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Research Article

Population-Level Effects of Lead Fishing Tackle on Common Loons

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ABSTRACT Poisoning from lead fishing tackle has been identified as the leading cause of mortality in adult common loons (*Gavia immer*). As a K-selected species, adult survival is a critical component in the population demography of loons, but the population-level effects of mortality from ingested lead tackle on loons have not been quantified. We used a long-term dataset (1989–2012) on common loon mortality in New Hampshire, USA, to describe the types of lead tackle ingested by loons, investigate methods of ingestion of lead tackle, document the number and rate of adult mortalities resulting from lead tackle, and test for a population-level effect of lead tackle on the loon population in New Hampshire. Nearly half (48.6%) of collected adult mortalities resulted from lead toxicosis from ingested lead fishing tackle, representing an adjusted annual mortality rate of $1.7 \pm 0.6\%$ (SD) of the statewide population. Jigs accounted for 52.6% and sinkers for 38.8% of the archived lead tackle objects removed from loons, a higher proportion of jigs than has been reported in previous studies. The timing of lead tackle mortalities and a high incidence of accompanying non-lead associated fishing gear (hooks, fishing line, leaders, swivels, wire), which peaked in July and August, suggest that loons obtain the majority of lead tackle from current fishing activity rather than from a reservoir of lead tackle on lake bottoms. To project the statewide loon population in the absence of lead fishing tackle as a stressor, we constructed a retrospective population model, which re-inserted loons that died from lead tackle into the population, and used linear regression to test for a population-level effect. We defined a population-level effect as a difference in the population growth rate (λ). We estimated that lead tackle mortality reduced the population growth rate (λ) by 1.4% and the statewide population by 43% during the years of the study. This study suggests that replacing lead fishing sinkers and jigs weighing $\leq$28.4 g with non-toxic alternatives would result in an immediate benefit to the loon population in New Hampshire. © 2017 The Wildlife Society.

KEY WORDS common loon, fishing tackle, *Gavia immer*, lead, mortality, New Hampshire, population-level effects, populations.

Ingested lead fishing tackle has been documented in 28 species of North American birds (Blus 1994, Scheuhammer and Norris 1995, Anderson et al. 2000, Scheuhammer et al. 2002, Franson et al. 2003), as a risk factor for 75 species (U.S. Environmental Protection Agency 1994), and as a leading cause of death for common loons (*Gavia immer*; Pokras and Chafel 1992, Stone and Okoniewski 2001, Sidor et al. 2003, Strom et al. 2009, Grade 2011). Because common loons may live for 30 years, do not breed until they are $\geq$4 years of age, and have a low fecundity of 0.53 chicks fledged/territorial pair/year on average (Evers et al. 2010), population viability is heavily influenced by adult survival (Grear et al. 2009); therefore, high rates of lead tackle mortality among adult loons have the potential to adversely affect populations.

The New Hampshire Department of Fish and Game classified the common loon as a threatened species in New Hampshire, USA. Since 1975, the Loon Preservation Committee (LPC; Moultonborough, NH) has worked to recover the state's population through intensive management activities, including providing artificial nesting platforms, protecting nest sites with signs and rope boundaries, working with dam operators to stabilize lake water levels during nesting, and educating the public (LPC, unpublished data). This intensive management and outreach has contributed to an increase in the statewide loon population from 135 adults in 1975 to 638 in 2012 (Table S1, available online in Supporting Information). However, fewer than half of the lakes predicted by Kuhn et al. (2011) to be suitable for loons are occupied, and loon densities remain at <25% of densities on oligotrophic lakes in Canada (Fox et al. 1980, McIntyre 1988, Timmermans et al. 2004).

The intersection of a state-threatened loon population and high fishing pressure in New Hampshire (Scheuhammer et al. 2002)

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suggests the potential for a population-level effect to loons from lead tackle mortality. Intensive monitoring of the state's loon population and mortality allows an assessment of the effects of lead tackle mortality on the population that is not possible for many other species and locations. Given the limited dispersal distances of loons from natal lakes or previous breeding territories to new potential breeding territories (Piper et al. 1997, 2012, Evers et al. 2010), we treated New Hampshire's loons as a closed population.

The goals of this study were to describe types and sizes of lead tackle ingested by loons collected in New Hampshire, investigate methods of ingestion of lead tackle, document the number and rate of adult mortalities resulting from lead tackle, and define and test for a population-level effect of lead tackle on the New Hampshire loon population. We hypothesized that the timing of collected mortalities from lead fishing tackle and the presence of associated tackle (hooks, fishing line, leaders, swivels, wires) in loons that died from lead tackle would differ by month and coincide with the timing of peak fishing pressure on New Hampshire lakes, suggesting most lead tackle is obtained from current fishing activity. We further hypothesized that the population growth rate of New Hampshire's observed loon population would differ from that of a modeled population with loons that died of lead ingestion re-inserted into the population, indicating a population-level effect from lead tackle mortality.

STUDY AREA

New Hampshire, located in the northeastern United States, is dominated by northern hardwood and spruce (*Picea* spp.)-fir (*Abies* spp.) forest, with 83% of the state forested (Morin and Widmann 2016). Average annual temperatures in New Hampshire range from −6.1°C in winter to 18.3°C in summer (New Hampshire State Climate Office 2014). The state has approximately 66,770 ha of lake surface area, of which 74% are oligotrophic lakes and the majority of the remainder are mesotrophic lakes (New Hampshire Department of Environmental Services, unpublished report). Loon carrying capacity and habitat models (Kuhn et al. 2011) predict that 550 lakes $\geq$5 ha in New Hampshire are suitable for whole or multiple loon territories or partial territories comprised of $>$1 lake.

