations, these records

were removed prior to calculating indices of breeding success. Ratings of human activity were highly correlated among months, so ratings for the month of August were arbitrarily selected as the measure of human activity for these analyses.

#### *Data coding*

Lake surface area values (hectares) were log transformed for modelling purposes. Because pH values on an individual lake varied little among years and were missing for some lakes in some years, the mean pH for each lake was used for all years. For some analyses, this fixed value was used to assign each lake to one of three pH classes: acidic ( $\text{pH} < 6$ ), neutral ( $\text{pH} 6 \text{ to } 8$ ), and alkaline ( $\text{pH} \geq 8$ ). The total number of pairs observed with at least one LY (i.e. number of successful pairs:  $N_{\text{succ1}}$ ), the number of pairs observed with at least two LY ( $N_{\text{succ2}}$ ), and the total number of pairs observed ( $TotPrs$ ) were calculated for each lake in each year surveyed. Two statistically independent indices of breeding success were considered:

1.  $P_{\text{succ1}}$ : the proportion of pairs with at least one LY. This index was the number of pairs observed with at least one LY (i.e. successful pairs) as a proportion of the total number of pairs observed on the lake (i.e.  $N_{\text{succ1}}/TotPrs$ ).
2.  $P_{\text{succ2}}$ : the proportion of successful pairs with at least two LY. This index was the number of pairs observed with two or three LY expressed as a proportion of the number of successful pairs (i.e.  $N_{\text{succ2}}/N_{\text{succ1}}$ ).

Because these response variables were proportions of the number of pairs observed on each lake, lakes with no pairs observed during a survey year were removed on a year-by-year basis prior to calculating proportions.

#### *Temporal variation*

Response variables were proportions reflecting the success or failure of loon breeding success, a distribution assumed to be approximately binomial. To model binomial data using generalised linear modelling procedures, the usual link function to associate the probability of a particular outcome with predictor variables is the logit (i.e.  $\log(\text{mean}/1-\text{mean})$ ) (Collett 1990). Logistic regression models using year as a class variable were used to test for the presence of annual variation in loon breeding success. Models with year as a continuous variable were used to test for trends, defined here as approximately linear (on a logit scale) changes in mean response value through time. All models were fit using PROC GENMOD (SAS Institute 1997) with a binomial error distribution and logit link functions specified. Response variables in the form of proportions frequently exceed the variability expected from an underlying binomial distribution (i.e. overdispersion) (Collett 1991). In the case of the CLLS, some

degree of overdispersion seems likely, because the measured fates of different pairs of loons on an individual lake are unlikely to be independent. Goodness-of-fit tests provided by PROC GENMOD suggested that there was, in fact, moderate overdispersion in the distributions of both Psucc1 and Psucc2. To correct for this, likelihoods, chi-square values, and standard errors were scaled by the amount of overdispersion using the DSCALE option in PROC GENMOD (SAS Institute 1997). To test for the significance of individual terms in the model, likelihood ratio tests were used to compare models with the additional terms against models without those terms (Collett 1991, SAS Institute 1997).

### *Effects of pH*

To test for the effects of lake acidity on loon reproductive success, it was necessary to also consider lake area, which could influence loon breeding success, and was correlated with lake pH (Appendix A). Initially, simple effects of acidity were tested using models that incorporated both lake area as well as year effects as covariates. Models considering year as both a class variable and a continuous variable were tested. To test whether the effects of pH varied among years (i.e., lake acidity had a greater impact on reproductive success in some years than others), regression models incorporating a year\*pH interaction were tested. Two types of tests were constructed. The first considered year as a class variable, which assumes no structure in the pattern of variation (i.e., the effects of pH may vary among years, but without necessarily having a consistent trend over time). The second modelled year as a continuous variable, which tests whether the effect of pH changed in a systematic fashion (either increasing or decreasing) over time. These tests were initially carried out treating pH as a continuous variable (which assumes a logit-linear relationship between pH and breeding success), but were also done using the three pH classes. The use of classes makes fewer assumptions about the structure of the relationship, and has the added advantages that the results can be readily graphed, but may be less sensitive because of the arbitrary nature of the classification.

### *Effects of human disturbance*

The effect of lake shoreline development on loon breeding success was tested with logistic regression models using year as a class variable. Similar models were used to test the effect of various levels of human activity on loon breeding success. Because human development and activity patterns are likely to vary with both lake area and pH, these parameters were tested after taking into account the effects of lake acidity, lake area and temporal variation (i.e. testing for residual variation related to human disturbance).

### *Geographic variation*

Lakes of varying acidity are not randomly distributed throughout Ontario, in part because their distribution depends upon the distribution of acidifying inputs, and on the prevailing soil types in each region. Thus, trends in loon productivity on lakes of various acidity levels could be confounded with geographical variation. To test for this effect, two approaches were considered. The first was to test whether there were any north-south gradients in productivity, by testing whether latitude was correlated with loon breeding success. The second was to repeat the analysis testing for pH effects with a subset of lakes in central Ontario where acid and neutral lakes appeared to be relatively interspersed.

### *Within-lake and within-year analyses*

Although some lakes were surveyed on multiple occasions, many were surveyed only once. Because these new lakes were not randomly selected each year, it is conceivable that changes in the distribution of surveyed lakes over time, if there were undetected geographic variation in breeding success, could cause some of the observed annual variation in breeding success. To test for, and control for this problem, analyses were also carried out within lakes that were surveyed for multiple years. To do this, regressions were run incorporating a lake identification term as a class variable. Due to sample size considerations, these within-lake analyses were run only for lakes surveyed between 1987 through 1997. Within this time period, all lakes surveyed for at least two years during that time were included. As in the more general models which incorporated all of the data, within-lake models were run using year both as a class variable and as a continuous variable, and interactions were tested with pH for both of these cases.

An opposite problem arises for testing the effects of parameters such as pH, in models that are testing for the effects of pH alone, irrespective of temporal variation (i.e. testing for pH not year\*pH). In this case, lakes that are surveyed in multiple years contribute many times to the analyses and, to the extent that responses on those lakes are correlated from one year to the next, could inflate sample sizes with non-independent points (pseudo-replication). Although this is not a problem for trend analysis, tests were also run to look at the effect of pH considering each year separately, thus ensuring that each lake was included only once in each analysis.

### *Power analyses*

Two survey designs were considered to estimate the statistical power with which CLLS data could be used to measure temporal trends in loon breeding success. For both analyses, variance estimates were obtained using CLLS data from 1987-1997. The first design was a "lake-year design", which assumed an analysis that considered the number of lakes surveyed each year, irrespective of whether the same or

different lakes were surveyed in each year. The assumption was that analysis for this lake-year design would involve using PROC GENMOD and a model statement with year as the main covariate to test for differences in breeding success between any two years. Pilot data were generated using data from each of the 10 pairs of successive years from 1987 – 1997 (e.g. 1987 versus 1988, 1988 versus 1989, etc.). The variance for each pair of years was calculated as the square of the estimated standard error of the year term, multiplied by the sample size in that year. The weighted mean of the 10 variance estimates was then calculated (based on sample size) and used in the power analyses. For sample sizes ranging from 50 to 1000 lakes per year, this variance estimate was used with the standard power equation to calculate the estimated difference detectable. The power equation used was:

$$Diff^2 = \frac{(Z_{\alpha} + Z_{\beta})^2 * Var}{n}$$

where,  $n$  = number of lakes per year,  $\alpha = 0.05$ ,  $\beta = 0.80$ , and  $Diff$  = estimated detectable difference. Because this difference value is estimated on a logit scale, it can be difficult to interpret the result unless it is backtransformed to the original scale. To do this, we transformed  $Diff$  using the equation:

$$Diff = \frac{\exp^{(-Diff)}}{1 + \exp^{(-Diff)}}$$

This represents the magnitude of decline that could be detected over the given time period assuming the breeding success in the first year was 0.5 (which represents 0 on the logit scale).

The second design was a within-lake design. This involved the assumption that the same lakes would be surveyed every year, and annual variation would be estimated by measuring variation within lakes. Again, pilot data were obtained from CLLS 1987-1997 data, using PROC GENMOD, this time with model statements including lakes as a class variable. The variance of the estimated change in productivity over time was estimated using lakes surveyed for various durations ranging from two consecutive years through the full 11 years of the survey period. As in the first analysis, all permutations were calculated for all different starting years (i.e., 10 slope estimate for lakes surveyed in two consecutive years, nine estimates for each of the nine periods with three consecutive years of surveys, etc.). As in the previous analyses, a weighted mean of variance estimates was calculated for each survey duration. Using sample sizes ranging from 50 to 1000 lakes per year, these variance estimates were used in the power equation above to generate an estimated percent annual change that could be detected at  $\alpha = 0.05$ , with power  $\beta = 0.80$ , assuming the same lakes were surveyed every year for the given number of years. As above, values were back-transformed from the logit scale for presentation.

## Results

### *Data summary*

The analyses presented here include both a lake-year approach (i.e. treating each lake-year combination as a single observation) and the more conservative within-lake approach. Thus, data were summarised from both perspectives. Loon data were available for 4212 lake-years but only 3600 lake-years had pH and area values. The majority (70%) of observations were of single pairs (Table 1). For 60 percent of lake-years at least one pair with at least one LY was observed (Table 1). About one-third (29%) of records referred to lakes on which at least one pair with at least two LY had been observed. Most records (78%) were for lakes classified as neutral, with fewer in the alkaline and acidic pH classes (14% and 9% respectively) (Table 2). Although most records were for lakes between 55 and 400 hectares in size, lake-years were fairly evenly distributed across lake size classes. The majority of records were for lakes with very little shoreline development but most records were for lakes with relatively high levels of human activity (Table 2).

The number of lakes surveyed varied among years, with the number of lakes lower during the period 1981-1986 relative to 1987 onwards (mean number lakes/year = 68 versus 290, respectively) (Table 2). The increase in the number of lakes surveyed from 1987 onwards was due to a concerted effort by Bird Studies Canada and the Canadian Wildlife Service to expand the survey in 1987 (see Wayland and McNicol 1990). Because of the increased sample size from 1987 onwards, analyses were carried out both considering all years, and considering only 1987 through 1997. In total, 1047 lakes were included in modelling datasets considering all years, and 944 lakes for models testing 1987-1997 patterns (Figure 1, Table 3). Thirty-seven percent of lakes were surveyed in only one year and another 20 percent surveyed for only two years (Table 3). Percentages were similar when only the 1987-1997 period was considered. The majority of lakes had pH levels approximately neutral (pH 6-8) and most were between 55 and 400 hectares in size, although substantial numbers were available in smaller and larger size classes (Table 3). In general, the percent of lakes surveyed in multiple years and in each pH and size class were similar between the full and 1987-1997 time periods (Table 3).

Higher lake pH was weakly but highly significantly correlated with larger lakes (Table A1, Figure A1), greater shoreline development, more intensive human activity and year (Figure A2) and was fairly strongly negatively correlated with latitude (Table A1). Larger lakes were associated with more intensive shoreline development and human activity, and increasing latitude (Table A1) but annual mean lake size did not change linearly over time (Table A1, Figure A3). Shoreline development was positively

correlated with human activity and negatively associated with latitude (Table A1). Annual mean values of shoreline development and human activity classes did not exhibit an obvious trend through time (Table A1, Figures A4, A5).

#### *Temporal variation in loon breeding success*

The mean proportion of pairs observed with at least one LY varied among years from 0.22 to 0.77 (overall mean = 0.52,  $n=3600$ ) ( $X^2=193.58$ , 16 df,  $p=0.0001$ ), with 1997 apparently a particularly bad year (Figure 2). Mean Psucc1 also varied significantly among years during the 1987-1997 time period ( $X^2=189.09$ , 10 df,  $p=0.0001$ ). When temporal effects were constrained to linear, there was a significant negative trend in Psucc1 over the full 17 years (slope on logit scale =  $-0.0581$ ,  $X^2=54.86$ , 1df,  $p=0.0001$ ) and a stronger negative trend for the 1987-1997 time period (slope on logit scale =  $-0.1261$ ,  $X^2=130.75$ , 1df,  $p=0.0001$ ). However, these models were not as good a fit as models allowing loon breeding success to vary among years (comparison of annual variation to linear trend: all years  $X^2=138.72$ , 15 df,  $p=0.0001$ ; 1987-1997 only  $X^2=58.34$ , 9 df,  $p=0.0001$ ).

