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The influence of biotic and abiotic factors on banded common loon (*Gavia immer*) reproductive success in a remote, mountainous region of the northeastern United States

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Abstract

Habitat degradation resulting from anthropogenic activities can threaten wildlife populations. Even wildlife existing in seemingly pristine areas are at risk of airborne pollutants and urban development. The common loon (*Gavia immer*), a top-trophic level predator in freshwater aquatic ecosystems, has previously experienced detrimental changes in reproductive success as a result of anthropogenic activities. However, long-term studies and large sample sizes are necessary to ascertain the impacts of various anthropogenic activities on this long-lived species. Using a multi-year dataset, we investigated the effects of multiple biotic and abiotic factors on the probability of adult male and female common loon hatching and fledging success. From 1998–2017, we banded individual loons, collected blood samples to assess mercury (Hg) exposure of the birds, and monitored their reproductive success. Adult female loon hatching success was negatively associated with the amount of rainfall received in a given year while fledging success was positively associated with the amount of shoreline development. Adult male loon hatching success was positively associated with the amount of shoreline development and fledging success was negatively associated with the number of other loon pairs on a lake.

Keywords Common loon · Reproductive success · Mercury · Development · Adirondack Park · Rainfall

Introduction

Wildlife is increasingly faced with multiple obstacles to successful survival and reproduction, even in seemingly pristine ecosystems. Some of these obstacles may be anthropogenic in nature, or derived as a result of anthropogenic activities. Pollution of ecosystems and development of habitat often disturb, degrade, or eliminate critical habitat (Wilcove et al. 1998). Subsequent repercussions to wildlife may include reduced likelihood of survival and lowered breeding propensity and output (Evers 2018). When these anthropogenic threats are combined with already-existing natural threats (i.e. predators, weather), individuals may be unable to successfully occupy these habitats.

Aquatic ecosystem pollution is a major threat to wildlife globally (Dudgeon et al. 2006). In the United States, mercury (Hg) pollution, primarily derived from coal-fired power plants in the Midwest, is a concern to both human and wildlife health (Weiss-Penzias et al. 2016). While atmospheric Hg emissions appear to have decreased in recent years (Zhang et al. 2016), wildlife is still vulnerable to mercury's neurotoxic effects. In freshwater ecosystems, mercury is available to aquatic organisms in the form of methyl mercury (MeHg; Eagles-Smith et al. 2016). The rate of Hg deposition and methylation depends on both lake and landscape characteristics, including lake acidity (lower lake pH increases methylation; Ullrich et al. 2001), the amount and distribution of wetlands in the area (wetlands increase methylation; Shanley et al. 2005), and the percentage of surrounding forest canopy cover (dense canopies scavenge more atmospheric Hg; Witt et al. 2009). Thus, even lakes in remote areas may be particularly susceptible to high levels of mercury if they are characterized by the aforementioned factors.

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The Adirondack Park in northern New York is a relatively remote region where Hg is present in the abiotic and biotic components of the ecosystem (Evers et al. 2007). Because MeHg bioaccumulates up the food chain, it has particularly detrimental effects to top-trophic level organisms (Fevold et al. 2003). The common loon (*Gavia immer*) is a top predator in many northern freshwater ecosystems, including the Adirondacks, and therefore is highly susceptible to Hg pollution. Previous research has found that loons with high blood Hg levels are more lethargic and less attentive to eggs and chicks (Evers et al. 2008). As a result, reproductive success in these high Hg birds can be 32% lower for females and 56% lower for males compared to loons with low Hg levels (Schoch et al. 2014). However, recent research from New York's Adirondack Park has found that loon Hg levels have stabilized in recent years (Schoch et al. in press). Thus, Hg may not impair loon reproductive success as it has in the past.

Conversely, shoreline development and human use of lakes may play a bigger role than Hg in reproductive failure. Because the peak breeding season of loons coincides with human recreational use (i.e. boating, camping, etc.) on and around lakes, loons may be particularly vulnerable to human-derived reproductive failure (McCarthy and DeStefano 2011). Indeed, previous research has found that shoreline development negatively affects loon nesting propensity (Radomski et al. 2014; Spilman et al. 2014) and hatching success (Heimberger et al. 1983). In the Adirondack Park, tourism is a major industry (Tuttle and Heintzelman 2013) and the Park's population more than doubles during the summer with the influx of seasonal residents (Larkin and Beier 2014). Consequently, recreational use of lakes and shoreline development may diminish the quality of loon nesting habitat and result in greater rates of reproductive failure.