METHODS

Population Monitoring, Mortalities, and Ingested Tackle

The LPC intensively monitors New Hampshire's common loon population to determine abundance, productivity, and mortality. Between 1989 and 2012, LPC monitored an average of 264 lakes/year, of which an average of 135 were occupied annually by loon pairs (Table S1). During these years, the statewide adult loon population averaged 500 ± 75 (SD) and grew from 367 adults in 1989 to 638 adults in 2012 (Table S1). A professional staff of 10 biologists monitored lakes, augmented by reports from 350 to 830 statewide volunteers that grew over time with the loon population (LPC, unpublished data). The LPC's monitoring protocol requires multiple visits by biologists to previously occupied loon lakes each year to determine occupancy and productivity and systematic monitoring of unoccupied lakes to detect loon dispersal to new lakes (Sidor et al. 2003). We regard these data as essentially a census of the statewide population rather than a more traditional and limited survey because of the intensity of monitoring and consistent monitoring of suitable but unoccupied lakes.

Loon Preservation Committee biologists monitor for loon mortalities during regular lake visits, supplemented by reports from volunteers and New Hampshire Fish and Game biologists. Systematic surveys and high recreational activity on New Hampshire's lakes from May through September increases the likelihood of detection, reporting, and collection of moribund or deceased loons during the primary times loons are present on breeding lakes. This study used data from 253 adult common loon carcasses collected between 1989 and 2012. No live animals were involved in this study, and carcasses of loons found dead were collected by LPC and state biologists under appropriate state and federal permits. Animal-welfare protocols for this study were approved by the Institutional Animal Care and Use Committee of Cummings School of Veterinary Medicine, Tufts University (protocol G961-08).

Our study focused on adult loon mortality because lead toxicosis from ingested tackle primarily affects this segment of the population (Pokras and Chafel 1992, Sidor et al. 2003). Mortality data included banded adult loons that belonged to the New Hampshire population collected throughout the year ($n = 41$) and unbanded adult loons collected in New Hampshire between May and September ($n = 212$). The latter were likely birds belonging to the New Hampshire population because these are the months when loons in New Hampshire are resident on freshwater lakes (LPC, unpublished data) and few loons are migrating through the state (Powers and Cherry 1983, Kenow et al. 2009). Given the apparent rapidity of death from lead toxicity in loons (Pokras and Chafel 1992, Sidor et al. 2003), loons that died from lead toxicosis during these months likely ingested tackle on New Hampshire lakes. To understand whether LPC's mortality collections were representative of overall loon mortality on the breeding lakes, we estimated the annual percentage of total expected freshwater mortalities that were collected by LPC using the following equation:

$$M_F = \frac{\bar{M}_c}{\bar{N}(1 - S_a)(0.42)} \times 100\%$$

where M_F is the estimated percentage of freshwater mortalities collected (May–Sep), $\bar{M}_c$ is the average number of mortalities collected annually from May to September, $\bar{N}$ is the average population size (Table S1), S_a is the adult survival rate for common loons (Mitro et al. 2008), and 0.42 is the fraction of the year from May to September. We used the value of 0.92 (Mitro et al. 2008) as the baseline rate of adult survival when estimating collection rates and for adult survival in our model because this is the only published mark-recapture study investigating adult survival rates for common loons. Mitro et al. (2008) used New Hampshire banding data from 1994 to 2001, overlapping with 8 of the 24 years of the present study. Mitro et al. (2008) included banded loons from Maine and Wisconsin in addition to New Hampshire but reported no geographical variation in survival rates between loons. Lacking data on within-year patterns of adult mortality (Augspurger et al. 1998), we assumed a constant rate of mortality from sources other than lead toxicity throughout the year and that the proportion of mortalities on breeding and wintering grounds was proportional to time spent in these locations.

Mortality results for 91 birds, including 59 mortalities from lead tackle, in the present study have been published (Pokras and Chafel 1992, Tufts University School of Veterinary Medicine and U.S. Fish and Wildlife Service 1992, Sidor et al. 2003), but we present 162 previously unreported mortalities, including 64 lead tackle cases. Tufts University School of Veterinary Medicine and U.S. Fish and Wildlife Service (1992) and Pokras et al. (2009) published details of 17 jigs and 21 sinkers or split shots included in the present study. We report 44 jigs and 24 sinkers or split shots for the first time. No mortality or lead tackle results have been published for loons in New Hampshire that died after 2000 ($n = 148$ total mortalities). We reviewed and re-analyzed all necropsy and tackle data from 1989 to 2012 to focus on population-level effects of lead tackle mortality on loons in New Hampshire.

The LPC sent carcasses for necropsy to the Cummings School of Veterinary Medicine at Tufts University (CSVM; North Grafton, MA, USA), the United States Geological Survey National Wildlife Health Center (NWHC; Madison, WI, USA), and the New Hampshire Veterinary Diagnostic Laboratory (NHVDL; Durham, NH; Table 1). We retained 18 birds that were not necropsied and for which the cause of death remains unknown (Table 1) in the dataset to estimate the proportion of lead tackle mortalities more accurately and conservatively. The procedure for the determination of the cause of death at CSVM and NHVDL is given in Sidor et al. (2003) and at NWHC, in cases of lead poisoning, in Franson et al. (2003). We re-examined evidence from each necropsy (Table 1) and classified the cause of death as lead tackle toxicosis if ≥ 2 of the following 5 conditions were met: tissue, blood, or body fluids were tested for lead and exceeded thresholds at which clinical signs of lead poisoning have been observed (Sidor et al. 2003, Franson and Pain 2011); the necropsy form reported the cause of death as lead toxicosis, indicated the presence of lead tackle in the gastrointestinal (GI) tract, or documented clinical pathology consistent with lead toxicosis; ≥ 1 tackle object was removed from the loon's GI tract, re-tested for the present study, and tested positive for lead; a radiograph showed a sinker or jig inside the loon's GI tract; and the field mortality collection report noted signs consistent with lead toxicosis.