Among successful pairs, the proportion observed with at least two LY appeared to vary among years from 0.30 to 0.57 (overall mean = 0.42,  $n = 2157$ ) but this variation was not statistically significant (all years:  $X^2=12.97$ , 16df,  $p=0.675$ ; 1987-1997:  $X^2=4.47$ , 10df,  $p=0.924$ ) (Figure 3). There was no evidence for a temporal trend in Psucc2 for either the full or later time period ( $X^2=0.0664$ , 1df,  $p=0.7971$  and  $X^2=0.1842$ , 1df,  $p=0.6678$ , respectively).

#### *Effects of pH*

Because lake area and pH were correlated (Figure A1), and because lake area could also influence loon productivity, it was necessary to consider lake area in the models testing for the effects of pH on loon breeding success. Lake area was significantly related to loon breeding success (Table 4), but even after controlling for annual variation and lake area, pH was highly significantly related to Psucc1 over the full 17 years and during the 1987-1997 period (Table 4). Lake pH had a similar significant relationship with Psucc2 (Table 4). There was no evidence for variation in pH effects among lakes of varying size for either Psucc1 or Psucc2 (non-significant pH\*lake-size interaction term; Table 4).

#### *Temporal variation in pH effects*

Within each acidity class, mean Psucc1 and Psucc2 appeared to vary considerably among years (Figures 5 and 6). Variation appeared to be particularly large in the acid class prior to 1987, but sample sizes in this class were very small during this period (Table 2), and much of this variation may have been due to

sampling error. Analyses of each year separately indicated that differences in mean Psucc1 among pH classes were significant in 1987, 1990, and 1994 through 1996 (Figure 4). In 1987, breeding success on acidic lakes was higher than that on neutral lakes, but from 1988 onwards, breeding success on acidic lakes was similar to or below mean values for neutral and alkaline classes (Figures 5 and 6). Mean Psucc2 differed significantly among pH classes in 1993 and 1994 (Figure 5).

To test whether this year to year variation was significant, a model was developed including a year class\*pH interaction. For all years and just 1987-1997, this model was a significantly better fit than a model without an interaction term, indicating that the effects of pH were not the same in all years (Table 5). Patterns were similar when pH was considered as a class and as a continuous variable (Table 5), suggesting that the relationship with pH was approximately linear, but also that grouping pH into classes for graphical purposes provides a reasonable representation of the pattern. In contrast, for Psucc2, although the proportion of broods with two young was lower on acid lakes, there was no evidence that the effect of acidity varied among years (non-significant interaction term; Table 5).

Tests for logit linear temporal changes in Psucc1 indicated that over the full 17 year period, trends differed among pH classes (Table 6, Figure 6). Post-hoc contrasts indicated that slopes for acid and neutral pH classes were significantly different from zero, and although they were not significantly different from each other, both were different from that for the alkaline class (Table 6). Generally similar patterns were observed when only the time period 1987-1997 was considered: trends in Psucc1 varied among pH classes and slopes for all three pH classes differed significantly from zero; only acid and alkaline classes differed significantly in slope (Table 6, Figure 7).

#### *Within-lake temporal variation in pH effects*

Repeating the preceding analyses considering only variation within lakes that were observed in multiple years (by controlling for differences among lakes with lake number as a class variable) produced similar results (Table 7). The effect of pH on Psucc1 again varied among years (Table 7). Results were similar for models including pH as a continuous and as a class variable. Models using year as a continuous variable indicated trends also varied by pH and by pH class, although the interaction effect was weaker than observed when year was considered as a class (Table 8).

#### *Effects of disturbance*

Shoreline development class did not have a significant effect on Psucc1 beyond the effects of annual variation, lake area and pH (Table 9). There was a significant effect of development on Psucc2, both for

the full set of years and for the 1987-1997 time period (Table 9) but this effect did not vary among years (all years:  $X^2=31.36$ , 52df,  $p=0.99$ , 1987-1997:  $X^2=25.54$ , 40df,  $p=0.96$ ). Human activity did not have an effect on Psucc1 or Psucc2 beyond those of annual variation, lake area and pH (Table 9).

#### *Geographic variation*

There was no association between lake latitude and Psucc1 or Psucc2, either for all years or for the 1987-1997 time period (Table 10). Analyses incorporating other geographic attributes (e.g. jurisdictional or arbitrarily defined regions) were explored but, because the spatial distribution of surveyed lakes was not independent of pH status (see Figure 8), pH and geographic effects could not be separated based on records from all surveyed lakes. Models run using data from a region in which acidic and neutral lake pH classes overlapped did not indicate significant effects of lake acidity. This result was not helpful in resolving confounded pH and region effects because the loss of significant effects may have been due to a large reduction of the sample size (i.e. from  $n = 3600$  to  $n = 1223$  lake-years) and a relatively narrow range in pH (mean = 6.4, range=3.2) remaining in the subset.

#### *Power to detect trends*

The estimated power to detect differences in loon breeding success between two years appeared to be similar whether surveys were assumed to be repeated on the same lakes every year, or whether new lakes were selected each year (Table 11). For example, based on CLLS data 1987-1997, surveys of 250 lakes each year (i.e. near the average number of lakes surveyed (290) during the 1987-1997 time period) might be expected to allow the detection of a 17.2 percent difference in the mean proportion of successful pairs (e.g. a change in mean breeding success from 0.5 to 0.414), assuming that new lakes are surveyed each year, or a 19.3 percent change, assuming the same lakes are surveyed each year. These two results are essentially the same, given the uncertainty in the variance estimates, and suggest that variation among lakes in productivity is not significantly greater than year-to-year variation within lakes.

If productivity is changing in a steady (logit-linear) fashion over time, then the power to detect a change increases over time, both due to the increased number of surveys, and due to the cumulative effect of a small annual change leading to a gradually larger change over time. Under these conditions, the annual and aggregate change that could be detected with various sample sizes is given in Table 12, based upon data from within-lake analyses of lakes that were surveyed every year. For example, if 250 lakes were surveyed for six years (a 5-year interval), a change of 2.7 percent per year, amounting to an aggregate of 13.5 percent over the interval, could be detected with  $\beta = 0.80$ . Over 11 years (a 10-year interval), a change of 1.0 percent per year, amounting to an aggregate change of 9.7 percent could be detected (e.g. a

change in mean productivity from 0.5 to 0.45). This is clearly an improvement over the 19.3 percent change that could be detected with only two years of surveys. Results from sampling different lakes would likely be similar, based upon the analyses in Table 11. However, it should be noted that the analyses of CLLS data from 1981-1997 indicate significant, large, annual variation in productivity in excess of linear changes. Thus, the assumption of a logit-linear change in productivity over time is unlikely to be realistic, and hence may not be a good basis for planning future survey design.

## Discussion

In general, the analyses presented here support the results of previous studies (e.g. Alvo et al. 1988, McNicol et al. 1995b) documenting a lower average breeding success for loon pairs on acidic lakes. However, they go beyond those earlier studies in showing that the relationship between breeding success and lake acidity has varied over time. The proportion of loon pairs breeding successfully on Ontario lakes declined from 1981-1997, particularly during 1987-1997, and this decline varied with lake pH. Relative to alkaline lakes, surveyed lakes below pH 6 appeared to become progressively poorer in their ability to sustain loon chicks through six weeks of age. Similar conclusions were reached whether the analyses considered all lakes, or just examined changes within lakes that were surveyed for multiple years. In addition, models allowing reproductive success to vary among years were a significantly better fit than models that constrained reproductive success to change in a logit-linear fashion over time. This indicates that the change was not a simple long-term decline, but that there were year-to-year fluctuations as well.

The overall decline in loon breeding success appears to have been detected largely during changes occurring from 1987-1997, a period during which larger sample sizes allowed more powerful resolution of temporal patterns. Although declines in breeding success occurred on lakes in all three pH classes, the decline for acid (pH<6) lakes was greatest and, at least during 1987-1996, appeared to diverge from the trend in alkaline lakes (Figure 4). Temporal variation, with good and bad years in breeding success is common among a variety of species, including loons (Croskery 1991).

The impact of this variation on loon population dynamics depends upon whether there have been concurrent changes in other parameters such as post-fledging and adult survival, emigration and immigration (Opdam 1991). It seems unlikely that survival rates would be higher for loons breeding on acid lakes, and it might be expected that post-fledging survival could be lower, if the same factors that

reduce breeding success also affect the condition of the young loons. Thus, it seems likely that loons breeding on acid lakes are making a relatively smaller contribution to sustaining populations of loons in Ontario than those breeding on more alkaline lakes. It is quite possible that the more acid lakes represent a population sink (i.e., sustained only by immigration from lakes in better health), although this cannot be confirmed without estimates of other demographic parameters, particularly post-fledging survival. In any case, if breeding success on acidic lakes continues to decline over time, their contribution to support of loon populations in Ontario will also decline. Any further decreases in the average acidity of Ontario lakes could exacerbate this problem.

Stabilisation or reduction in the proportion of acidic lakes on Ontario landscapes appears unlikely to occur soon. Although progress has been made in reducing acidifying emissions and some chemical recovery has occurred among certain lake types, recovery is expected to be very slow for many lakes (Mallory et al. 1998, McNicol et al. 1998). For those lakes in the CLLS survey with pH readings from multiple years, no change in pH was noticed for most lakes. In addition, almost 100,000 highly sensitive lakes in eastern Canada are expected to continue to receive damaging levels of acidifying inputs, even after current emissions restrictions are fully implemented (Acidifying Emissions Task Group 1997).

As noted above, changing success rates on CLLS surveyed lakes cannot be extrapolated to trends in the status of regional or provincial loon populations because estimates of other rates (e.g. immigration, post-fledging survival, adult survival) were not available. Furthermore, because the selection of CLLS lakes was not based on a stratified or otherwise randomised design, the observed patterns in breeding success may not be representative of patterns in all geographic regions or all lake types in Ontario. Nevertheless, it seems likely that the surveyed lakes are a fairly good representation of lakes within the inhabited parts of Ontario (i.e., lakes with at least one cottage or recreational home). Recruitment of volunteers has been heavily based on advertising through venues such as *Cottage Life* magazine that is likely to reach people in many parts of Ontario. It is conceivable that changes over time in the distribution of surveyed lakes could drive some of the annual variation in breeding success. In fact, there was a slight tendency for lakes selected for surveys in more recent years to be less acid. Nevertheless, the within-lake analyses indicate that changes in the distribution of the sample cannot explain the observed annual variation in the relative effects of lake acidity, because the patterns were the same within lakes surveyed in multiple years.

There was no change in the mean pH of individual lakes in the CLLS sample set during these years. However, the pattern of diverging breeding success in the acid and other lake classes from 1993 through

1996 suggests a progressive impairment of the ability of acid lakes to support breeding loons. Water birds, including loons, have been shown to adjust to lake acidification by shifting to alternative food sources (Alvo et al. 1988, Bendell and McNicol 1995). Food webs in these lakes may continue to deteriorate as prey species with intermediate tolerance to acidity decline (Haines 1981). Successfully nesting loon pairs frequently use the same nest site in subsequent years (McIntyre 1988); for pairs that breed successfully on acidic lakes, the accumulation of toxicological or other effects might also progressively impair the ability of pairs to reproduce in subsequent years. Loons raising chicks on small lakes or lakes with limited food resources often feed themselves during visits to neighbouring lakes (Alvo et al. 1988, Barr 1996). As the buffering capacity of neighbouring lakes is exceeded, loons which may have been able to sustain their young by feeding elsewhere might be expected to find progressively fewer alternative lakes still productive. Future analyses of CLLS data, incorporating the spatial relationships among lakes, may provide some insight into these and other potential landscape level effects.

The primary focus of the analyses presented here was to provide information relevant to understanding the recovery through time, or lack thereof, of Ontario lakes subjected to acidifying inputs. The significant annual fluctuations in breeding success that were observed on top of the long-term trends suggest that other factors also influence year-to-year variation in breeding success. As noted earlier, such fluctuations are expected for many species. They could potentially be related to factors such as annual variation in phenology, weather conditions, fluctuations in lake levels, etc. Although some of these factors are potentially important for conservation, a full exploration of these factors is beyond the scope of the current analyses.