Other lake and environmental characteristics may also influence loon reproductive success. Prolonged or intense wet periods may make loon nests more susceptible to flooding, particularly considering common loons typically place nests ≤50 cm of the shoreline's edge and ≤10 cm above the water's surface (Windels et al. 2013). The presence of a dam on a lake may further exacerbate the effects of water level fluctuations from rainfall (Hake et al. 2005). Lake size may also influence both hatching and fledging success, with larger lakes offering more choices for suitable nesting habitat and more hiding spots from predators (Hammond et al. 2012; Field and Gehring 2015). Finally, the number of other loon pairs on a lake may impact fledging success, as conspecific intruders may attack and kill chicks of other territorial pairs (Jukkala and Piper 2015).

In this study, we investigated the effect of blood Hg, shoreline development, and lake use on loon reproductive success (i.e. probability of chicks successfully hatching and of chicks living to fledging age) in the Adirondack Park from 2001–2017. We also examined the relative influence of other factors on reproductive success including total amount of rainfall in a breeding season, the presence of a dam, lake size, and the number of other territorial loon pairs on a lake. We expected that as loon Hg levels and lake shoreline development and use increased, hatching and fledging success would decrease. We also expected that higher total amounts of rainfall and the presence of a dam would be associated with lower hatching success. We expected that as lake size increased, hatching and fledging success would increase. Finally, we expected that as the number of territorial pairs on a lake increased, fledging success would decrease.

Methods

Study area

We conducted our study in New York's Adirondack Park, a 25,000 km^2 forested, mountainous area in northern New York with more than 2800 lakes and ponds. Land ownership is an approximately equal mix of public and private (Glennon and Kretser 2013). The park is home to ~132,000 permanent residents as well as 200,000 seasonal residents (Larkin and Beier 2014).

Sampling and banding loons

From 1998 to 2017, we captured and banded loons on a subset of study lakes each breeding season throughout the Park. We chose study lakes based on the presence of adults with chicks because adults without chicks are very difficult to capture. From 1998–2004, we captured birds for a two-week period, and from 2004–2017 we captured birds for a one-week period. Some study lakes were visited multiple times over the course of the study. We captured loons using spotlighting and playback techniques (Evers et al. 2008). Upon capture, we banded loons using US Geological Survey aluminum bands and a unique combination of plastic colored bands for individual identification. We banded chicks if they were large enough to carry an adult band (usually at least 9 weeks of age, with a foot width of >/=24 mm). We collected blood from the tibiotarsal vein of captured loons for Hg analysis following established protocols (Evers et al. 2008).

Mercury analysis

Laboratory analysis of Hg levels from blood samples was conducted by the Animal Health Diagnostic Laboratory, Pennsylvania State University, the Trace Element Research

Laboratory at Texas A&M, and the Biodiversity Research Institute in Portland Maine (following Evers et al. 1998). Samples were analyzed for total Hg rather than MeHg, as >95% of blood Hg in birds is in the methyl form (Wolfe et al. 2007).

Nest monitoring

We monitored reproductive success of banded loons on 111 lakes from late May to mid/late August of 1998–2017. Loons did not use all of the monitored lakes for breeding (82/111 lakes with documented breeding attempts of banded loons). We chose monitoring lakes based on their watershed (so as to ensure that every watershed within the park contained monitoring lakes), accessibility, and whether there were previous or ongoing scientific studies conducted by other researchers on lake chemistry, mercury, or acid deposition. Lakes were not always monitored in consecutive years. Each year, trained field staff monitored lakes weekly for breeding loons using 10×40 binoculars from a canoe or kayak. Upon finding a nest, observers documented nest location and number of eggs present. In some cases, a nest was never found but chicks were observed on the lake. Monitoring continued throughout the field season until the nest failed, chicks disappeared, or chicks fledged. Chicks were presumed to have fledged if they reached 6 weeks of age, as chicks 6 weeks or older have a high likelihood of surviving to fledging (Evers et al. 2008). From 1998–2000, monitoring was conducted by a few volunteers, and so was relatively unstructured and haphazard, and generally only successful nests were reported. Because of this, we excluded these years from the dataset.