We identified, weighed, and measured each tackle item in archived gizzard contents and tested each object using Lead-Check Swabs^{TM} (3M, St. Paul, MN, USA), which detect lead in metal products at levels >0.2% (2,000 ppm; 3M 2011). We weighed each tackle item on a digital scale to the nearest 0.01 g and measured each item's length along the longest axis with calipers to the nearest 0.01 mm. Ingested tackle erodes in the gizzard because of grinding action and stomach acids; and, in the case of jigs, hooks or other attachments break off and often dissolve or are passed prior to death (Pokras et al. 2009). We report the mass and length of eroded lead jigheads and sinkers.

Methods of Lead Tackle Ingestion

We examined the timing of lead tackle mortalities and the presence of non-lead associated tackle (hooks or hook fragments, fishing line, swivels, leaders, wires) in loons that died from ingested lead tackle to investigate whether loons acquire lead tackle from current fishing activity (ingesting a fish with attached tackle or striking at a bait or fish being retrieved by an angler) or from a reservoir of lost lead tackle on the lake substrate. If the latter, we would expect the rate of lead tackle mortality to be relatively constant during the time loons are resident on lakes and would not expect associated tackle to be present in the loons' gizzards because it is unlikely that a loon would mistake a lead object with associated tackle for a pebble to ingest as grit (Franson et al. 2001). We performed a chi-square test on monthly lead tackle mortality totals from May to September to test for independence between the number of deaths and the

Table 1. Evidence for diagnosing lead toxicosis from ingested lead fishing tackle in collected common loon carcasses from the New Hampshire, USA, loon population, 1989–2012.

			Evidence supporting diagnosis of lead tackle ingestion as cause of death for each loon				
Necropsy status[a]	**All documented mortalities**	**Lead tackle mortalities**	**Blood or tissue lead levels**[b]	**Necropsy forms**	**Archived tackle object**	**Radiograph**	**Field mortality report**
CSVM	222	119	70	111	96	78	63
NWHC	6	1	1	1	0	0	1
NHVDL	2	1	1	1	0	0	1
Not necropsied							
COD known	5	2	0	0	1	1	2
COD unknown	18	0					
Total	253	123	72	113	97	79	67

[a] CSVM, Cummings School of Veterinary Medicine at Tufts University; NHVDL, New Hampshire Veterinary Diagnostic Laboratory; NWHC, U.S. Geological Survey National Wildlife Health Center; COD, cause of death.

[b] Not all loons were tested for lead because of technological and funding constraints.

month they occurred, calculated Pearson's residuals to determine if the number of deaths was different between months, and used Pearson's contingency coefficient (*C*) to measure the strength of association between the number of deaths and the month they occurred (an effect size). We used the same analysis to test whether the presence of non-lead associated tackle in lead tackle mortalities differed by month. Because hook fragments found inside loons that ingested jigs may have been part of the original jig, to be conservative we did not classify hooks in these loons as associated tackle. We performed statistical tests using the R statistical program (R version 3.1.0, www.R-project.org, accessed 15 January 2013).

We conducted observations of the timing of fishing activity in New Hampshire, using Squam Lake as a proxy, to correlate with the timing of collected lead tackle mortalities. Squam is a 2,738-ha oligotrophic lake in central New Hampshire that is well-known to anglers and experiences fishing pressure that is representative of other lakes in the state. We conducted 167 30-minutes observations from a motorboat at random times during daylight hours from May to August 2010–2011 within randomly selected loon territories. We classified a boat as a fishing boat if the occupants were actively engaged in fishing, or a boat under power was a bass boat or other fishing-type boat and multiple fishing rods were observed in the boat.

Population Projections

To assess potential population-level effects of lead fishing tackle mortality on loons in New Hampshire, we retrospectively projected a range of adult population sizes had the loons collected from 1989 to 2012 that died from lead tackle ingestion survived. Density-independent and deterministic 2- and 3-stage Lefkovitch matrices and 4 × 4 and 7 × 7 Leslie matrices were not robust and predicted $\leq$85% of the observed population (LPC, unpublished data), likely because the use of average values for productivity and survival parameters did not capture their inherent stochasticity. Therefore, we did not use these matrices and instead developed a rigorous retrospective model for projections using observed population numbers and productivity values and estimated survival rates for each year of the study. We created a model in Microsoft Excel (Microsoft, Redmond, WA, USA) to add an estimate of the number of loons that died of lead tackle ingestion annually to the observed population and projected population growth in the absence of lead tackle mortality (i.e., projected population). We also projected a conservative estimate for the projected population based on lead tackle mortalities actually collected by LPC (i.e., conservative projection).

We assumed an equal sex ratio in loons (Grear et al. 2009), equal survival rates between the sexes (Mitro et al. 2008), equal annual survival rates for adult loons $\geq$3 years old, equal survival rates between breeding and non-breeding adults (Grear et al. 2009), and a stable age distribution, lacking data to the contrary. We used the following equation to calculate the number of loons in the model for the projected population:

$$L_t = A_t + \left(\frac{A_t\, b_t}{2}\right) m_t\ S_j + J_{1,t}\ S_j + J_{2,t}\ S_j$$

where L_t is the number of loons in the model in time *t*, A_t is the number of adult loons in the model in time *t*, b_t is the rate of pairing propensity in time *t* from LPC's monitoring data (Table S1), S_j is the annual sub-adult survival rate ($S_j = 0.80$; Piper et al. 2012), $J_{x,t}$ is the number of surviving sub-adult loons in the model aged *x* years in time *t*, and m_t is the number of chicks surviving/territorial pair alive in mid-August in time *t* (Table S1). We define a territorial pair as 2 loons that defend a territory for $\geq$4 weeks and have the potential to nest. Our use of observed values for m_t when modeling the absence of lead tackle mortality is conservative because these values include reductions in productivity resulting from the loss of adults to mortality from lead tackle ingestion (Grear et al. 2009). We used the value of S_j presented in Piper et al. (2012) for Wisconsin because data are lacking for sub-adult survival rates for loons in New England. The equation we used to calculate *b* is from Grear et al. (2009):

$$b_t = \frac{TP_t}{\frac{UA_t}{2} + TP_t}$$

where TP_t is the observed number of territorial pairs in time *t* and UA_t is the observed number of unpaired adults in time *t* (Table S1).