It would also be valuable to learn more about the stages in the breeding cycle when breeding failure occurs, and how this varies among years, both in relation to lake acidity, and in relation to other factors such as disturbance (which had at least a limited impact on the number of young raised by successful pairs), annual phenology, water levels, or weather patterns. The data as currently summarised in the data base, do not provide sufficiently precise information to examine the timing of mortality, because little information is stored on the exact timing of observations and survey effort by participants. Starting in 1997, the survey recording forms were modified to ask volunteers to record the precise weeks when loons were observed, as well as their actual observations during each week. Such information will allow accurate estimation of age-specific chick survival rates, and can be used to learn more about the causes and timing of breeding failure. Future analyses based on this more precise information will be valuable for trying to ascertain potential causes of temporal and lake-to-lake variation in breeding success of loons.

## Future Monitoring

The Canadian Lakes Loon Survey has played a cost effective and important role in understanding the effects of lake acidification on lake inhabitants and has contributed to modelling efforts directed towards projecting recovery patterns of lakes under various emissions scenarios (e.g., Wayland and McNicol 1990, McNicol et al. 1995a,b). The current analyses have shown that the survey is also valuable for measuring temporal variation in breeding success, as well as changes in the effects of lake acidity over time.

Nevertheless, from the perspective of future monitoring, it may be worthwhile to re-evaluate whether the CLLS remains the most efficient way to address these types of questions, whether the current design could be improved to increase the power to detect changes, and whether the survey could be improved in other ways. For the purposes of this evaluation, the primary objective is assumed to be monitoring variation in breeding success, measured as the proportion of pairs raising young to fledging. This measure was selected because, as discussed elsewhere in the report, this appears to be well monitored by the CLLS and is a sensitive indicator of the health of lakes in Ontario. Nevertheless, it could also be valuable to consider potential causal relationships, particularly with respect to the stage in the breeding cycle when breeding failure may be occurring. Thus, some of the questions to consider in the design of future programs to monitor loon productivity are:

1. Is the CLLS the most appropriate way to monitor breeding success of loons over time?
2. What are the sample sizes and what is the best sample allocation to detect changes?
3. How can the survey be improved to enhance power for detecting the timing of breeding failure?
4. Could the survey be improved by supplementing the volunteer-based observations with additional data from professional or other more highly trained surveyors?

### *Extensive and intensive monitoring strategies*

The majority of data collected under the CLLS are collected by volunteers. Volunteer-based surveys of wildlife or other natural resources have the potential to provide information over large areas and over long time periods at relatively low costs. Relative to intensive surveys by wildlife professionals, however, volunteer surveys have some important limitations. Observer experience, when unaccounted for, can affect the precision of trend estimates and may even influence the direction of trend estimates (e.g. Link and Sauer 1998). When data collection requires sophisticated natural history knowledge or identification skills, volunteer-based surveys may be particularly vulnerable to variation in observer experience.

Volunteer-based surveys may also have limitations in the types of data that can be collected. For example,

volunteers may be less likely to survey or to report negative data (e.g. forests without birds, lakes without loon pairs), which can affect the types of questions that can be addressed. Another attribute of many volunteer surveys is that site selection may not be based on an ideal sampling design. This is particularly true if volunteers select the sites (as in the CLLS), but could also be a problem due to failure to complete or carry-out pre-selected surveys, due to constraints such as land ownership affecting access or distance of sites from volunteer's home. Consequently, sites with certain characteristics may be underrepresented in the sample or site characteristics of interest may be confounded with geographic or other attributes. Furthermore, there may be a greater tendency for missing data. For example, volunteers may intend to collect data, but fail to complete the survey in any given year for a wide variety of personal reasons. Also, continuity of survey sites can be reduced as volunteers drop out of the survey, and new volunteers select alternative sites. Depending upon the relative contributions of within and among-site variance, this could reduce survey power (Urquhart et al. 1998).

Alternatives to large scale volunteer surveys include intensive and repeated monitoring of a more limited sample of sites, selected with an appropriate randomised sampling scheme to ensure they are representative of the population of sites of interest (e.g. Thompson et al. 1998). Consistent monitoring of sites through time by skilled observers offers the prospect of decreased observer effects, more precise and potentially more accurate measures of breeding success, and more reliable coverage of the selected sites. However, the major limitation of this approach is that it tends to be much more expensive, and monitoring adequate numbers of lakes may be prohibitively expensive. Thus, the reduction in variance associated with measures of individual lakes by skilled observers, especially if the natural variability is high (as tends to be the case for binary variables such as success rates), may not be nearly sufficient to compensate for the reduced sample sizes associated with higher costs. Furthermore, if adjustments are required which compromise the sample selection or size, samples may not adequately represent regional variation (Stoddard et al. 1998).

#### *The CLLS as a tool for monitoring loon productivity*

Previous studies (e.g. Alvo et al. 1988, Wayland and McNicol 1990) have demonstrated that Common Loon breeding success, when summarised in terms of the presence and number of LY, provides information on the pH and food web status of lakes used for rearing chicks. The analyses presented here demonstrate further that data collected through the CLLS have sufficient precision to discern among-year variation in breeding success and to identify within-year and among-year differences in lake pH classes. When interpreted in the context of the causal relationships documented by other studies, these findings support the argument that the CLLS has the potential to provide statistically defensible information on

temporal patterns in lake pH and food web status, particularly if sample sizes in the range of those for the 1987-1997 period are maintained.

Power analyses, based on data currently available (Table 11) suggest that the power of the survey is not strongly affected by whether the same lakes are surveyed every year, or whether new lakes enter the sample each year. Urquhart et al. (1998) presented a detailed assessment of the power to detect trends under monitoring strategies ranging in survey consistency from annual visits to the same set of lakes to single visits to a new set of lakes each year. A mixed pattern of lake visits with an varied schedule of visits to lakes was found to have high power to detect both lake and year effects. Power analyses suggest that in order to detect a 20 percent change between years, a sample size of about 250 lakes each year would be required. To detect changes with similar precision within pH classes would require a similar sample size in each pH class. Although variation among observers may have some impact on the precision of estimates, CLLS surveys do not require a high level of natural history or observational skill and results of volunteer surveys have compared favourably to those of professional biologists (Wayland and McNicol 1990). CLLS training materials use detailed text descriptions and diagrams to help program participants recognise and classify loon chicks to age class. Because counting from one to three large young per pair is not a particularly difficult task (unlike, for example, identifying a wide variety of singing bird species by call), there is unlikely to be much bias related to observer skills or experience. As a result, the variance in this measure is unlikely to be greatly reduced by substituting professional observers for volunteers. If this is the case, the sample sizes required for a professional, intensive survey would be similar to those for the volunteer survey. Surveying 250 or more lakes each year, with paid staff, would likely be prohibitively expensive, and would not necessarily lead to any improvement in data quality relative to the current volunteer-based surveys in the CLLS.

Thus, it is probably most cost effective to continue to support volunteer based surveys in the CLLS to monitor loon productivity over time. However, this does not preclude the possibility that additional surveys by paid staff could be useful to fill in gaps in coverage, or to address other questions, related to the timing or causes of breeding failure, or the proportion of lakes on which loons do not attempt to breed (see below).

Despite its apparent power, the CLLS does have a number of limitations. One of these concerns the selection of lakes which, because it is not randomised, may not be representative of lakes throughout Ontario. Although it is never possible to ensure a representative sample without a random sampling scheme, post-hoc stratification based upon attributes such as water chemistry, geographic locations,

surrounding land-use, etc., may allow better extrapolation of survey results to lakes throughout the province. To do this, would require examining the distribution of surveyed lakes, relative to lakes that were not surveyed, with respect to these various attributes, using GIS and various data bases. Such an analysis might also be useful to help direct future recruitment efforts to areas that are under-represented.

Another limitation is that volunteers are less likely to survey lakes without loon pairs, because many volunteers may be uninterested in surveying lakes without loons or may not appreciate the value of providing negative data. Thus, the attributes of lakes with and without pairs cannot be assessed under the current protocol. This limitation is not likely to have a significant impact on the use of breeding success indices such as the one used here, which consider only those pairs that attempted to breed. However, interpretation of patterns using such a breeding success index should be restricted to lakes on which pairs were still present late in the breeding season. Lakes on which loons were unpaired, or on which loons may have departed early in the breeding season (perhaps due to early breeding failure) may be under-represented in the sample.

#### *Enhancing the CLLS to address other questions*

This report has focussed on monitoring loon breeding success, measured as the proportion of pairs fledging young over each season. However, there are a number of other questions that could potentially be addressed by the survey that would also be relevant to a monitoring strategy. One of these concerns the proportion of lakes on which loons attempt to breed. The sample in the current analysis only includes lakes on which at least one pair remained through the season. If changes in water chemistry due to acidifying inputs affect the probability that a loon pair will attempt to breed on a lake, this will not be detected by the current survey. Other data collection methods designed to collect records of lakes without loon pairs (e.g. a returnable postcard) might be integrated with the CLLS to help provide estimates of breeding pair densities and contribute to an understanding of breeding loon habitat selection criteria.

Furthermore, the survey data, as they have been gathered in most years, are of limited value for determining the timing of failure if breeding was not successful. Surveyors are discouraged from searching for, or checking, nests, because of possible disturbance that they might cause to the nest. Surveyors are asked to record the number of Downy (< 3 weeks), Small (3-6 weeks) and Large (> 6 weeks) young observed for each pair. However, it has not been clear from most survey forms whether the young were actually observed at each of these earlier stages, or whether the volunteer inferred that there must have been downy and small young, because large young were observed. As a result, analyses of survival between age classes are likely to be strongly biased because downy and small young that died

will be under-represented in the sample. To address this problem, the survey forms were redesigned in 1997, to encourage surveyors to record precisely when each survey was carried out, and what was observed in each week of the survey. Compliance with the new form design was lower than desired during the first year (many returning surveyors continued to record data in the former fashion, despite the change in the form) but appears to have improved in 1998. Once sufficient data collected with the new forms are available, it will be possible to assess the power of the survey for addressing questions related to the timing of breeding failure and hence, thus increasing power to infer possible direct causes of failure.

#### *Recommendations for future survey design*

The preceding analyses suggest that, from the perspective of survey power, it is not critical whether the same lakes or new lakes are surveyed each year. Nevertheless, there are some advantages to maintaining continuity within lakes. Particularly because new lakes are not randomly chosen, repeated coverage of at least some of the lakes can be used to test whether changes in productivity or other measures are due to changes that are occurring throughout the population, rather than changes in the sample of lakes being observed. Furthermore, new lakes may lead to some increased costs because of the need to obtain lake chemistry data for each lake. The analyses in this report do not suggest that allocation of additional resources to more intensive monitoring of a subsample of CLLS lakes would be necessary to enhance power. Nevertheless, efforts to retain participants in the program can be encouraged, and will lead to more repeated annual surveys on lakes. Furthermore, it may be possible to target some recruitment efforts towards lakes that have been surveyed for multiple years.

From the perspective of future allocation, priority should be given to maintaining or increasing current sample sizes, and in particular, increasing the sample in more acid lakes. Although a truly randomised allocation of CLLS survey lakes is not likely, recruitment efforts could be targeted to address, wherever possible, problems identified with spatial or other types (e.g. pH classes) of interspersions.

Data on the breeding success of Common Loons, provided by the Canadian Lakes Loon Survey, have the potential to provide information relevant to tracking the recovery of Ontario lakes and their food webs from acidification. Indices of loon breeding success or chick survival rates may also be useful measures of lake responses to some emerging issues (e.g. ultraviolet light penetration, climate change effects) (e.g. Schindler et al. 1996, Clair et al. 1998). Identification of future lake conservation concerns, directed recruitment efforts, and the more intensive survival information collected since 1997 have the potential to allow the CLLS to make contributions beyond those demonstrated both here and previously.

## **Acknowledgements**

The Canadian Lakes Loon Survey is a joint program of Bird Studies Canada, a non-profit organisation dedicated to the research and conservation of wild birds and their habitats, and the Canadian Wildlife Service – Ontario Region. Financial support for the program was provided by contributions from Environment Canada (Canadian Wildlife Service – Ontario Region), Ontario Ministry of Natural Resources, Northern Reflections, and donations from program participants. Charles M. Francis (Bird Studies Canada) provided valuable statistical and other advice, conducted power analyses, and assisted with preparation of the manuscript. Kathy Jones helped in many ways both in co-ordinating the volunteers for the survey in recent years, and in assisting with reorganising the data base to enable the present analyses. Andrew Couturier provided GIS support and volunteers Ted Maddeford and Hugh MacArthur assisted with managing survey kits and processing incoming data forms. Don McNicol (Environment Canada), and Mark Mallory (Environment Canada) made helpful comments and suggestions during the course of the work presented here. Environment Canada, through Don McNicol, provided water chemistry data. Finally, the efforts of the thousands of CLLS volunteers are gratefully acknowledged.