Quantification of predictor variables

For our mercury variable, we assigned a mercury value to each year of reproductive data based on the time period in which we captured the bird. Birds that were captured from 1998–2009 received the same individual mercury value for each of those years within that time period. For example, if a bird was captured in 2005, we assigned the mercury value from 2005 to each year of reproductive data in the period from 1998–2009. If a bird was captured more than once from 1998–2009, we averaged the mercury values from each year it was captured in that period and assigned the average to each year of reproductive data within that time period. We performed the same procedure with birds captured from 2010–2017. If a bird was captured in the 1998–2009 period and again in the 2010–2017 period, then it had two separate mercury values for each year of reproductive data based on the time period. We ascribed Hg values in this way because previous research (Schoch et al. in press) found that Hg values increased from 1998–2009 and showed no significant change from 2010–2016. We felt that ascribing the same Hg value to each year of reproductive data for a bird only captured once during the study would not be representative, particularly for those birds captured early in the study that were monitored until the end of the study. Further, using the reproductive data for only the year in which the bird was captured provided a biased and uninformative sample, as typically only birds that already have chicks are captured.

To quantify shoreline development, we used data from the annual loon census conducted by the Adirondack Center for Loon Conservation and the Wildlife Conservation Society (unpublished data). Since the initiation of the census in 2001, volunteer observers count loons for a 1-h time period on a single day in July on lakes throughout the Adirondack Park. Observers are asked to quantify the amount of shoreline development on lakes using a scale of 0 (67–100% developed), 1 (34–66%), and 2 (0–33%). We used these data as our shoreline development variable for our study lakes that overlapped with the loon census lakes ($n = 69/82$ lakes). We confirmed that the observer quantification matched our own assessment of each study lake using aerial orthoimagery in ArcGIS Pro 2.2.0 (ESRI, Redlands, CA, USA). For the remaining 13 study lakes that were not monitored in the loon census, we quantified shoreline development ourselves using imagery.

To quantify lake use, we used additional data from the loon census. Observers are also asked to document the presence or absence of a boat ramp (0 = ramp present, 1 = ramp absent) and accessibility of the lake (0 = public access, 1 = limited/no access). Using these data, the data collected from the New York State Department of Environmental Conservation (NYS DEC) on the presence of primitive campsites (0 = campsites present, 1 = campsites absent) and campgrounds (0 = campground present, 1 = campground absent), and the shoreline development data, we created a total lake use variable by summing up the scores of each individual variable (i.e. shoreline development, boat ramp, lake accessibility, primitive campsites, and campgrounds) for each lake. Lower composite scores (ranging between 0–6) would indicate higher usage of a lake by humans.

We also used data from NYS DEC to determine the presence or absence of a dam on each lake. If one of our study lakes was connected to a lake with a dam, we considered our study lake to have a dam. We estimated the total amount of rainfall annually on study lakes between May 15 and August 15 from 2001 to 2017 from the nearest of three long-term weather stations in the Adirondack Park (National Centers for Environmental Information 2017). We used the rainfall data of the weather station that was closest to each individual lake. We quantified lake area in ArcGIS. Finally, we determined the number of other territorial pairs on each lake for a given year based on observations by field technicians.

Statistical analysis

We used generalized linear mixed models to examine the effect of blood Hg, shoreline development, total lake use, rainfall, presence of a dam, the number of other pairs on the lake, lake size, and year on the probability of chicks successfully hatching for adult males and females. We conducted the analyses separately for each sex to eliminate issues of pseudoreplication, as some banded birds were mated together, and thus had duplicated, non-independent nesting data. We excluded nests where we were unsure if chicks were depredated before or after hatching. We used the same aforementioned variables with the exception of presence of a dam to determine the best predictors of the probability of ≥1 chick successfully fledging for adult males and females. We excluded those cases where we could not determine whether or not a chick fledged (i.e. because they were not yet 6 weeks old by the end of the monitoring period). In each model, we specified random effects of individual and lake. We used Akaike's Information Criterion to rank models. We considered models with AIC ≤2 to be competitive models (Burnham and Anderson 2002). We also used parameter estimates and 85% confidence intervals to further evaluate strength of models (Arnold 2010). All analyses were conducted in SAS 9.4.

Results

We banded a total of 243 individual adult loons ($n = 124$ males, $n = 118$ females, $n = 1$ sex undetermined) and 99 chicks from 1998–2017. Of the chicks, we determined 4 were females and 3 were males based on subsequent recaptures of either the chick after they reached adulthood or their mating partner. Of the 122 female loons, we removed birds from the dataset that had never bred ($n = 7$), were missing Hg values ($n = 5$), or for which we only had breeding data from 1998, 1999, or 2000 ($n = 5$). We also included breeding data from a loon that was banded after being rescued from fishing line entanglement. Collectively, we used data from 445 nests of 106 female loons on 70 different lakes. Of the 127 male loons, we removed males from the dataset that had never bred ($n = 2$), were missing Hg values ($n = 2$), or for which we only had breeding data from 1998, 1999, or 2000 ($n = 3$). Collectively, we used data from 526 nests of 120 male loons on 71 different lakes.