We calculated the number of adult loons, A_t, for the projected population in time *t* using the following equation:

$$A_t = A_{Pb,t}\ Z_t\ S_{a,t} + A_{t-1}\ S_{a,t} + A_{3,t}\ S_{a,t}$$

where $A_{Pb,t}$ is the number of adult loons collected by LPC in time *t* that died of ingested lead fishing tackle, Z_t is an adjustment factor (see below) to raise the number of collected lead mortalities in time *t* to the number of expected lead mortalities, A_{t-1} is the number of adult loons in the model in time $t-1$, $A_{3,t}$ is the number of loons produced in the model transitioning to year 3 in time *t*, and $S_{a,t}$ is the adult survival rate in time *t*. The model applies $S_{a,t}$ to the component values of A_t prior to calculating productivity, resulting in a conservative number of breeding loons and productivity output in the modeled population for each year. We calculated the annual adjustment factor, Z_t, using

$$Z_t = \frac{N_t\left(1 - S_{a,b}\right)(0.42)}{M_c}$$

where N_t is the observed number of adults in time *t* in the population (Table S1), $S_{a,b}$ is the baseline rate of adult survival from Mitro et al. (2008), 0.42 is the fraction of the year from May to September, and M_c is the number of adult loon mortalities from all causes collected each year of the study (Table S1). We assumed that the proportion of mortalities on breeding and wintering grounds was proportional to time spent in these locations, lacking data on the ratio of saltwater to freshwater mortalities (Augspurger et al. 1998).

In the equation for A_t, we multiplied $A_{Pb,t}$ by $S_{a,t}$ to adjust for potential mortality from causes other than lead tackle ingestion. To calculate $S_{a,t}$, we used the value of 0.92 (Mitro et al. 2008) as the baseline rate of adult survival ($S_{a,b}$). Because lead tackle mortality in loons is likely additive (Gauthier et al. 2001, Lavers et al. 2009), we assumed that the adult survival rate would be higher in the absence of lead fishing tackle than the published rates of Mitro et al. (2008), which were based on band return data of loons subject to lead fishing tackle mortality. To estimate the annual adult survival rate in the absence of lead tackle, we calculated the rate of estimated total lead tackle mortalities each year as a percentage of the adult loon population and added this to $S_{a,b}$ using the following equation:

$$S_{a,t} = S_{a,b} + \frac{A_{Pb,t}\ Z_t}{N_t}$$

To generate our projected population, we added A_t to the observed population from LPC's monitoring data, N_t (Table S1). Stochastic events are inherent in observed population numbers, and stochastic variability in productivity was incorporated into the projected population by using the observed value of m for each year. To calculate the conservative projected population, we removed the adjustment factor (Z_t) from the 2 equations in which it appeared, leaving only collected lead tackle mortalities.

We calculated a 95% confidence interval for the adult survival rate using the values presented in Mitro et al. (2008) for loons in New England. We used the upper confidence interval presented in Mitro et al. (2008) for loons in New England without adding the per capita lead tackle mortality rate because this would produce a result that is biologically unrealistic. For sub-adult survival, we used the lower (0.79) and upper (0.81) range of values reported by Piper et al. (2012).

We estimated observer error in LPC's population monitoring dataset of live loons by calculating a combined detection probability using methods presented in Fletcher and Hutto (2006) because there are no published data on detection errors specific to loons or independent censuses of New Hampshire's loon population. We used data on large, open-water aquatic birds from that study, including the American white pelican (*Pelecanus erythrorhynchos*), double-crested cormorant (*Phalacrocorax auritus*), Canada goose (*Branta canadensis*), mallard (*Anas platyrhynchos*), and common merganser (*Mergus merganser*). We calculated a 95% confidence interval for this detection probability and applied it to observed values of adults, territorial pairs, and unpaired adults in LPC's dataset. We applied only an upper 95% confidence interval to observed values of surviving chicks to account for missed chicks because double counting is an unlikely source of error for unfledged chicks (Evers et al. 2010).

To compare the difference in slope between the observed and projected populations, we grouped them into one combined response and regressed the populations on time and a categorical variable using the following analysis of covariance model

$$Y_t = \beta_0 + \beta_1\ X_{1,t} + \beta_2\ X_{2,t} + \beta_{12}\left(X_{1,t}\ X_{2,t}\right) + \varepsilon_t$$

where Y_t is the dependent variable (the difference between observed and projected populations) at time t, $X_{1,t}$ is the time variable, $X_{2,t}$ is the dummy variable ($X_{2,t} = 0$ if count is observed population, 1 if projected population), and ε_t is the error. The interaction term is the effect of a change in the time variable on the mean loon population dependent on group (observed or projected), which we used to assess the difference in slope between the 2 populations for each test.