## Literature Cited

- Acidifying Emissions Task Group. 1997. Towards a national acid rain strategy. Report submitted to the National Air Issues Coordinating Committee. 98 pp.
- Alvo, R., D.J.T. Hussell, and M. Berrill. 1988. The breeding success of common loons (*Gavia immer*) in relation to alkalinity and other lake characteristics in Ontario. *Can. J. Zool.* 66:746-752.
- Barr, J.F. 1988. Aspects of common loon (*Gavia immer*) feeding biology on its breeding ground. *Hydrobiologica* 321:119-144.
- Belant, J.L., J.F. Olson, and R.K. Anderson. 1993. Evaluation of the single survey technique for assessing common loon populations. *J. Field Ornithol.* 64:77-83.
- Bendell, B.E. and D.K. McNicol. 1995. The diet of insectivorous ducklings and the acidification of small Ontario lakes. *Can. J. Zool.* 73:2044-2051.
- Blancher, P.J., D.K. McNicol, R.K. Ross, C.H.R. Wedeles, and P. Morrison. 1992. Towards a model of acidification effects on waterfowl in eastern Canada. *Envir. Poll.* 78:57-63.
- Clair, T.A., J. Ehrman, and K. Higuchi. 1998. Changes to the runoff of Canadian ecozones under doubled CO<sub>2</sub> atmosphere. *Can. J. Fish. Aquat. Sci.* 55:2464-2477.
- Croskery, P.R. 1991. Common loon, *Gavia immer*, nesting success and young survival in northwestern Ontario. *Can. Field-Nat.* 105:45-48.
- Frank, R., H., H. Lumsden, J.F. Barr, and H.E. Braun. 1983. Residues of organochlorine insecticides, industrial chemicals, and mercury in eggs and in tissues taken from healthy and emaciated common loons, Ontario, Canada, 1968-1980. *Arch. Environ. Contam. Toxicol.* 12:641-654.
- Haines, T. A. 1981. Acidic precipitation and its consequences for aquatic ecosystems: a review. *Trans. Amer. Fish. Soc.* 110: 669-707.
- Harris, L.D. 1988. The nature of cumulative impacts on biotic diversity of wetland vertebrates. *Environ. Manage.* 12: 675-694.
- Heimberger, M., D. Euler, and J. Barr. 1983. The impact of cottage development on common loon reproductive success in central Ontario. *Wilson Bull.* 95:431-439.
- Link, W.A. and J.R. Sauer. 1998. Estimating population change from count data: application to the North American Breeding Bird Survey. *Ecol. Applic.* 8:258-268.
- Longcore, J.R., H. Boyd, R.T. Brooks, G. M. Haramis, D.K. McNicol, J.R. Newman, K.A. Smith, and F. Stearns. 1993. Acidic depositions: effects on wildlife and habitats. *Wildl. Soc. Tech. Rev.* 93-1. 42 pp.
- Mallory, M.L., D.K. McNicol, D.A. Cluis, and C. Laberge. 1998. Chemical trends and status of small lakes near Sudbury, Ontario, 1983-1995: evidence of continued chemical recovery. *Can. J. Fish. Aquat. Sci.* 55:63-75.

- McNicol, D.K., B.E. Bendell, and R.K. Ross. 1987. Studies on the effects of acidification on aquatic wildlife in Canada: waterfowl and trophic relationships in small lakes in northern Ontario. Occ. Paper No. 62. Can. Wildl. Serv., Ottawa, ON. 76 pp.
- McNicol, D.K., J.J. Kerekes, M.L. Mallory, R.K. Ross, and A.M. Scheuhammer. 1995a. The Canadian Wildlife Service LRTAP Biomonitoring Program. Part 1. A strategy to monitor the biological recovery of aquatic ecosystems in eastern Canada from the effects of acid rain. Tech. Rep. Ser. No. 245. Canadian Wildlife Service.
- McNicol, D.K., M.L. Mallory, and H.S. Vogel. 1995b. Using volunteers to monitor the effects of acid precipitation on Common Loon (*Gavia immer*) reproduction in Canada: the Canadian Lakes Loon Survey. *Water, Soil and Air Pollution* 85:463-468.
- McNicol, D.K., M.L. Mallory, C. LaBerge, and D. A. Cluis. 1998. Recent temporal patterns in the chemistry of small, acid-sensitive lakes in central Ontario, Canada. *Water, Air, and Soil Poll.* 105:343-351.
- McIntyre, J. W. 1989. *The Common Loon: Spirit of the Northern Lakes*. Univ. Minnesota Press, Minneapolis. 229 pp.
- McIntyre, J. W. and J.F. Barr. 1997. Common Loon (*Gavia immer*). In *The Birds of North America*, No. 313 (A. Poole and F. Gill, eds.). The Academy of Natural Sciences, Philadelphia, PA, and The American Ornithologists' Union, Washington, D.C.
- Natural Resources Canada. 1997. *Concise Gazetteer of Canada*. Canada Communication Group – Publishing, Ottawa, ON. 636 pp.
- Opdam, P. 1991. Metapopulation theory and habitat fragmentation: a review of holarctic breeding bird studies. *Landscape Ecol.* 5:93-106.
- SAS Institute. 1997. *SAS/STAT Software: Changes and Enhancements Through Release 6.12*. SAS Institute Inc., Cary, NC, USA.
- Scheuhammer, A.M. and P.J. Blancher. 1994. Potential risk to common loons (*Gavia immer*) from methylmercury exposure in acidified lakes. *Hydrobiol.* 279/280:445-455.
- Schindler, D.W., P.J. Curtis, B.R. Parker, and M.P. Stainton. 1996. Consequences of climate warming and lake acidification for UV-B penetration in North American boreal lakes. *Nature* 379:705-708.
- Stoddard, J.L., C.T. Driscoll, J.S. Kahl, and J.H. Kellogg. 1998. Can site-specific trends be extrapolated to a region? An acidification example for the northeast. *Ecol. Appl.* 8:288-299.
- Strong, P.L.V. 1990. The suitability of the common loon as an indicator species. *Wildl. Soc. Bull.* 18:257-261.
- Thompson, W.L., G.C. White, and C. Gowan. 1998. *Monitoring Vertebrate Populations*. Academic Press, Inc., New York, NY. 365 pp.
- Titus, J.R. and L.W. VanDruff. 1981. Response of the common loon to recreational pressure in the Boundary Waters Canoe Area, northwestern Minnesota. *Wildl. Monogr.* No. 79.

- Twiss, M.P. and V. G. Thomas. 1998. Preventing fishing-sinker-induced lead poisoning of common loons through Canadian policy and regulative reform. *J. Env. Manage.* 53:49-59.
- Urquhart, N.S., S.G. Paulsen, and D.P. Larsen. 1998. Monitoring for policy-relevant regional trends over time. *Ecol. Applic.* 8:246-257.
- Wayland, M. and D.K. McNicol. 1990. Status report on the effects of acid precipitation on common loon reproduction in Ontario: the Ontario Lakes Loon Survey. Tech. Rep. Ser. no. 92, Canadian Wildlife Service. 26 pp.

Table 1. Sample sizes based on lake-years (i.e. each surveyed lake counting as one observation each year) expressed in terms of pair numbers and breeding success, before and after removal of records with missing lake area and pH.

Survey Year	<b>Before</b>	<b>After</b>	
	Number of lake-years	Number of lake-years	<i>Percent of total</i>
<u>Number of Pairs</u>			
1	2982	2506	70
2	649	581	16
3 or 4	447	401	11
5 to 8	100	83	2
9 to 16	22	18	1
17 or more	12	11	0
Total	4212	3600	100
<u>Breeding success</u>			
no young	1716	1443	40
≥ 1 Pr with ≥ 1LY	2496	2157	60
≥ 1 Pr with 2-3 LY	1213	1043	29

Table 2. Sample sizes in terms of lake-years for variables describing lake characteristics before and after removal of records with missing lake area and pH values. Annual number of lakes in each lake descriptor class reflect sample sizes used for within-lake analyses.

Class	Before			After			Number of lakes used in modeling (by survey year)													
	Number of lake-years	Number of lake-years	Percent of total	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997
<b>Lake pH</b>																				
Acid (pH <6)	314	309	9	10	5	11	3	2	4	18	21	36	38	30	19	23	25	22	26	16
Neutral (pH 6 - 8)	2845	2802	78	35	65	84	42	53	40	184	175	227	230	251	219	225	292	261	233	186
Alkaline (pH 8 +)	491	489	14	10	11	12	8	9	4	20	34	49	41	43	35	42	53	41	43	34
missing	562	0	0																	
Total	4212	3600	100	55	81	107	53	64	48	222	230	312	309	324	273	290	370	324	302	236
<b>Lake Area<sup>1</sup></b>																				
7 ha or smaller	18	13	0	2	0	0	0	1	0	3	1	2	0	0	0	0	0	0	4	0
7.5 to 55 ha	1061	872	24	10	13	18	9	11	11	62	63	108	87	88	61	70	75	63	78	45
55.1 to 400 ha	1775	1620	45	31	28	49	25	28	19	97	95	122	137	147	131	130	173	156	139	113
400.1 to 2900 ha	914	866	24	10	29	34	16	19	13	49	59	65	72	73	61	70	96	79	63	58
2900.1 to 22000 ha	207	200	6	1	11	5	3	5	5	10	10	14	12	14	17	17	22	23	15	16
22000.1 or larger	39	29	1	1	0	1	0	0	0	1	2	1	1	2	3	3	4	3	3	4
missing	198	--	--																	
Total	4212	3600	100	55	81	107	53	64	48	222	230	312	309	324	273	290	370	324	302	236
<b>Shoreline Development</b>																				
0	1769	1415	45	0	25	0	18	13	12	98	113	147	124	151	114	116	139	133	138	76
1	466	399	13	0	9	0	7	8	1	21	24	38	32	38	30	39	58	39	35	27
2	525	465	15	0	8	0	2	11	4	35	35	29	44	40	44	43	56	48	45	24
3	547	508	16	0	10	0	7	0	0	33	35	45	42	57	42	42	69	54	45	29
4	350	323	10	0	24	0	14	0	1	25	20	30	20	26	29	30	28	33	31	21
Total	3657	3110	100	0	76	0	48	32	18	212	227	289	262	312	259	270	350	307	294	177
<b>Human Activity</b>																				
1	102	76	3	0	1	0	0	0	0	6	7	5	0	12	4	8	8	9	13	3
2	79	66	3	0	0	1	1	1	0	10	13	4	0	6	9	5	2	8	3	3
3	351	268	12	0	5	8	3	6	7	37	38	22	0	29	26	23	20	18	18	10
4	145	101	5	0	0	5	2	1	1	14	4	6	0	11	9	6	17	14	4	8
5	484	375	17	0	12	4	4	3	4	15	23	33	0	51	35	43	59	43	29	20
6	554	470	21	0	13	8	6	9	7	64	25	27	0	30	41	40	67	55	44	40
7	813	106	5	0	27	26	17	22	13	10	55	65	0	79	93	83	76	64	49	50
8	864	780	35	0	17	19	15	20	14	62	64	66	0	73	45	57	99	93	76	72
Total	3392	2242	100	0	75	71	48	62	46	218	229	228	0	291	262	265	348	304	236	206

<sup>1</sup> Class sizes defined to correspond approximately to groups of  $\ln(\text{Area})=2$  in width.

Table 3. Number of lakes used in logistic regression models, summarised for two time periods by the number of years surveyed, lake pH and area class.

Class	Number of lakes (all years)	Percent of total	Number of lakes (1987-1997)	Percent of total
<u>Number years surveyed</u>				
1	391	37	323	34
2	191	18	189	20
3	97	9	91	10
4	85	8	87	9
5	63	6	52	6
6	39	4	38	4
7	61	6	59	6
8	33	3	36	4
9	22	2	26	3
10	21	2	26	3
11	9	1	17	2
12	18	2	--	
13	9	1	--	
14	4	0	--	
15	4	0	--	
Total	1047	100	944	100
<u>Lake pH</u>				
Acid (pH <6)	123	12	108	11
Neutral (pH 6 - 8)	804	77	726	77
Alkaline (pH 8 +)	120	11	110	12
Total	1047	100	944	100
<u>Lake Area</u>				
7 ha or smaller	12	1	9	1
7.5 to 55 ha	333	32	306	32
55.1 to 400 ha	453	43	409	43
400.1 to 2900 ha	206	20	180	19
2900.1 to 22000 ha	38	4	35	4
22000.1 or larger	5	0	5	1
Total	1047	100	944	100

Table 4. Results of logistic regression models testing for the effects of lake area and pH on loon breeding success after controlling for annual variation.