The probability of chicks successfully hatching for female loons was best predicted by amount of rainfall, with this model holding 69% percent of the weight (Table 1a). As rainfall increased, hatching success decreased ($\beta = -0.100$, SE = 0.037, 85% CI = −0.173, −0.027; Fig. 1). Shoreline development was also an important predictor of hatching success, with success increasing as development increased ($\beta = -0.668$, SE = 0.267, 85% CI = −1.194, −0.142; Fig. 2). Hg was not a strong predictor of hatching success ($\beta = -0.035$, SE = 0.134, 85% CI = −0.299, 0.230) and was ranked below the null model. For male loons, shoreline development was the best predictor of chicks successfully hatching, with this model holding 32% percent of the weight (Table 1b). As development increased,

Table 1 Model selection results for the nine candidate models predicting probability of chicks successfully hatching for (a) female and (b) male loons in the Adirondack Park, 2001–2017

Model	K	AIC_c	ΔAIC_c	$-2\text{Log}L$	w_i
(a)					
Total rainfall	2	563.39	0	557.39	0.69
% shoreline developed	2	567.11	3.72	559.11	0.11
Year	2	568.73	5.34	530.73	0.05
No. of other pairs	2	569	5.61	562.95	0.04
Null	1	569.42	6.03	565.42	0.03
Total use	2	569.58	6.19	563.58	0.03
Dam	2	570.89	7.5	564.89	0.02
Lake size	2	571.33	7.94	565.33	0.01
Hg	2	571.35	7.96	565.35	0.01
(b)					
% shoreline developed	2	664.17	0	658.17	0.32
No. of other pairs	2	665.44	1.27	659.44	0.17
Hg	2	666.12	1.95	660.12	0.12
Total rainfall	2	666.21	2.04	660.21	0.11
Null	1	666.5	2.33	662.5	0.10
Total use	2	666.56	2.39	660.56	0.10
Dam	2	668.03	3.86	662.03	0.05
Lake size	2	668.34	4.17	662.34	0.04
Year	2	679.75	15.58	642.4	0.00

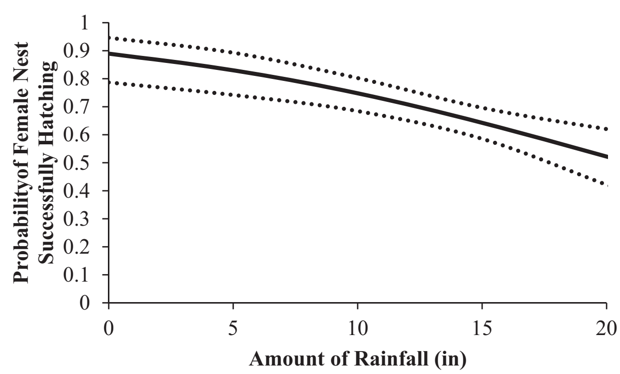

Fig. 1 Probability of female loon nests successfully hatching chicks as a function of amount of rainfall (cumulative total from May 15–August 15) in the Adirondack Park from 2001–2017. Dotted lines represent 85% confidence intervals

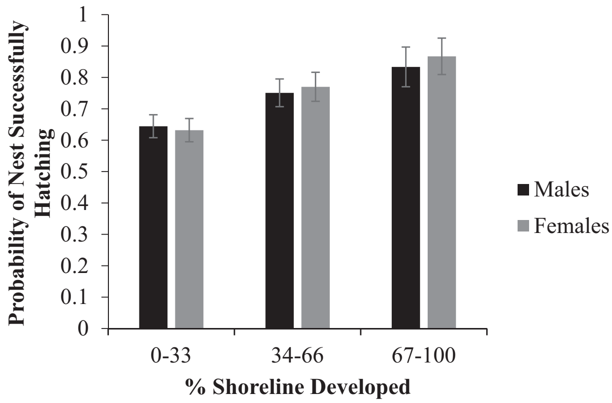

Fig. 2 Probability of male and female loon nests successfully hatching chicks as a function of the % of shoreline developed in the Adirondack Park, 2001–2017. Error bars represent standard error