Regression diagnostics confirmed that the error terms in our model were not independent, and autocorrelation and partial autocorrelation plots showed exponential decrease with increased lags and one statistically significant lag value, respectively. These plots suggested errors followed an autoregressive process of order 1 (AR[1]). For an AR(1) time-series process, the underlying time-series process can be summarized by a linear model in which we predict the time series at the present time period using the value at the previous time. The AR(1) model is written $x_t = \delta + \phi_1\ x_{t-1} + w_t$, where x_t is the value of the time series at time t, x_{t-1} is the value at time $t-1$, δ and ϕ_1 are regression coefficients, and w_t are the errors with $w_t \sim N\left(0,\sigma_w^2\right)$. For cases when the errors follow an AR(1) process, the Cochrane-Orcutt procedure is a remedial measure, which can be applied iteratively to a regression model to eliminate correlated errors (Cochrane and Orcutt 1949). We applied this procedure once, and the resulting model diagnostics and a Durbin–Watson test indicated that no further action was required.

After addressing the correlated errors, we fit the model to our data and assessed the interaction term through statistical (P value) and biological significance (effect size; Fernie et al. 2005). We based the biological significance of the interaction term on Cohen's f^2, a measure of effect size for $\geq$1 predictors within a multiple regression model (Cohen 1988). Cohen's f^2 is given by:

$$f^2 = \frac{R_{AB}^2 - R_A^2}{1 - R_{AB}^2}$$

where B is the interaction term, A is the set of all other variables, R_{AB}^2 is the proportion of variance accounted for by A and B together, and R_A^2 is the proportion of variance accounted for by A. The numerator of the expression reflects the proportion of variance uniquely accounted for by B, in excess of all other variables (Cohen 1988).

RESULTS

Mortalities and Tackle

From 1989 to 2012, 48.6% of adult common loon mortalities collected in New Hampshire resulted from lead toxicosis caused by $\geq$1 pieces of ingested lead fishing tackle (123 of 253 collected mortalities; Table 2). The average annual per capita rate of documented lead tackle mortality for the

Table 2. Causes of mortality for banded common loons known to be part of the New Hampshire, USA, loon population and loons collected in New Hampshire between May and September, 1989–2012.

Cause of death	No.	%
Lead fishing tackle	123	48.6
Unknown	35	13.8
Trauma, unknown	21	8.3
Aspergillosis	14	5.5
Trauma, boat	12	4.7
Monofilament entanglement	10	4.0
Trauma, conspecific	9	3.6
Lead, unknown object	8	3.2
Non-lead fishing gear	8	3.2
Gunshot	3	1.2
Other[a]	10	4.0
Total	253	100

[a] Includes loons that died of the following causes: botulism, egg binding, electrocution, emaciation, gizzard perforated by foreign object, infection, ingested lead shot, oil, parasites, trauma from predator.

New Hampshire population was 1.0 ± 0.5% (SD; range = 0.2–2.1%). The LPC collected an average of 10 adult loons/year (range = 3–17). This represents an average of 60% of freshwater adult loon mortalities expected annually, based on a 0.08 annual adult mortality rate (Mitro et al. 2008). Adjusting for this collection rate results in an average annual mortality rate of 1.7 ± 0.6% from ingested lead tackle.

One hundred sixteen of 117 (99.1%) archived sinkers, jigs, swim baits, internal weights, or other types of tackle weights removed from loons tested positive for lead. The exception was a brass sinker, and the loon from which this sinker was removed had also ingested a lead jig. Jigs accounted for 52.6% ($n = 61$ jigs in 57 loons) and sinkers for 38.8% ($n = 45$ sinkers in 34 loons) of the archived lead tackle objects removed from loons, with the remaining 8.6% of lead tackle objects including swim baits, internal weights from lures, and other types of tackle weights ($n = 10$ objects in 9 loons). These numbers do not include tackle documented on radiographs or in necropsy reports but not preserved. Tackle may not be identifiable to specific type on radiographs, and some lead tackle from the early years of the study may have been misidentified on necropsy forms. Examining the evidence on the level of loons rather than number of tackle objects, 59.4% of the loons for which tackle was archived ingested a jig, 35.4% ingested a sinker, and 9.4% ingested another type of lead tackle. These percentages exceed 100% because some loons ingested >1 type of lead object. Eroded jigheads without hooks or attachments removed from loons weighed between 1.02 g and 18.43 g and eroded sinkers weighed between 0.26 g and 30.43 g (Table 3).

Methods of Lead Tackle Ingestion

The number of collected lead tackle mortalities differed by month, based on the chi-square test ($\chi^2 = 27.08$, $P \leq 0.001$) and associated contingency correlation ($C = 0.92$), a large effect size according to Cohen's guidelines for effect sizes (Cohen 1988). The number of loons collected that died from lead tackle ingestion increased 2.5 times between June and July (Fig. 1), and July and August differed from May, June, and September (Jul residuals = 2.35, Aug residuals = 2.35). Lead tackle mortalities collected statewide each month correlated closely with monthly rates of fishing boats/hour on our proxy lake ($R^2 = 0.96$ for an exponential equation; Fig. 1). The presence of non-lead associated tackle in loons that died from lead tackle ingestion differed by month ($\chi^2 = 18.92$, $P \leq 0.001$; $C = 0.89$, a large effect size as defined in Cohen [1988]) and increased between June and July by 3.0 times. July and August differed from other months for associated tackle (Jul residuals = 2.22, Aug residuals = 2.22), and the presence of non-lead associated tackle in loons that died from lead tackle ingestion correlated closely with monthly rates of fishing boat activity ($R^2 = 0.93$ for an exponential equation; Fig. 1).