Years	Model terms		Statistics from Type 1 analysis		
	Response	Covariates	df	Scaled Chi-square <sup>1</sup>	P>Chi
1981-1997	Nsucc1/TotPrs (# obs=3600)	<u>year class</u>	16	195.39	0.0001
		<u>lnarea</u>	1	14.79	0.0001
		<u>pH</u>	1	19.31	0.0001
		<u>lnarea*pH</u>	1	2.50	0.1138
1987-1997	Nsucc1/TotPrs (# obs=3192)	<u>year class</u>	10	191.39	0.0001
		<u>lnarea</u>	1	15.29	0.0001
		<u>pH</u>	1	25.14	0.0001
		<u>lnarea*pH</u>	1	1.25	0.2632
1981-1997	NSucc2/NSucc1 (# obs=2157)	<u>year class</u>	16	13.11	0.6649
		<u>lnarea</u>	1	7.13	0.0076
		<u>pH</u>	1	15.25	0.0001
		<u>lnarea*pH</u>	1	3.41	0.0649
1987-1997	NSucc2/NSucc1 (# obs=1904)	<u>year class</u>	10	4.52	0.9209
		<u>lnarea</u>	1	6.89	0.0087
		<u>pH</u>	1	15.67	0.0001
		<u>lnarea*pH</u>	1	3.25	0.0714

<sup>1</sup> Chi-square values adjusted for overdispersion. See text for explanation.

Table 5. Results of logistic regression models testing for varying effects of pH among years after controlling for lake area.

Model	Years	Response	Model terms		Statistics from Type 1 analysis		
				Covariates	df	Scaled Chi-square <sup>1</sup>	P>Chi
Year class and pH class	1981-1997	Nsucc1/TotPr s (# obs=3600)		<u>year class</u>	16	196.07	0.0001
				<u>lnarea</u>	1	14.85	0.0001
				<u>pH class</u>	2	19.21	0.0001
				<u>year class*pH class</u>	32	47.20	0.0407
	1987-1997	Nsucc1/TotPr s (# obs=3192)		<u>year class</u>	10	191.99	0.0001
				<u>lnarea</u>	1	15.34	0.0001
				<u>pH class</u>	2	22.96	0.0001
				<u>year class*pH class</u>	20	33.56	0.0292
Year class and pH	1981-1997	Nsucc1/TotPr s (# obs=3600)		<u>year class</u>	16	196.57	0.0001
				<u>lnarea</u>	1	14.88	0.0001
				<u>pH</u>	1	19.43	0.0001
				<u>year class*pH</u>	16	39.05	0.0011
	1987-1997	Nsucc1/TotPr s (# obs=3192)		<u>year class</u>	10	192.05	0.0001
				<u>lnarea</u>	1	15.34	0.0001
				<u>pH</u>	1	25.08	0.0001
				<u>year class*pH</u>	10	21.41	0.0184

<sup>1</sup>Chi-square values adjusted for overdispersion. See text for explanation.

Table 6. Results of logistic regression models testing for within-lake variability in the effects of pH among years. Only lakes surveyed for two or more years between 1987 and 1997 were included in analysis.

Model	Years	Model terms		Statistics from Type 1 analysis		
		Response	Covariates	df	Scaled Chi-square <sup>1</sup>	P>Chi
Year and lake as class	1987-1997	Nsucc1/TotPrs (# obs=2456)	Lake ID	473	444.84	0.8193
			<u>year class</u>	10	173.38	0.0001
			<u>year class*pH</u>	10	21.41	0.0184
Year, lake and pH as class	1987-1997	Nsucc1/TotPrs (# obs=2456)	Lake ID	473	447.30	0.7966
			<u>year class</u>	10	174.34	0.0001
			<u>year class*pH</u> <u>class</u>	20	42.39	0.0025

<sup>1</sup> Chi-square values adjusted for overdispersion. See text for explanation.

Table 7. Results of logistic regression models testing for linear trends and differences in trends among pH classes, in the proportion of loon pairs with at least one large young.

Years	Model terms		Statistics (Type 1 analysis)			Slopes by pH class				
	Response	Covariates	df	Scaled Chi-square <sup>1</sup>	P>Chi	pH Class	Slope (logit scale)	p for H <sub>0</sub> :slope=0	Difference among classes	Contrast (p)
1981-1997	Nsucc1/TotPrs (# obs=3600)	<u>year</u>	1	55.29	0.0001	Alkaline	-0.0073	0.7152	a	vs Neutral (0.0047)
		<u>lnarea</u>	1	6.81	0.0091	Neutral	-0.1696	0.0001	b	vs. Acid (0.1858)
		<u>pH class</u>	2	15.96	0.0003	Acidic	-0.1135	0.0004	b	vs. Alkaline (0.0045)
		<u>year*pH class</u>	2	10.72	0.0047					
1987-1997	Nsucc1/TotPrs (# obs=3192)	<u>year</u>	1	132.40	0.0001	Alkaline	-0.0824	0.0045	a	vs Neutral (0.0606)
		<u>lnarea</u>	1	14.46	0.0001	Neutral	-0.2319	0.0001	ab	vs. Acid (0.0631)
		<u>pH class</u>	2	22.83	0.0001	Acidic	-0.1422	0.0001	b	vs. Alkaline (0.0062)
		<u>year*pH class</u>	2	7.83	0.02					

<sup>1</sup> Chi-square values adjusted for overdispersion. See text for explanation.

Table 8. Results of logistic regression models testing for within-lake linear trends in the proportion of loon pairs with at least one large young. Only lakes surveyed for two or more years between 1987 and 1997 were included in analysis.

Model	Years	Model terms		Statistics from Type 1 analysis		
		Response	Covariates	df	Scaled Chi-square <sup>1</sup>	P>Chi
Lake as class	1987-1997	Nsucc1/TotPrs (# obs=2456)	Lake ID	473	432.59	0.9085
			<u>year</u>	1	113.32	0.0001
			<u>year *pH</u>	1	4.10	0.043
Lake and pH as class	1987-1997	Nsucc1/TotPrs (# obs=2456)	Lake ID	473	432.81	0.9072
			<u>year</u>	1	113.38	0.0001
			<u>year *pH class</u>	2	6.10	0.0474

<sup>1</sup> Chi-square values adjusted for overdispersion. See text for explanation.

Table 9. Results of logistic regression models testing the contributions of shoreline development and human activity on loon breeding success after controlling for annual variation and lake area and pH.

Model	Years	Model terms		Statistics from Type 1 analysis		
		Response	Covariates	df	Scaled Chi-square <sup>1</sup>	P>Chi
Development	1981-1997	Nsucc1/TotPrs (# obs=3133)	<u>year class</u>	14	166.31	0.0001
			<u>lnarea</u>	1	10.08	0.0015
			<u>pH</u>	1	25.50	0.0001
			<u>development class</u>	4	1.84	0.7653
	1987-1997	Nsucc1/TotPrs (# obs=2959)	<u>year class</u>	10	165.67	0.0001
			<u>lnarea</u>	1	10.29	0.0013
			<u>pH</u>	1	24.90	0.0001
			<u>development class</u>	4	1.77	0.778
	1981-1997	NSucc2/NSucc1 (# obs=1884)	<u>year class</u>	14	9.44	0.8021
			<u>lnarea</u>	1	4.51	0.0337
			<u>pH</u>	1	20.51	0.0001
			<u>development class</u>	4	10.99	0.0267
1987-1997	NSucc2/NSucc1 (# obs=1772)	<u>year class</u>	10	5.60	0.8478	
		<u>lnarea</u>	1	4.44	0.0352	
		<u>pH</u>	1	18.98	0.0001	
		<u>development class</u>	4	12.42	0.0145	
Human Activity	1981-1997	Nsucc1/TotPrs (# obs=2889)	<u>year class</u>	14	188.21	0.0001
			<u>lnarea</u>	1	7.42	0.0065
			<u>pH</u>	1	20.94	0.0001
			<u>activity class</u>	7	2.26	0.9443
	1987-1997	Nsucc1/TotPrs (# obs=2587)	<u>year class</u>	9	486.77	0.0001
			<u>lnarea</u>	1	7.01	0.0081
			<u>pH</u>	1	20.58	0.0001
			<u>activity class</u>	7	2.95	0.8894
	1981-1997	NSucc2/NSucc1 (# obs=1790)	<u>year class</u>	14	6.38	0.9559
			<u>lnarea</u>	1	10.05	0.0015
			<u>pH</u>	1	16.07	0.0001
			<u>activity class</u>	7	3.45	0.8407
1987-1997	NSucc2/NSucc1 (# obs=1595)	<u>year class</u>	9	3.58	0.9366	
		<u>lnarea</u>	1	10.41	0.0013	
		<u>pH</u>	1	15.47	0.0001	
		<u>activity class</u>	7	4.76	0.6891	

<sup>1</sup> Chi-square values adjusted for overdispersion. See text for explanation.

Table 10. Results of logistic regression models testing for the effects of latitude on loon breeding success after controlling for annual variation and lake area and pH.

Years	Model terms		Statistics from Type 1 analysis		
	Response	Covariates	df	Scaled Chi-square <sup>1</sup>	P>Chi
1981-1997	Nsucc1/TotPrs (# obs=3591)	<u>year class</u>	16	193.18	0.0001
		<u>lnarea</u>	1	14.53	0.0001
		<u>pH</u>	1	19.36	0.0001
		<u>latitude</u>	1	1.05	0.3059
1987-1997	Nsucc1/TotPrs (# obs=3183)	<u>year class</u>	10	189.15	0.0001
		<u>lnarea</u>	1	15.0173	0.0001
		<u>pH</u>	1	25.0606	0.0001
		<u>latitude</u>	1	0.4947	0.4818
1981-1997	NSucc2/NSucc1 (# obs=2155)	<u>year class</u>	16	13.23	0.6559
		<u>lnarea</u>	1	6.93	0.0085
		<u>pH</u>	1	15.04	0.0001
		<u>latitude</u>	1	1.73	0.1883
1987-1997	NSucc2/NSucc1 (# obs=1902)	<u>year class</u>	10	4.64	0.9137
		<u>lnarea</u>	1	6.69	0.0097
		<u>pH</u>	1	15.44	0.0001
		<u>latitude</u>	1	0.71	0.405

<sup>1</sup> Chi-square values adjusted for overdispersion. See text for explanation.

Table 11. Comparison of the change that could be detected with various sample sizes, based upon sampling the same lakes repeatedly over time, versus selecting new lakes each year. Numbers represent the percentage change in the mean proportion of pairs with at least one large young, that could be detected over a one-year interval (i.e. two survey years) with various sample sizes, assuming  $\alpha=0.05$ ,  $\beta=0.80$ . Variance estimates for the within-lake analyses were obtained from sample CLLS data from 1987-1997 considering changes between pairs of years on all lakes surveyed for two consecutive years. Variance estimates for the among-lake analyses were obtained by including all lakes from 1987-1997, and considering each lake-year as a separate sample. Estimates are back transformed from a logit scale, as described in the text.