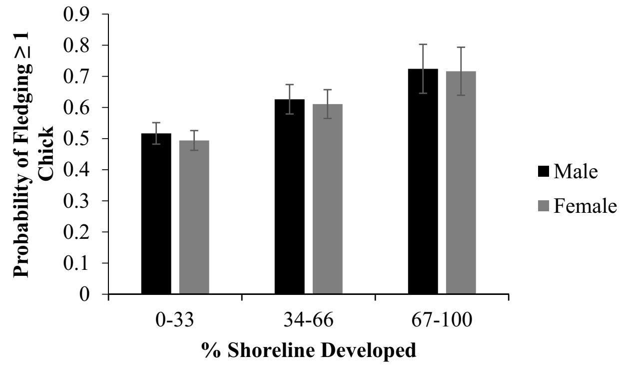

Fig. 3 Probability of male and female loons fledging ≥1 chick as a function of the % of shoreline developed in the Adirondack Park, 2001–2017. Error bars represent standard error

Table 2 Model selection results for the eight candidate models predicting probability of successfully fledging ≥1 chick for (**a**) female and (**b**) male loons in the Adirondack Park, 2001–2017

Model	K	AIC_c	ΔAIC_c	$-2\text{Log}L$	w_i
(a)					
% shoreline developed	2	604.95	0	598.95	0.47
Total use	2	605.65	0.7	599.65	0.33
Null	1	608.87	3.92	604.87	0.07
Total rainfall	2	609.43	4.48	603.43	0.05
Lake size	2	610.32	5.37	604.32	0.03
Hg	2	610.77	5.82	604.77	0.03
No. of other pairs	2	610.93	5.98	602.93	0.02
Year	2	618.47	13.52	580.87	0.00
(b)					
No. of other pairs	2	705.14	0	699.14	0.33
% shoreline developed	2	705.32	0.18	699.32	0.30
Total use	2	707.67	2.53	701.67	0.09
Hg	2	707.84	2.7	701.84	0.09
Null	1	707.92	2.78	703.92	0.08
Total rainfall	2	707.98	2.84	701.98	0.08
Lake size	2	709.82	4.68	703.82	0.03
Year	2	718.75	13.61	682.75	0.00

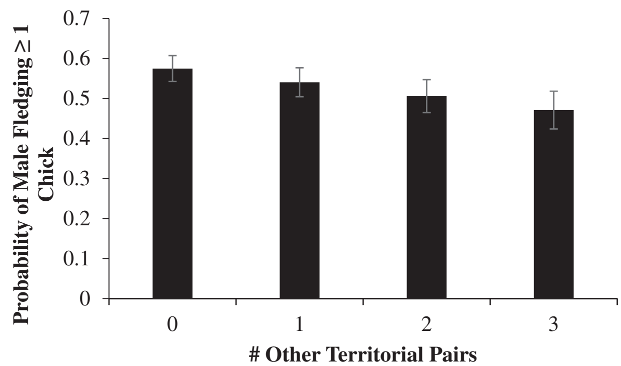

Fig. 4 Probability of a male loon fledging ≥1 chick as a function of the number of other territorial pairs on a given lake in the Adirondack Park, 2001–2017. Error bars represent standard error

hatching success increased ($\beta = -0.508$, SE = 0.247, 85% CI = −0.994, −0.022; Fig. 2). Hg was not a strong predictor of hatching success of male loon parents ($\beta = -0.189$, SE = 0.247, 85% CI = −0.419, 0.036).

The probability of a chick successfully fledging for female loons was best predicted by shoreline development, with this model holding 47% of the total weight (Table 2a). Total lake use also was an important predictor of successful fledging, with this model holding 33% of the weight. As development ($\beta = -0.475$, SE = 0.205, 85% CI = −0.880, −0.071; Fig. 3) and lake use ($\beta = -0.195$, SE = 0.084, 85% CI = −0.360, −0.030) increased, the likelihood of successfully fledging a chick increased. Hg was not an important predictor of fledging probability ($\beta = 0.037$, SE = 0.116, 85% CI = −0.191, 0.265). For male loons, the number of other territorial pairs on the lake was the best predictor of a chick successfully fledging, with this model holding 33% percent of the weight (Table 2b). With more pairs on the lake, fledging success decreased ($\beta = -0.139$, SE = 0.035, 85% CI = −0.207, −0.071; Fig. 4). Shoreline development was also a strong predictor of fledging success, with success increasing as development increased ($\beta = -0.449$, SE = 0.214, 85% CI = −0.871, −0.028; Fig. 3). Hg was not an important predictor of fledging success ($\beta = -0.160$, SE = 0.106, 85% CI = −0.370, 0.049).

