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Sustainability assessment of Lesser Yellowlegs *Tringa flavipes* harvested in the Americas

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The Lesser Yellowlegs *Tringa flavipes* has declined markedly over the last several decades, and harvest by humans is emerging as a significant conservation challenge for Lesser Yellowlegs during migration and at wintering sites in the Americas. We used a Prescribed Take Level (PTL) framework to update the previous sustainability assessment conducted by Watts *et al*. (2015). We first used survey-wide abundance indices for the Lesser Yellowlegs from the Breeding Bird Survey (BBS; 1967-2019) and Christmas Bird Count (CBC; 1967-2021) to fit a Bayesian state-space logistic model, generate posterior estimates of population carrying capacity and maximum population growth rate, and to make abundance index predictions for the current decade. We included annual take (harvest) rates of 0.035-0.235 in the model, which were estimated from the best available information on population sizes and harvest levels. Our model-based predictions for survey-wide abundance estimates for Lesser Yellowlegs on the BBS and CBC will remain below the 2.5th percentiles of carrying capacity during the current decade, which is considered a minimal conservation objective. We then applied the PTL framework, formulated using three levels of conservation concern to reflect management objectives and two ranges of population size to represent the total and flyway populations of Lesser Yellowlegs. Under all scenarios, our PTL estimates ranging from 5,000 ± 1,945 (SD) individuals to 38,910 ± 13,238 were lower than the 79,450 ± 20,562 individuals estimated by Watts *et al*. (2015). Considering that a minimum of 18,316–46,940 individuals are harvested annually, Lesser Yellowlegs are likely being overharvested. The analytic framework presented here can be used to assess the sustainability of other shorebird populations to harvesting in the Americas, determine take levels that are compatible with the intent of international agreements and domestic laws, and inform policy and regulatory decision making.

Keywords

Bayesian state-space logistic model

Breeding Bird Survey

Caribbean

Christmas Bird Count

hunting

South America

shorebirds

Prescribed Take Level

INTRODUCTION

The Lesser Yellowlegs *Tringa flavipes* is a medium-sized, long-distance migratory shorebird that breeds in the boreal wetlands of Canada and Alaska and winters in coastal and interior wetlands of the southern United States and throughout Mexico, Central and South America, and the Caribbean (Tibbitts & Moskoff 2020). Like many of North America's breeding shorebirds, the Lesser Yellowlegs has declined significantly during recent decades. Lesser Yellowlegs declined at an annual rate of –1.0% (95% Bayesian credible interval [BCI] = –3.6 to 1.5%) on the survey-wide Breeding Bird Survey (BBS) during 1967-2019 (Sauer *et al*. 2020) and at an annual rate of –1.02 (95% confidence interval = –1.63 to –0.33) on the Christmas Bird Count (CBC) during 1967-2021 (Meehan *et al*. 2022). Additionally, count data from the Alaska Landbird Monitoring Survey, Northwestern Interior Forest Conservation Region, indicated an annual rate of change of –9.2% (BCI = -15.00 to –0.60) from 2005 to 2013 (Handel & Sauer 2017). Abundance of Lesser Yellowlegs at migration sites in Canada and the USA decreased by >60% during 1980-2019, with the rate of decline worsening in recent years (Smith *et al*. 2023). The consistency of declines among datasets resulted in the Lesser Yellowlegs being designated recently as threatened in Canada (Hope *et al.* 2019, COSEWIC 2020) and as a migratory bird of national conservation concern in the USA (USFWS 2021).

Limiting factors responsible for Lesser Yellowlegs declines are not fully known, although overharvest by sport and subsistence hunting has emerged as a potential conservation concern (Watts *et al.* 2015, Watts & Turrin 2016, AFSI Harvest Working Group 2020, Andres *et al.* 2022). The Lesser Yellowlegs is one of the most widely and frequently harvested shorebirds in the Caribbean Basin (AFSI Harvest Working Group 2020). Based on hunter bag checks, logbook analyses, and interviews with hunters, a minimum of 18,316–46,940 Lesser Yellowlegs are killed annually in Martinique (range = 1,118–5,741; Canadian Wildlife Service unpubl. data), Guadeloupe (1,982–2,513; B. Andres unpubl. data), Barbados (6,100–9,150; Wege *et al.* 2014, W. Burke pers. comm.), Guyana (1,283–2,386; Andres *et al.* 2022), and Suriname (7,833–27,150; D. Mizrahi unpubl. data). Other countries also harvest Lesser Yellowlegs, such as Brazil and French Guiana, but reliable data on harvest levels are currently unavailable.