Population-Level Effects

The observed New Hampshire loon population and error limits in 2012 were 638 ($599 \leq N \leq 679$) adult loons (Table S1), with a population growth rate (λ) of 1.023 ($1.018 \leq \lambda \leq 1.029$) from 1989 to 2012. The projected population with the effects of lead tackle mortality removed was 911 ($793 \leq N \leq 1{,}512$) adult loons with a λ of 1.038 ($1.031 \leq \lambda \leq 1.061$). The interaction term from our regression model to test the slopes between the observed and projected population indicated a difference in slopes for the 2 populations ($t_{44} = 5.49$, $P \leq 0.001$; $f^2_{\text{Interaction}} = 0.72$, a large effect size as defined in Cohen [1988]). The conservative projection, incorporating only collected lead tackle mortalities, yielded a λ of 1.032 ($1.025 \leq \lambda \leq 1.045$) and 795 ($688 \leq N \leq 1{,}045$) adult loons (Fig. 2). The interaction term for the test between the observed and the conservative projection likewise indicated a difference ($t_{44} = 3.49$, $P = 0.001$; $f^2_{\text{Interaction}} = 0.29$, a medium effect size as defined in Cohen [1988]).

DISCUSSION

Mortalities and Tackle

Our study found that mortality from lead fishing tackle ingestion is the leading documented cause of death for adult loons in New Hampshire, exceeding all other known causes of death combined and the second leading known cause of

Table 3. Archived tackle objects recovered from carcasses of banded common loons known to be from the New Hampshire, USA, loon population and loon carcasses collected in New Hampshire between May and September, 1989–2012. All objects are eroded from their original size, and jigheads lack hooks and other attachments.

		Mass (g)				Length (mm)			
Lead object	n	$\bar{x}$	SE	Median	Range	$\bar{x}$	SE	Median	Range
Jighead	61	3.89	0.42	2.97	1.02–18.43	17.22	0.78	16.80	6.90–34.30
Sinker	45	4.26	0.95	1.57	0.26–30.43	13.20	1.49	9.80	0.60–56.80

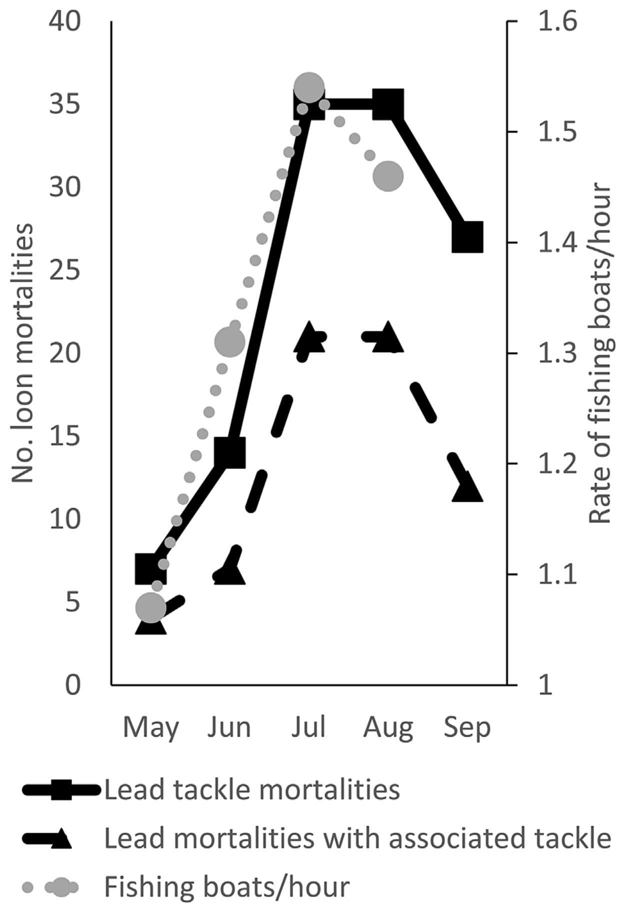

Figure 1. Timing of fishing activity on Squam Lake, New Hampshire, USA, 2010–2011, documented statewide lead fishing tackle mortality of common loons, and lead mortalities with non-lead associated tackle, 1989–2012.

death by nearly 6 times (Table 2). The lead tackle mortality rate of 48.6% of collected adult loons in this study is similar to rates of 44% to 65% found in earlier studies of adult common loon mortality on breeding grounds in the northeastern states (Pokras and Chafel 1992, Tufts University School of Veterinary Medicine and U.S. Fish and Wildlife Service 1992, Sidor et al. 2003, Pokras et al. 2009). Franson et al. (2003) reported a 7.5% rate of lead toxicosis in predominantly live northeastern loons, which, given the evidence suggesting a rapid death following lead ingestion in loons (Pokras and Chafel 1992, Sidor et al. 2003), were unlikely to be carrying ingested lead tackle. Sidor et al. (2003) noted that LPC's high rate of annual carcass recovery (28%), and, consequently, the 60% average freshwater recovery rate in this study, likely provides an accurate representation of relative causes of mortality of loons on New Hampshire breeding grounds.

This study documented a much higher proportion of loons dying from ingested lead-headed jigs (59.4%) than previous studies, with the closest being 42.9% in New York (Stone and Okoniewski 2001). Although previous studies have also examined tackle in loons from New Hampshire (Franson and Cliplef 1992, Franson et al. 2003) and reported on tackle found in loons in New England up to 2000 (Tufts University School of Veterinary Medicine and U.S. Fish and Wildlife Service 1992, Pokras et al. 2009), the higher proportion of jigs found in our study may have resulted from different fishing tactics in New Hampshire compared with the larger New England region or from misidentifications of jigheads as sinkers when common loon mortality from lead tackle was an emerging issue.