Number of lakes per year	Percentage change that could be detected	
	Same lakes each year	Changes in lakes each year
50	41.1	36.9
100	29.9	26.7
150	24.7	22.0
200	21.5	19.1
250	19.3	17.2
500	13.7	12.2
1000	9.7	8.6

Table 12. Estimated percent change in productivity in mean proportion of pairs with at least one large young that could be detected ( $\alpha=0.05$ ,  $\beta=0.80$ ), assuming a logit-linear decline in productivity over periods ranging from two to 11 years. Variance estimates for the power analyses were obtained from observed variances of within-lake changes in CLLS data for the relevant time periods from 1987-1997. These analyses assume that all lakes are surveyed each year, although similar results would be expected if new lakes were surveyed each year (Table 11). Percent change is expressed in two ways: the annual change that could be detected over each time period, and the aggregate change that this represents over the survey period.

a) Percent annual change that could be detected

Number of lakes per year	Number of years surveyed									
	2	3	4	5	6	7	8	9	10	11
50	41.1	19.8	12.0	8.2	6.1	4.7	3.8	3.1	2.5	2.2
100	29.9	14.1	8.5	5.8	4.3	3.4	2.7	2.2	1.8	1.5
150	24.7	11.5	6.9	4.8	3.5	2.7	2.2	1.8	1.4	1.3
200	21.5	10.0	6.0	4.1	3.0	2.4	1.9	1.5	1.2	1.1
250	19.3	8.9	5.4	3.7	2.7	2.1	1.7	1.4	1.1	1.0
500	13.7	6.3	3.8	2.6	1.9	1.5	1.2	1.0	0.8	0.7
1000	9.7	4.5	2.7	1.8	1.4	1.1	0.8	0.7	0.6	0.5

b) Percent aggregate change over n-years that could be detected

Number of lakes per year	Number of years surveyed									
	2	3	4	5	6	7	8	9	10	11
50	41.1	38.0	34.6	31.9	29.5	27.7	26.0	23.9	22.1	21.4
100	29.9	27.6	25.0	23.0	21.2	19.8	18.6	17.1	15.8	15.3
150	24.7	22.7	20.5	18.9	17.4	16.3	15.2	14.0	12.9	12.5
200	21.5	19.8	17.8	16.4	15.1	14.1	13.2	12.1	11.2	10.9
250	19.3	17.7	16.0	14.7	13.5	12.6	11.8	10.9	10.0	9.7
500	13.7	12.6	11.4	10.4	9.6	9.0	8.4	7.7	7.1	6.9
1000	9.7	8.9	8.1	7.4	6.8	6.4	5.9	5.5	5.0	4.9

Figure 1. Locations of Canadian Lakes Loon Survey lakes used in analysis of temporal patterns in Ontario loon breeding success, 1981 - 1997.

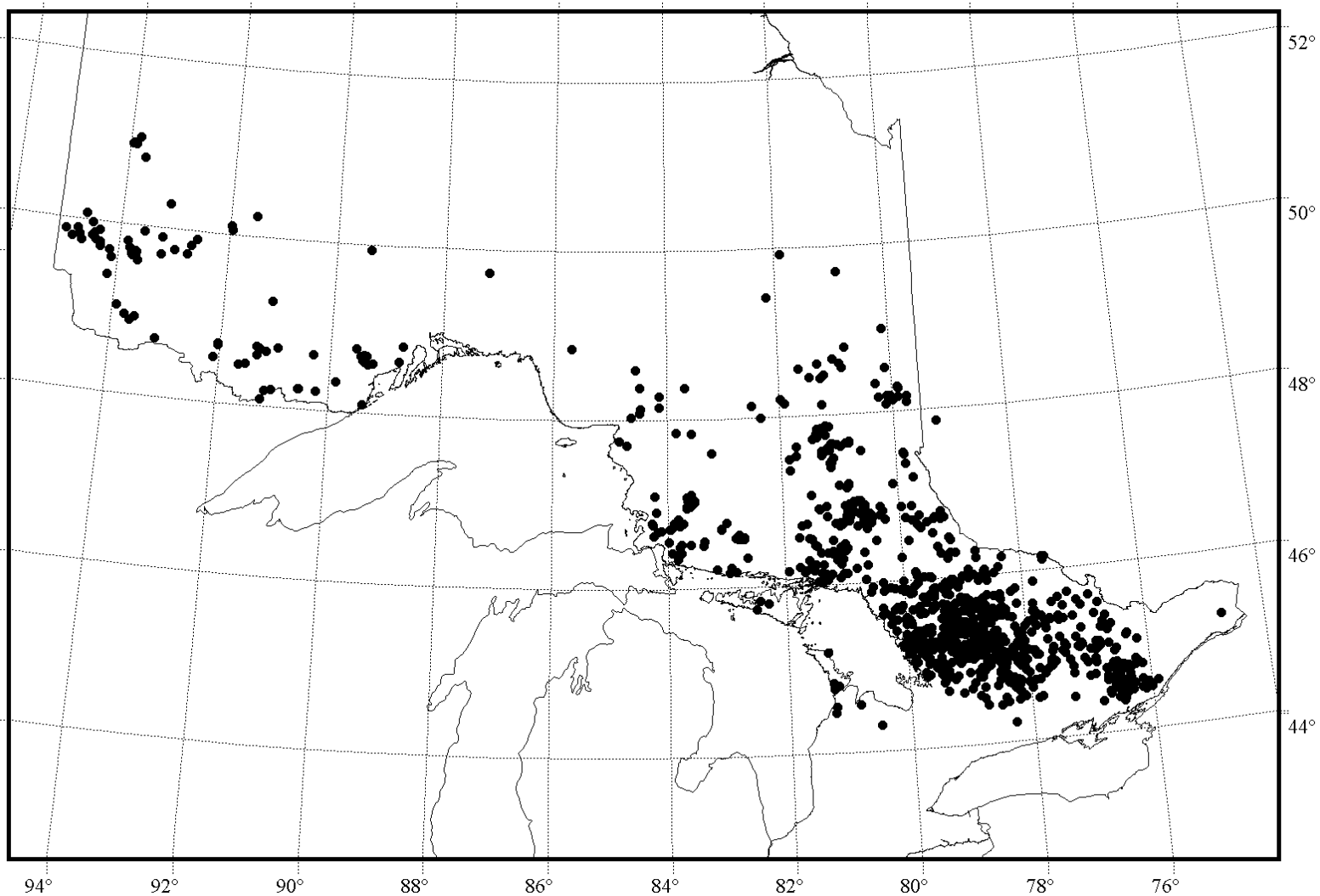


Figure 2. Mean ( $\pm$  2 standard errors) proportion of pairs observed with at least one large young, 1981-1997.

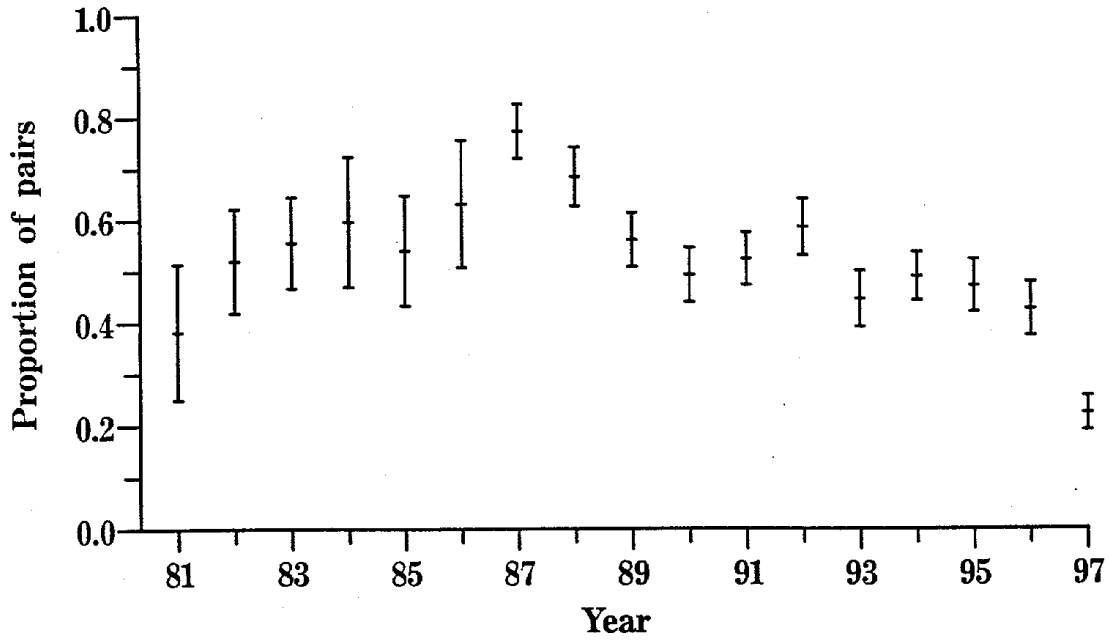


Figure 3. Mean ( $\pm$  2 standard errors) proportion of successful pairs observed with at least two large young, 1981-1997.

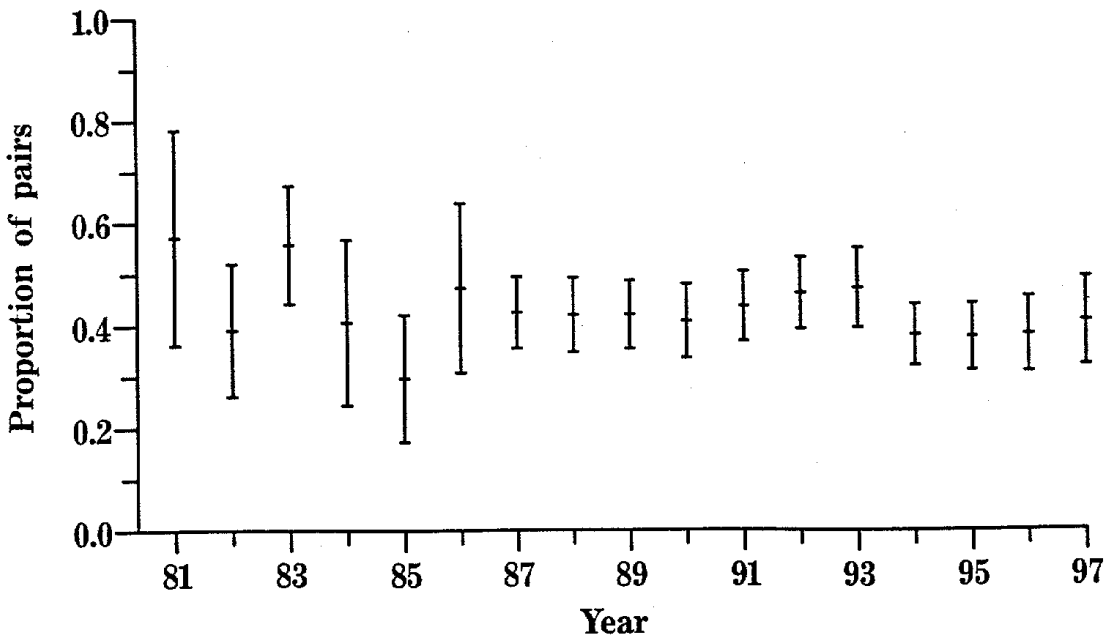


Figure 4. Mean proportion of pairs observed with at least one large young, summarised by lake pH class, 1981-1997. Means differed among pH classes in some years (1987:  $X^2=8.58$ , 2df,  $p=.0137$ ; 1990:  $X^2=6.81$ , 2df,  $p=.0332$ ; 1994:  $X^2=13.25$ , 2df,  $p=.0013$ ; 1995:  $X^2=6.44$ , 2df,  $p=.04$  and 1996:  $X^2=8.99$ , 2df,  $p=.0111$ ).

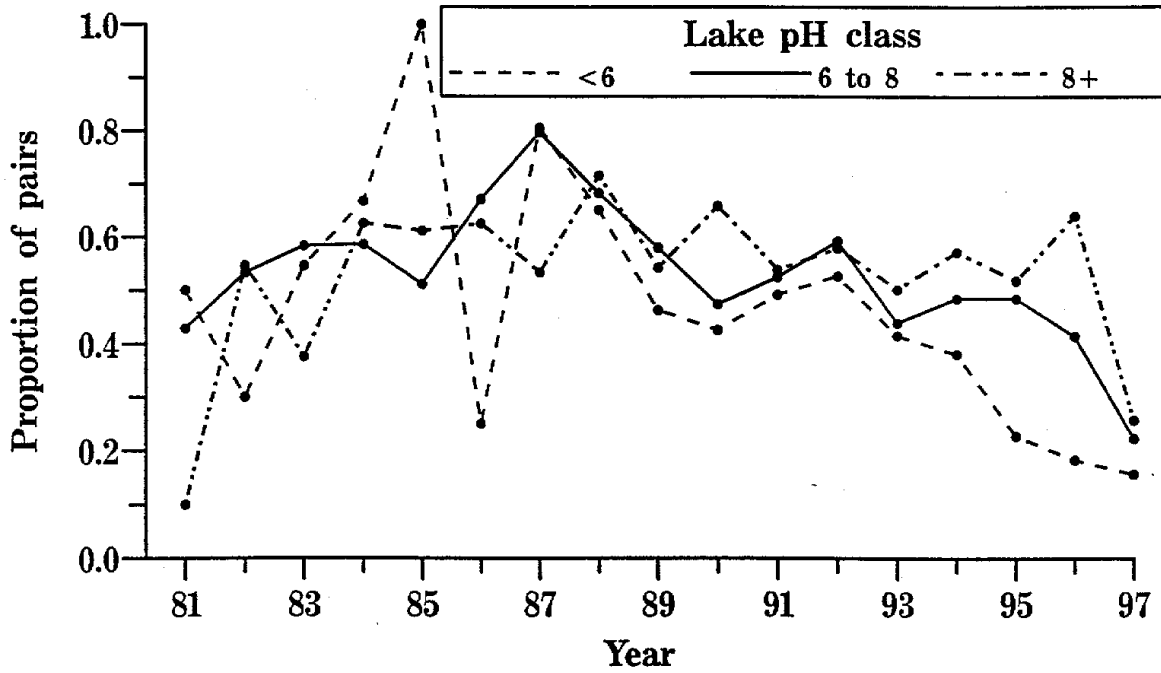


Figure 5. Mean proportion of successful pairs observed with at least two large young, summarised by lake pH class, 1981-1997. Means differed among pH classes in two years (1993:  $X^2=6.4$ , 2df,  $p=.0407$  and 1994:  $X^2=13.22$ , 2df,  $p=.0013$ ).