Motivated by the consistent declines described above and the urgent need to identify and address limiting factors, we undertook a re-assessment of sustainable mortality limits for Lesser Yellowlegs. A Potential Biological Removal (PBR) assessment completed by Watts *et al.* (2015) resulted in an annual sustainable mortality estimate of 79,450 ± 20,562 (SD) Lesser Yellowlegs, which was based on a continental population size of 660,000 individuals (range = 495,000–990,000) and a recovery factor (F) that reflected low conservation or management concern. Since then, new information on the level of management concern and population size and preliminary assessments of harvest levels have become available. Furthermore, a recent study determined that Lesser Yellowlegs breeding in eastern Canada are more likely to migrate through areas where they are exposed to greater harvest than birds breeding in Alaska to central Canada (McDuffie *et al.* 2022), which emphasizes the need to consider the potential disproportionate impacts of harvest on a smaller proportion of the global population (i.e., Atlantic Americas Flyway population).

PBR and Prescribed Take Level (PTL) are simulation methods grounded in fundamental aspects of harvest theory derived from the standard and generalized population logistic model (see Fig. 1, equations 1 & 2 in Wade 1998, and Figs. 1-3 and equations 1-6 in Runge *et al.* 2009). Both methods use maximum population growth rate (r_{max}) and population size (N) to assess sustainable human-caused mortality limits. Using the demographic invariant method of Niel & Lebreton (2005), estimates of r_{max} that are not influenced by take (harvest) rates (i.e., $tr = T/N$, where T = total take) can be obtained from information about age at first reproduction (α) and adult survival rate (S; Dillingham & Fletcher 2008, Watts *et al.* 2015). Here we present an update on the sustainable take levels for Lesser Yellowlegs and provide a flexible PTL framework useful for assessing shorebird population sustainability to harvest in the Americas. We also provide model-based abundance index predictions for Lesser Yellowlegs over the next decade under varying harvest rates.

METHODS

Bayesian state-space logistic model

We assumed linear density dependence and modeled annual changes in survey-wide abundance indices of Lesser Yellowlegs on the BBS (Sauer *et al.* 2020) and CBC (Meehan *et al.* 2022) with the standard logistic equation (Runge *et al.* 2009, Rivera-Milán *et al.* 2022). That is,

$$N_{t+1} = N_t + r_{max} N_t \left[1 - \left(\tfrac{Nt}{K}\right)\right] - T_t \qquad (1)$$

where r_{max} is the maximum intrinsic rate of population growth, K is the population carrying capacity, N_t is the true unknown abundance index of the population, and T_t is the total number of individuals taken in year t. Because of the continued declines described above, we used N = 400,000–527,000 individuals (COSEWIC 2020) for total breeding population of Canada and the USA, rather than the previous population estimates of 660,000 (Andres *et al.* 2012) or 495,000–990,000 used by Watts *et al.* (2015) to assess harvest sustainability. To consider the portion of the population breeding in eastern Canada that had greater exposure to harvest (McDuffie *et al.* 2022), we also used N = 200,000–399,000. Total take (T_t) = $N_t tr_t$, where tr_t is the take rate between year t and $t + 1$. That is, $tr_t = T_t/N_t$, with lower and upper bounds of 18,316/527,000 = 0.035 and 46,940/200,000 = 0.235. We generated annual take rates randomly as part of the Markov Chain Monte Carlo (MCMC) algorithm with the uniform distribution (i.e., $tr_t \sim$ Uniform [0.035, 0.235]) to account for uncertainty about the number of individuals harvested during migration and at wintering sites.

Because the posterior estimates of r_{max} can be influenced by the annual take rates specified in the Bayesian state-space logistic model, we used the demographic invariant method of Niel & Lebreton (2005; see their equation 15) to inform the prior distribution with 2.5th and 97.5th percentiles (i.e., $r_{max} \sim$ Uniform [0.245, 0.589]) and conducted a sensitivity analysis with different tr_t values (e.g., $tr_t \sim$ Uniform [0.01, 0.60]). We used the normal distribution and 10,000 iterations in program R v.4.0.4 (R Development Core Team 2021) and R package *fitdistrplus* v.1.1-8 (Dellignette-Muller & Dutang 2015) to estimate r_{max} with the demographic invariant method, assuming α = 1.3 (SD = 0.19; 2.5-97.5th percentiles = 0.92-1.68) and S = 0.76 (SD = 0.02; 2.5-97.5th percentiles = 0.72-0.80; Bird *et al.* 2020, COSEWIC 2020, Tibbitts & Moskoff 2020). Watts *et al.* (2015; see their equation 3 and Table 1) also used the demographic invariant method to estimate r_{max}, assuming α = 1-2 and S = 0.60-0.74.