The weights and sizes of eroded lead jigheads and sinkers reported here were similar to those from other studies. The heaviest eroded jighead removed from loons included in our analyses weighed 18.43 g, although an eroded jighead found inside a loon collected in New Hampshire in December 2010 (excluded because of uncertain population origin) weighed 20.93 g. The heaviest eroded sinker documented in this study weighed 30.43 g, but Franson et al. (2003) reported an eroded sinker weighing 78.2 g. The size of tackle loons are capable of ingesting is demonstrated by a previously unreported saltwater jighead and hook remnant weighing 116 g removed from a loon recovered on the coast of Massachusetts (M. A. Pokras, CSVM, personal communication). Although the erosion rate of a lead object in a loon gizzard is unknown, studies of erosion of lead shot (Cook and Trainer 1966, Finley et al. 1976) and lead tackle (M. A. Pokras, personal communication) in avian gizzards demonstrate that erosion rates can be substantial.

Methods of Lead Tackle Ingestion

Our findings indicate a peak in the timing of lead tackle mortalities in July and August, coinciding with a peak of fishing activity on our proxy lake, which suggests that common loons obtain the majority of ingested lead tackle from current fishing activity (i.e., eating a fish that has ingested a lead jig or sinker and broken the line, or striking at tackle or a fish being retrieved by an angler). This is in contrast to what has been stated in previous studies (Pokras and Chafel 1992, Tufts University School of Veterinary Medicine and U.S. Fish and Wildlife Service 1992, Scheuhammer et al. 2002, Pokras et al. 2009, Haig et al. 2014), which suggested loons obtain lead from a reservoir of lost tackle on the substrates of lakes, mistaking lead for pebbles ingested to help break up food (Franson et al. 2001). If ingested lead was obtained primarily from lake substrates, we would expect the rate of lead tackle mortality to be relatively constant during the time loons are resident on lakes. Franson and Cliplef (1992) noted that 10 of the 14 (71.4%) lead mortalities in their study were collected in July, August, and September, a grouping the authors suggest may be associated with fishing activity. This peak is likely not an artifact of time spent foraging. Time activity budgets indicate that loons spend less time foraging during incubation and chick rearing periods (15–40%; Evers 1994, Barr 1996, McCarthy 2010), typically June through August in New Hampshire (LPC, unpublished data), than during the pre-nesting period (49–57%; Evers 1994, Barr 1996, Paruk 1999, McCarthy 2010).

The majority (54.5%) of loons with ingested lead tackle also had ingested non-lead associated tackle. We would not expect loons looking for pebbles to ingest an object with line, hooks, or other wire objects attached. The number of loons dying from lead tackle that also had non-lead associated tackle peaked in July and August, further suggesting ingestion of tackle from current fishing activity. In our analysis, we

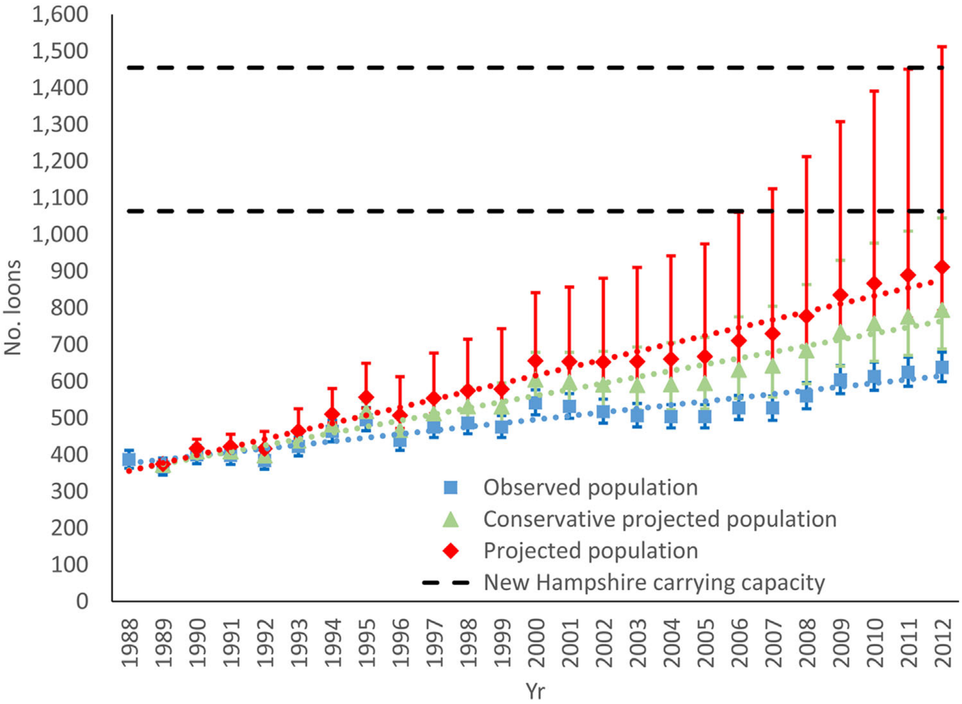

Figure 2. Number of observed adults in the common loon population in New Hampshire, USA, and projected adult population in absence of mortalities from lead fishing tackle, 1989–2012. Error bars indicate 95% confidence intervals. The projected population is based on the estimated number of adult loons that died of ingested lead fishing tackle. The conservative projected population is based on mortalities actually collected from 1989–2012. The 2 dashed lines mark the estimated range of carrying capacity for loons in New Hampshire. The upper dashed line is based on data of loon density presented by Fox et al. (1980), McIntyre (1988), and Timmermans et al. (2004) and the lower dashed line is based on modeling data (Loon Preservation Committee, unpublished report).

conservatively excluded loons with ingested jigheads that retained a hook fragment but no other associated tackle at the time of necropsy because these hooks could have come from the ingested jig. Including these loons, on the assumption that a loon would not mistake a jig with an attached hook for a pebble, the occurrence of associated tackle in loons that died from ingested lead tackle increases to 64.2%. Many loons lacking associated tackle at the time of necropsy may have lost these items from erosion in the gizzard or from being passed prior to death (Stone and Okoniewski 2001). The speed at which non-lead associated tackle breaks down depends on the size and chemical composition of the object; but, based on clinical cases, non-stainless hooks seem to digest within 2 weeks (S. L. Bartlett, Wildlife Conservation Society, unpublished data; M. A. Pokras, personal communication). Given the apparent rapidity of digestion or elimination of non-lead associated tackle, rates of ingestion from current fishing activity may be higher than what is presented here.