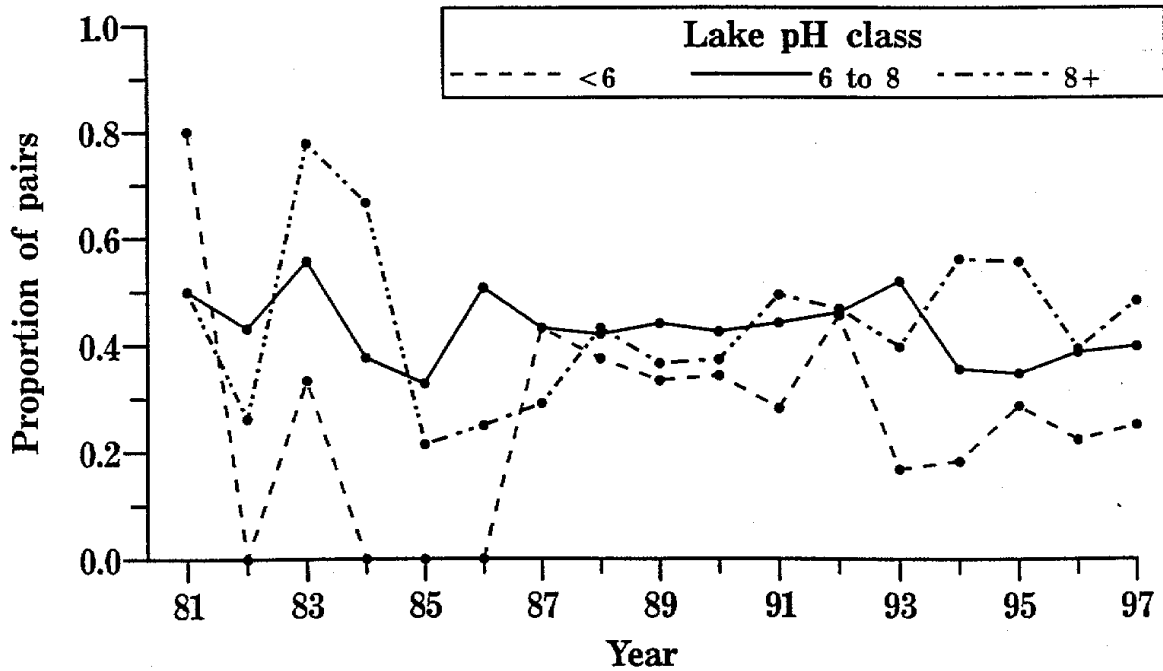


Figure 6. Predicted probabilities of at least one successful pair, by lake pH class, 1981-1997. Probabilities were generated by logistic regressions controlling for lake area and done by pH class. (Lines smoothed using spline fit and tension parameter of 70.)

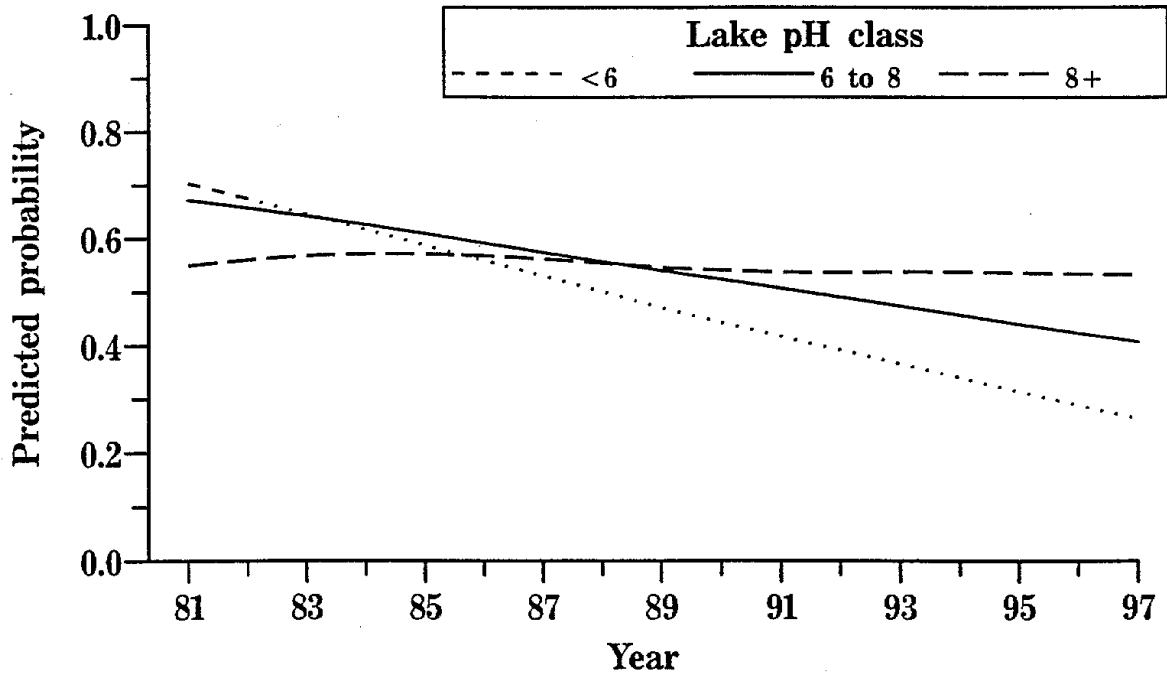


Figure 7. Predicted probabilities of at least one successful pair, by lake pH class, 1987-1997. Using data collected during this time period, probabilities were generated by logistic regressions controlling for lake area and done by pH class. (Lines smoothed using spline fit and tension parameter of 70.)

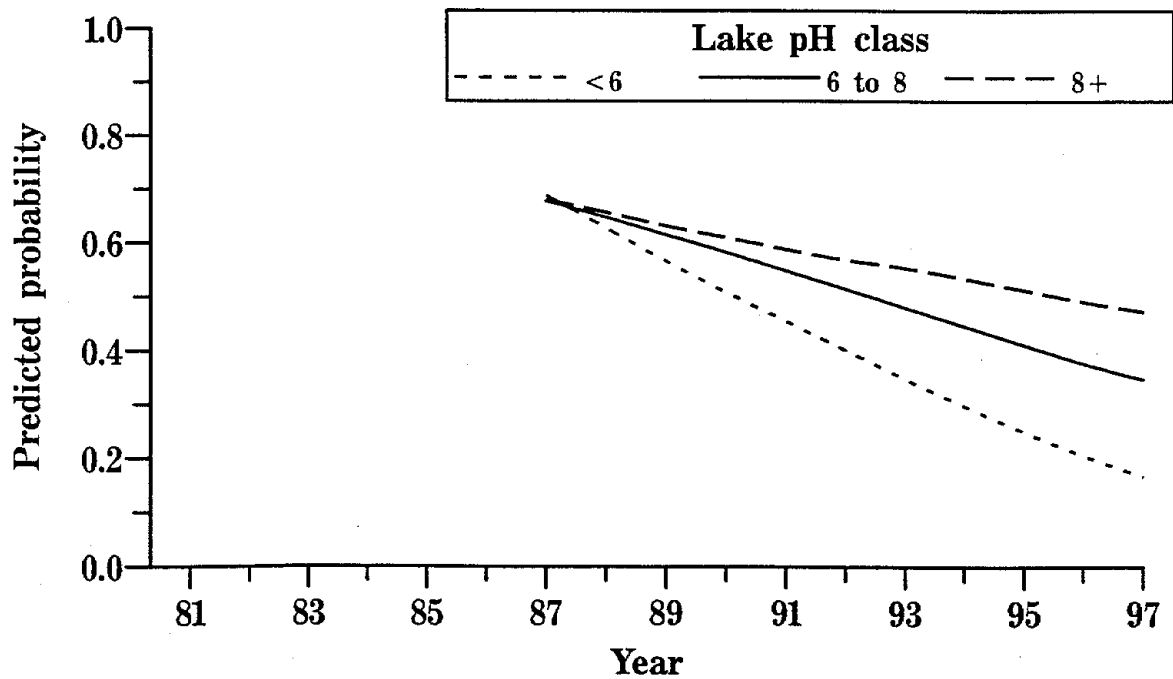
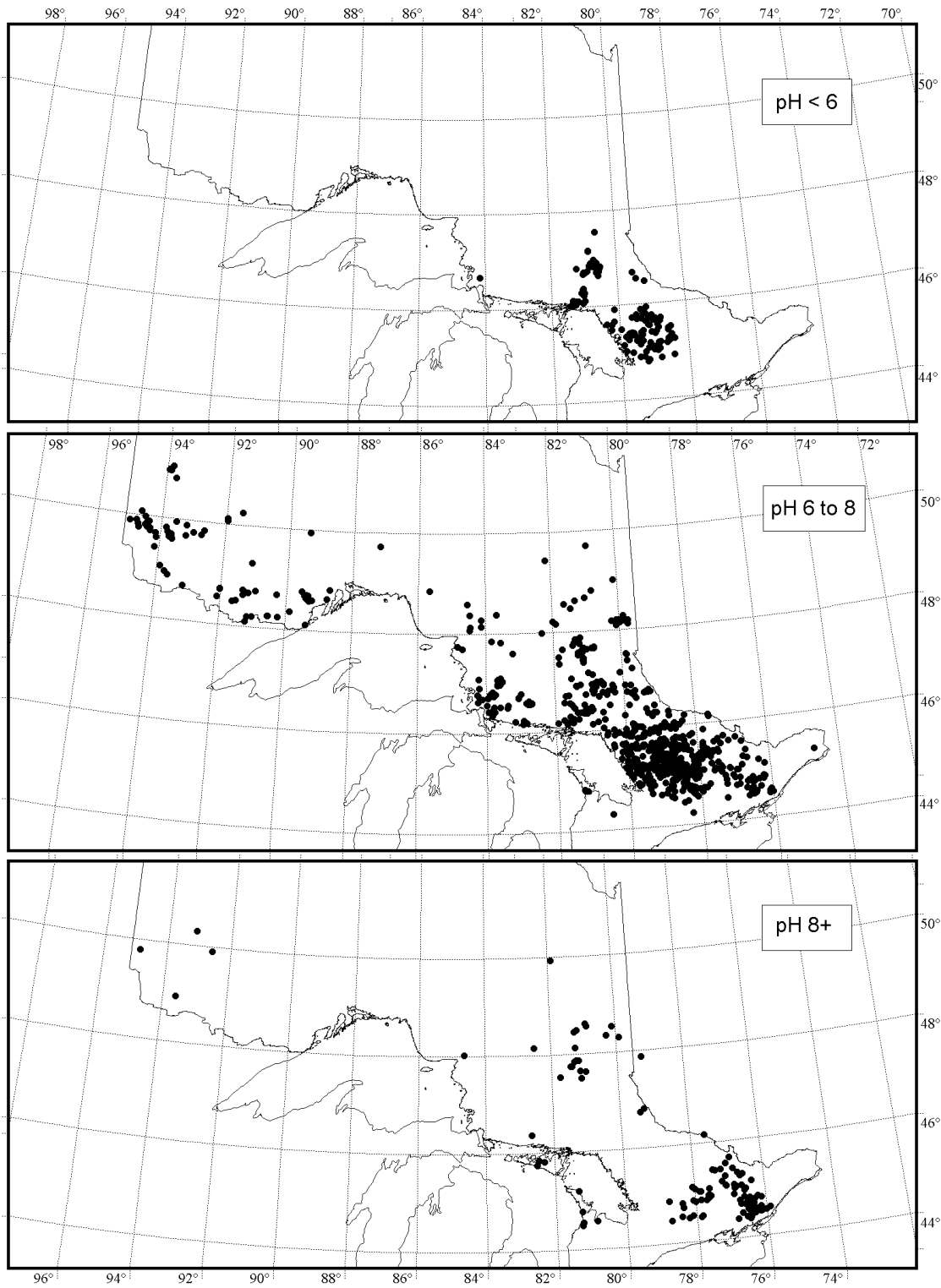


Figure 8. Locations of Canadian Lakes Loon Survey lakes used in analysis of temporal patterns in Ontario loon breeding success, separated by lake pH class.