Table 1. Posterior estimates of the mean and variance (SD, percentiles) of carrying capacity (*K*) and maximum intrinsic rate of growth (r_{max}), based on the Bayesian state-space logistic model and survey-wide abundance indices of Lesser Yellowlegs in the Breeding Bird Survey (1967-2019) and Christmas Bird Count (1967-2021).

				Percentiles		
	Parameter	**Mean**	**SD**	**2.5th**	**50th**	**97.5th**
Breeding Bird Survey	K	1.51	0.23	1.12	1.49	2.01
	r_{max}	0.274	0.029	0.246	0.265	0.350
Christmas Bird Count	K	58.92	9.69	44.42	57.72	80.69
	r_{max}	0.382	0.089	0.254	0.367	0.565

Process model - The unknown abundance index was reparameterized as a proportion of population carrying capacity (N_t/K) to reduce autocorrelation of the MCMC samples. We assumed the error of state model predictions (ε) was lognormally distributed with mean 0 and estimated standard deviation (s_{process}). Based on this reparameterization, we projected the BBS and CBC survey-wide abundance indices for Lesser Yellowlegs forward in time with

$$P_{t+1} = [P_t + r_{max} P_t (1 - P_t) - \tfrac{Tt}{K}]\, e^{\varepsilon t}. \tag{2}$$

We modeled the abundance index proportion of the first year using a lognormal distribution with mean P_0 and variance σ^2_{P0}. That is,

$$P_1 \sim Lognormal\,(P_0, \sigma^2_{P0}). \tag{3}$$

Observation model - The BBS and CBC survey-wide abundance indices are unitless representations of the number of individuals detected and the counting effort per sampling unit (Sauer *et al.* 2020, Meehan *et al.* 2022). While the process model in the state-space formulation accounted for our incomplete understanding of Lesser Yellowlegs population dynamics, we related the true unknown abundance index (y_t) to the BBS and CBC survey-wide abundance indices to account for observation variance ($\sigma^2_{t,observation}$). We transformed the survey-wide abundance indices to the natural logarithm scale and bootstrapped standard errors to the standard deviations of the corresponding lognormal distribution. To complete the observation model of the state-space formulation, we related the true unknown abundance index (N_t) = P_tK to the survey-wide estimated abundance indices with

$$log\,(y_t) = log\,(P_t\, K) + \mu_t \tag{4}$$

where

$$\mu_t \sim Normal\,(0, \sigma^2_{t,observation}). \tag{5}$$

We estimated the unobserved population parameters and true unknown abundance index under the assumption of conditional independence for each time step. We assumed equal mortality probability for all Lesser Yellowlegs regardless of age and sex class and which migratory route and wintering site were used along the Atlantic Americas Flyway (Reed *et al.* 2018, COSEWIC 2020, McDuffie *et al.* 2022). We also assumed additive natural and human-induced mortality, although the state-space logistic model formulation allowed for compensation through linear density-dependent population growth (Runge *et al.* 2009, Rivera-Milán *et al.* 2022).

We specified uniform priors for maximum population growth rate (r_{max} ~ Uniform [0.245, 0.589]), population carrying capacity (K ~ Uniform [0.1, 5.0] for the BBS abundance index and K ~ Uniform [10, 100] for the CBC abundance index), and the mean of initial abundance index on the log scale (BBS P_0 ~ Uniform [–5, 0] and CBC P_0 ~ Uniform [–100, 0]). For the standard deviations of process error and initial annual abundance index proportion, we also specified uniform priors (BBS σ_{process} and σ_{P0} ~ Uniform [0, 5], and CBC σ_{process} and σ_{P0} ~ Uniform [0, 100]). We generated parameter posterior distributions by running program JAGS v.4.3.0 (Plummer 2003) with R package *R2JAGS* v.0.7-1 (Su & Yajima 2021). We generated 250,000 iterations and used the first 50,000 iterations for a burn-in period. We thinned three Markov chains by 25 to obtain samples of 8,000 iterations per chain. We checked for convergence of the MCMC algorithm with trace plots and node summary statistics (e.g., Brooks-Gelman-Rubin diagnostic statistic $\hat{R} < 1.01$) and made posterior predictive checks with Bayesian *P*-values (P_B = 0.1-0.9; Gelman & Hill 2007). We present results as means and standard deviations with 2.5th, 50th, and 97.5th percentiles.