Following implementation of lead tackle restrictions in the United Kingdom, there was a rapid decline in lead mortality among the mute swan (*Cygnus olor*) population (Sears and Hunt 1991, Kirby et al. 1994, Newth et al. 2013). Our data indicate that restrictions on the use of non-toxic lead tackle would have similar immediate benefits to loons.

Population-Level Effects

As a K-selected species with a low natural mortality rate, whose statewide density is <25% that described for loon populations on large oligotrophic lakes in Canada (Fox et al. 1980, McIntyre 1988, Timmermans et al. 2004) and half what suitable habitat can support (Kuhn et al. 2011), New Hampshire's loons fit the model of a species and population for which anthropogenic mortality is additive rather than compensatory (Gauthier et al. 2001, Lavers et al. 2009). We defined a population-level effect as a difference in the growth rate between the observed population and a modeled population with lead tackle removed as a stressor. By this definition, lead tackle mortality has had an effect on New Hampshire's loons at a population level ($P \leq 0.001$; effect size: $f^2 = 0.72$), reducing λ by 1.4% and resulting in a 43% decrease in New Hampshire's loon population based on our retrospective model. Even our conservative projection, based only on collected mortalities, indicated a reduction in λ by 0.9% and a 24% decrease in loon numbers ($P = 0.001$; effect size: $f^2 = 0.29$). Chronic annual mortality from lead tackle at an average of 1.7 ± 0.6% of loons in New Hampshire resulted in a significant decrease in λ, similar to the findings of Finkelstein et al. (2010) for chronic 1% added annual mortality affecting short-tailed albatross (*Phoebastria albatrus*) populations, a K-selected species with comparable life-history characteristics to loons.

In a K-selected species with a small and state-threatened population (638 adult loons in New Hampshire in 2012), we believe a 43% reduction in population size to be biologically significant. Effects size tests, used as an assessment of biological importance (Fernie et al. 2005), reported a large effect for the projected population (Cohen 1988). In the unlikely circumstance that LPC collected 100% of loons dying from ingested lead tackle, we would still posit a 24% reduction in population size, equal to a medium effect size (Cohen 1988). Since 1989, slow ($\bar{x} = 2.3\%/yr$) loon population growth has occurred with the support of intensive management and public education efforts. From 1989 to 2012, an average of 43% of chicks were hatched from nests managed through the provision of artificial nesting rafts, protective signs and ropelines, or water level management (LPC, unpublished data). Management has increased over the years; and, by 2012, 87% of chicks hatched in New Hampshire came from managed territories (LPC, unpublished data). Population growth resulting from these efforts may "conceal the lack of true recovery" of the state's loon population (Finkelstein et al. 2012:11453). As the leading cause of mortality in a state-threatened population of a K-selected species facing multiple co-occurring stressors, lead tackle mortality is likely a contributing factor to the apparent inability of the New Hampshire loon population to become self-sustaining.

Our reporting of the number of loons that died from lead tackle ingestion and the impact of lead tackle on the New Hampshire population presented in this study should be regarded as conservative. The LPC's intensive monitoring program increases the likelihood of mortality detection, but loons dying of lead poisoning may be underrepresented in mortality studies because lead-caused mortalities may be difficult to find (Franson and Cliplef 1992). Our analyses excluded 8 loons collected between October and April that died of lead tackle ingestion but were of uncertain population origin, although it is likely that some of these were from the New Hampshire population, 6 loons with toxic lead levels but lacking a lead object at time of necropsy, 3 loons that died of toxic lead levels and either contained a lead object that was so highly eroded it could not be positively identified as fishing tackle or the lead object was not archived and we lacked information to positively identify it as fishing tackle, and 1 loon with an ingested lead split shot sinker that displayed signs of lead poisoning prior to euthanasia but with inconclusive liver lead levels. The inclusion of these loons would have increased the collected number of lead mortalities by 15%. In addition, field necropsy and clinical reports for 5 birds indicated lead poisoning or the presence of lead fishing tackle; but these cases did not meet our evidentiary standards, so we categorized them as dying of unknown causes. Each assumption we made while creating our model was toward a more conservative result. Consequently, the results of both population projections could substantively underestimate the effects of lead tackle on New Hampshire's loon population.

This study provides quantifiable evidence to support the statement of Mitro et al. (2008:671) that "small changes in survival (<3%) can result in significant population declines in long-lived species." We suggest that, as the leading cause of adult loon mortality in New Hampshire, mortality from lead fishing tackle has significantly reduced the population and may inhibit its continued recovery in the face of co-occurring anthropogenic stressors and emerging threats.

MANAGEMENT IMPLICATIONS

To our knowledge, this study is the first that quantifies the population-level effects of lead tackle, and it provides a model for investigating effects of stressors on intensively monitored species with long-term datasets. Intensive management over the past 40 years has resulted in gradual increases in New Hampshire's loon population, but our study suggests that lead tackle ingestion has likely inhibited the recovery of this state-threatened species. The impact of 1% added mortality and a 1% change in the population growth rate for K-selected species such as loons should not be underestimated by wildlife managers or policy makers.

Our data showing that the majority of lead tackle ingestion in loons results from current fishing activity suggest that replacing lead fishing sinkers and jigs weighing $\leq$28.4 g with non-toxic alternatives would provide an immediate benefit to loon populations and would likely benefit other wildlife species known to ingest lead fishing tackle.

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