Discussion

Hg did not have a strong effect on the likelihood of loons successfully hatching or fledging chicks, although we note that Hg was a competitive model in predicting male loon hatching success. We expect that Hg impacts males more than females because males are larger than females, eat larger prey, and thus have higher Hg loads, and females have the ability to depurate Hg into eggs (Scheuhammer et al. 1998; Burgess et al. 2005). Interestingly, previous work in this system has documented a large negative effect of blood Hg on loon productivity using data from 1999–2007 (Schoch et al. 2014). Different analysis methods between our paper and Schoch et al. (2014) could account for the inconsistencies observed. Alternatively, Hg may no longer be significantly impacting reproductive success as it once was. Indeed, the Clean Air Act Amendments of 1990 and the 2011 Mercury and Air Toxic Standard Act strengthened regulations on mercury emissions and have resulted in declines in atmospheric Hg (Castro and Sherwell 2015). For at least one watershed in the Adirondacks, these declines have translated to declines in Hg wet deposition (Mao et al. 2017) and MeHg concentrations (Gerson and Driscoll 2016). For loons, blood Hg levels have stabilized in recent years (Schoch et al. in press). Thus, Hg may no longer be as important in driving loon reproductive success or, conversely, Hg's effect may be obscured by other concurring adverse threats such as shoreline development, predation, or water level fluctuations.

Shoreline development was an important predictor of male hatching and fledging success, as well as female fledging success. Surprisingly, however, the likelihood of successfully hatching eggs and fledging chicks increased as the amount of shoreline development increased. Specifically, there was a significant difference in reproductive success of loons inhabiting lakes that were 67–100% developed and 34–66% and 0–33% developed, but there was no difference between the latter two categories. We note that only 4 of 70 lakes for female loons and 5 of 71 lakes for male loons were classified as 67–100% developed, thus it is difficult to ascertain whether this result is an artifact of low sample size. However, other studies have similarly found no effects of development on loon productivity (Caron and Robinson (1994; Badzinski and Timmermans 2006; McCarthy and DeStefano 2011; Field and Gehring 2015). From one author's (N. Schoch) personal experience monitoring loons for 20 years in the Adirondack Park, many loons seem habituated to humans and are unbothered by human use of lakes. If there is an actual relationship of higher reproductive success on highly-developed lakes, we theorize that this pattern could be explained by decreased occupancy of bald eagles (*Haliaeetus leucocephalus*)—an important predator of loon eggs (McCarthy et al. 2010), chicks (Paruk 1999), and even adults (Vliestra and Paruk 1997)—on these lakes. While we do not know the relationship between bald eagles and shoreline development in the Adirondack Park, previous research has found that bald eagles avoid using or nesting near areas occupied by humans (Saalfield and Conway 2010; Watts et al. 2015). We recommend that future research investigate the relationship between common loons, bald eagles, and shoreline development.

Other factors such as rainfall and the number of other territorial pairs on a lake had an influence on loon reproductive success. Rainfall was particularly important in predicting chick hatching success of female loons. Loon nests are vulnerable to flooding given their placement at the shoreline's edge. As significant rain events are expected to increase in the northeast due to climate change (Schoof and Robeson 2016), we expect that flooding could become a major concern for loon productivity. For male loons, the number of other territorial pairs on the lake was an important predictor of both hatching and fledging success. Territorial intrusions by conspecifics are frequent during the breeding season, and both males and females defend territories (Piper et al. 2000). Competition for territories may be more costly for males, as unlike for females, they can lead to sometimes fatal contests (Piper et al. 2008).

Collectively, our results point to a diversity of factors impacting reproductive success in common loons in the Adirondack Park. We expect that some of these factors will exhibit temporal variations in their contributions to reproductive success. Hg, for example, may become more important if current Hg regulations are weakened (Thomson et al. 2018). As previously mentioned, rainfall may also play a more important role in future years given the projected increase in annual rainfall amount and intensity in the northeast (Guilbert et al. 2015). Further, the Adirondack Park may be close to carrying capacity for breeding common loons, as territorial interactions are becoming more frequent and loons are increasingly observed on lakes with no history of occupancy (Schoch unpublished data). Thus, the number of territorial pairs on a lake could hinder both male and female reproductive success in the future. Closely monitoring such factors will be necessary to ensure that common loons persist as an iconic species of wilderness in northern freshwater ecosystems.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethics All applicable national and institutional guidelines for the care and use of animals were followed.

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