**Appendix A**

Table A1. Spearman correlations among covariates used in modelling loon breeding success (correlation coefficient / p / sample size).

	<u>PH</u>				
<u>LNAREA</u>	0.23739				
	0.0001				
	3600				
		<u>LNAREA</u>			
<u>DEVELOP</u>	0.17452	0.31026			
	0.0001	0.0001			
	3133	3133			
			<u>DEVELOP</u>		
<u>ACTAUG</u>	0.16676	0.48339	0.60753		
	0.0001	0.0001	0.0001		
	2889	2889	2640		
				<u>ACTAUG</u>	
<u>YEAR</u>	0.0829	0.0106	0.01161	0.03963	
	0.0001	0.5249	0.5159	0.0332	
	3600	3600	3133	2889	
					<u>YEAR</u>
<u>LAT</u>	-0.30007	-0.05891	-0.38988	-0.33821	0.04177
	0.0001	0.0004	0.0001	0.0001	0.0123
	3591	3591	3125	2882	3591

Figure A1. Relationship between pH and area (log transformed) of Ontario CLLS lakes 1981-1997.

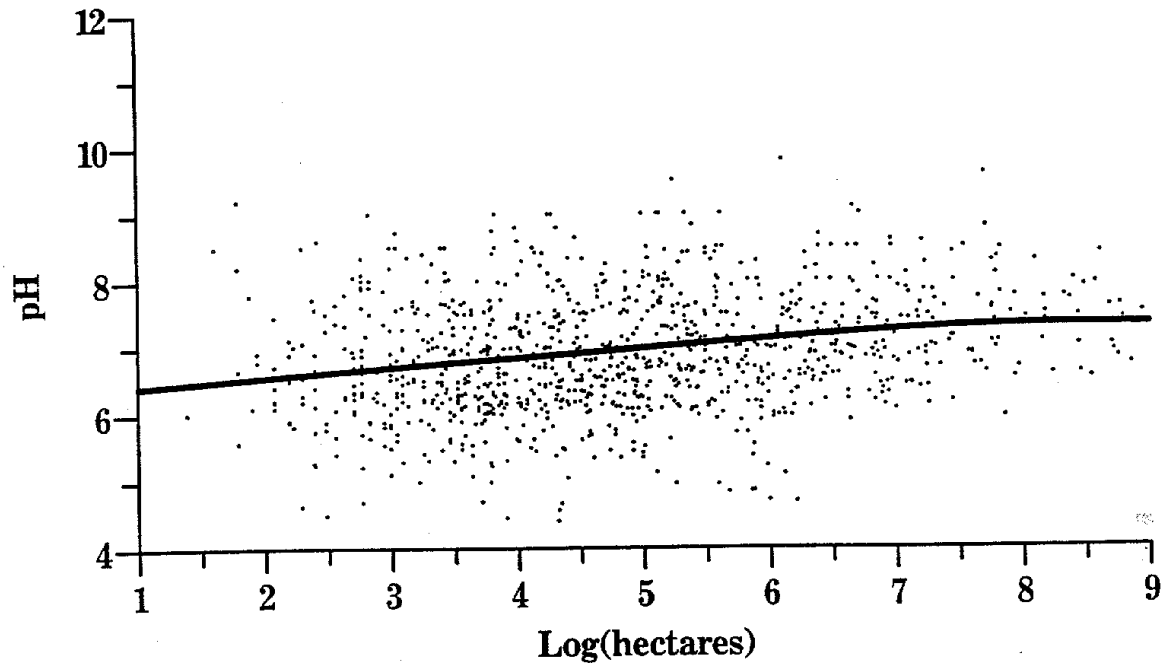


Figure A2. Mean ( $\pm$  2 standard errors) pH of Ontario CLLS lakes in each year 1981-1997.

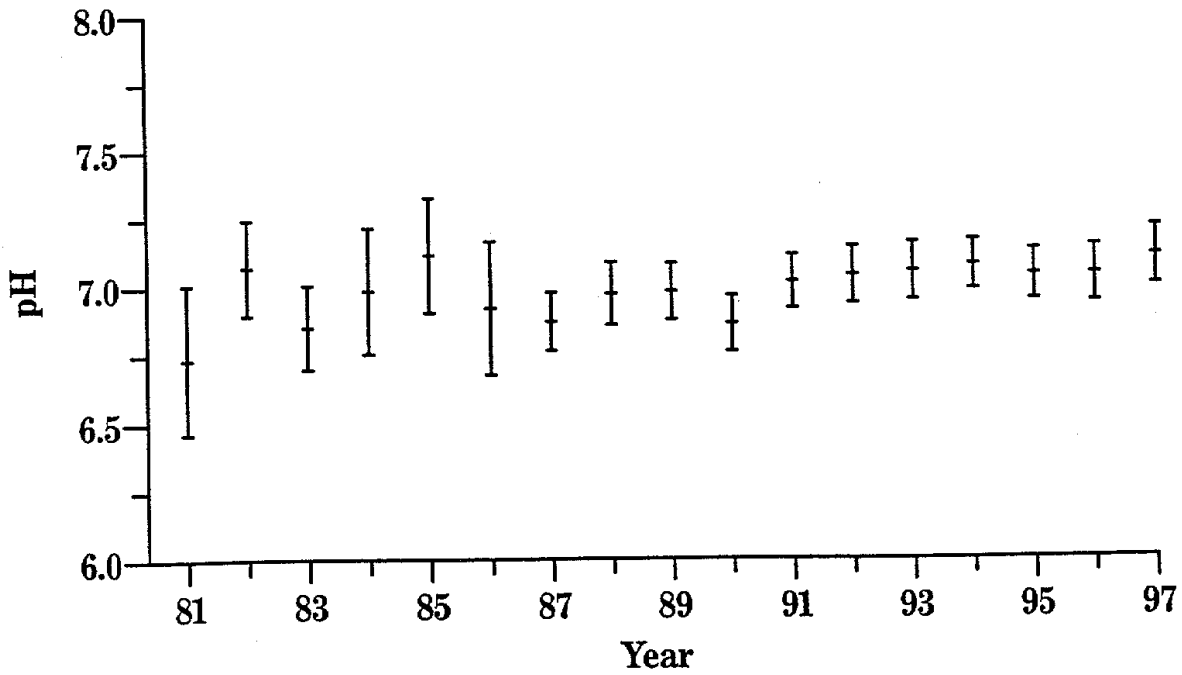


Figure A3. Mean ( $\pm$  2 standard errors) area of Ontario CLLS lakes in each year 1981-1997.

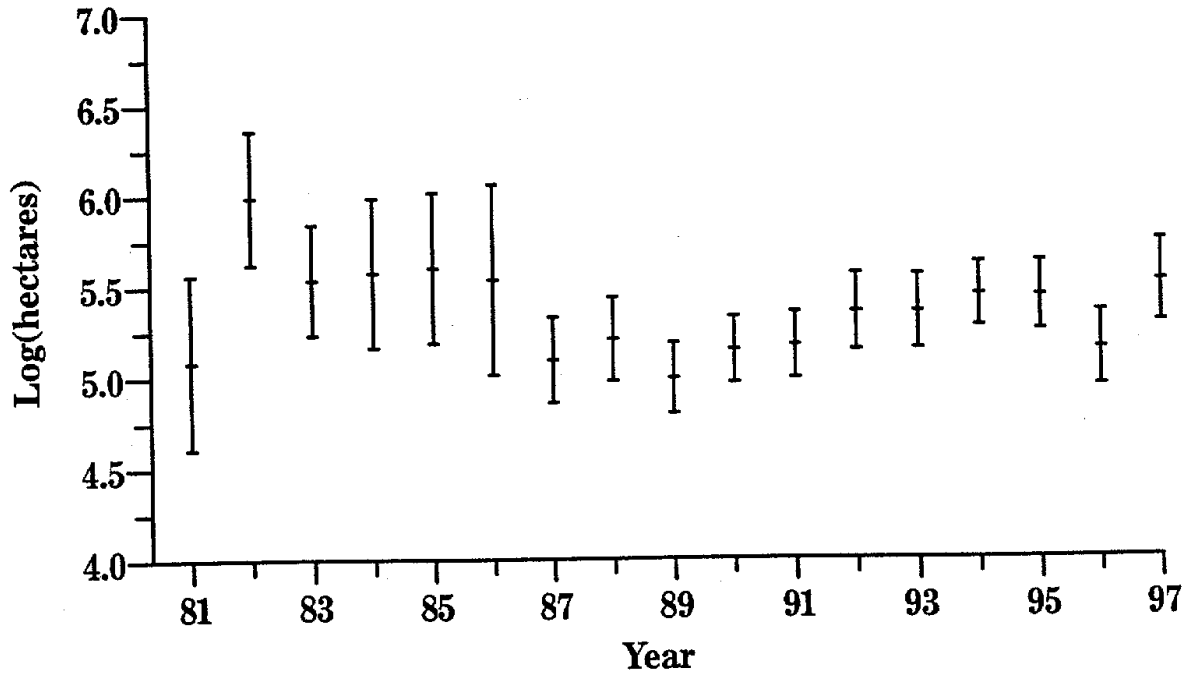


Figure A4. Mean ( $\pm$  2 standard errors) shoreline development class of Ontario CLLS lakes in each year 1981-1997.

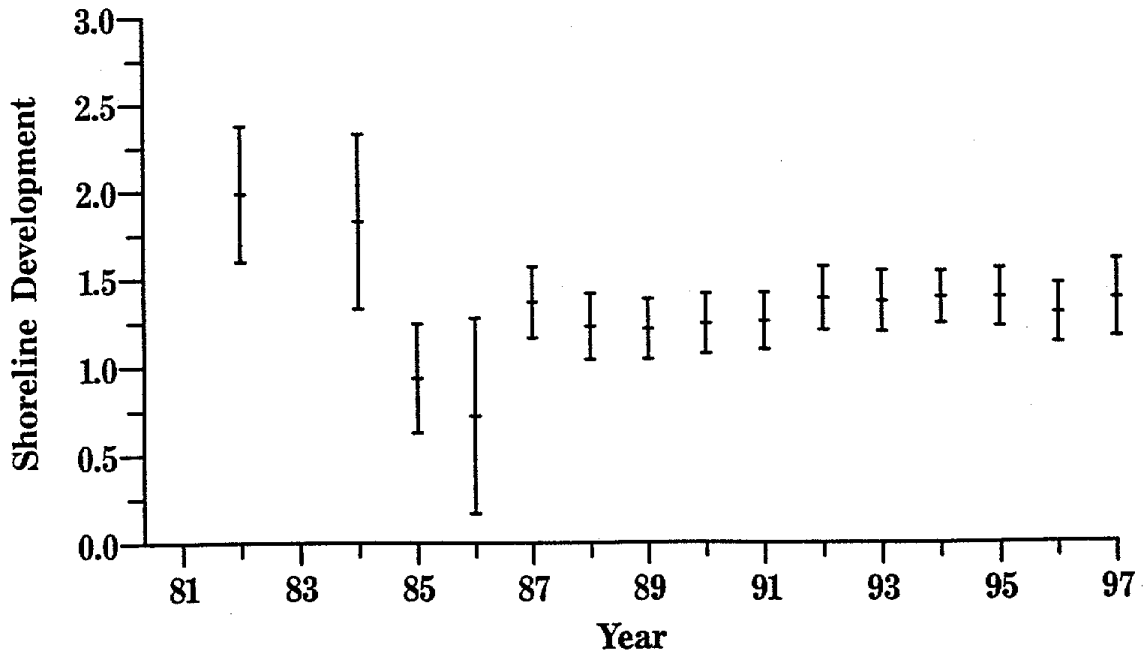


Figure A5. Mean ( $\pm$  2 standard errors) human activity class of Ontario CLLS lakes in each year 1981-1997.