Prescribed Take Level

We estimated Prescribed Take Level as

$$PTL = F \times N \times \frac{r_{max}}{2}. \tag{6}$$

We used the Bayesian state-space logistic model posterior estimates of r_{max} (i.e., mean, SD, and 2.59–97.5th percentiles) and the lognormal distribution (Dillingham & Fletcher 2008; see their equations 3-5) to estimate the mean of population size and the coefficient of variation from lower and upper bounds (N = 200,000-399,999 or

400,000-527,000). In the PTL framework, the recovery factor (F) varies from 0.1 to 1.0 and expresses the management objective; in our case, the level of conservation concern for Lesser Yellowlegs. We used $F = 0.1$, 0.3, and 0.5 to represent high, moderate, and low conservation concern, respectively. For PTL estimation (i.e., mean, SD, and 2.5-97.5th percentiles), we used the normal distribution and 10,000 iterations in R packages *popbio* v.2.7 (Stubben & Milligan 2007) and *fitdistrplus* v.1.1-8 (Dellignette-Muller & Dutang 2015).

RESULTS

Bayesian state-space logistic model

Markov chains and node summary statistics showed convergence of the MCMC algorithm (Brooks-Gelman-Rubin diagnostic statistic mean $\hat{R} = 1.003$, SD = 0.003, 2.5-97.5th percentiles = 0.997-1.009, based on the BBS 1967-2019 abundance index; $\hat{R} = 1.002$, SD = 0.001, 2.5-97.5th percentiles = 1.000-1.004, based on the CBC 1967-2021 abundance index). Bayesian P-values showed no evidence of model lack of fit (mean $P_B = 0.51$, SD = 0.04, 2.5-97.5th percentiles = 0.45-0.56, based on the BBS 1967-2019 abundance index; mean $P_B = 0.50$, SD = 0.02, 2.5-97.5th percentiles = 0.46-0.56, based on the CBC 1967-2021 abundance index). The BBS survey-wide abundance index averaged 0.66 (SD = 0.28, 2.5-97.5th percentiles = 0.34-1.64) and the model-based abundance index averaged 0.65 (SD = 0.12, 2.5-97.5th percentiles = 0.45-0.92) during 1967-2019 (Fig. 1a). The CBC survey-wide abundance index averaged 34.08 (SD = 15.30, 2.5-97.5th percentiles = 5.13-63.97) and the model-based abundance index averaged 34.14 (SD = 4.71, 2.5-97.5th percentiles = 25.70-44.05) during 1967-2021 (Fig. 1b).

The BBS-predicted abundance index (mean = 0.58; SD = 0.17; 2.5th, 50th, 97.5th percentiles = 0.31, 0.55, 0.97) during 2020-2030 (Fig. 1a) remained below the 2.5th percentile of K (1.12; Table 1). The CBC-predicted abundance index (mean = 31.55; SD = 5.39; 2.5th, 50th, 97.5th percentiles = 21.34, 31.45, 42.41) during 2022-2030 (Fig. 1b) also remained below the 2.5th percentile of K (44.42; Table 1). The average of the BBS and CBC posterior estimates of r_{max} (Table 1) was 0.328 (SD = 0.084; 2.5th, 50th, 97.5th percentiles = 0.161, 0.328, 0.493). With the demographic invariant method, r_{max} averaged 0.418 (SD = 0.088; 2.5th, 50th, 97.5th percentiles = 0.245, 0.418, 0.589). At low density and under optimal conditions ($\alpha = 1$ year and $S = 0.80$-0.90), r_{max} averaged 0.376 (SD = 0.033, percentiles = 0.316-0.447). The BBS and CBC posterior estimates of r_{max} were sensitive to the annual take rates specified in the Bayesian state-space logistic model. For example, with prior $r_{max} \sim$ Uniform (0.245, 0.589) and $tr_t \sim$ Uniform (0.01, 0.60), the average of the BBS and CBC posterior estimates of r_{max} was 0.536 (SD = 0.053; 2.5th, 50th, 97.5th percentiles = 0.435, 0.537, 0.641).

Prescribed Take Level

Using the total population size range (Table 2; mean = 459,130, SD = 32,336) and the BBS and CBC mean r_{max}, PTLs of Lesser Yellowlegs ranged from 7,738 individuals, if considered high conservation concern, to 38,910, if considered low conservation concern (Table 2). Applying

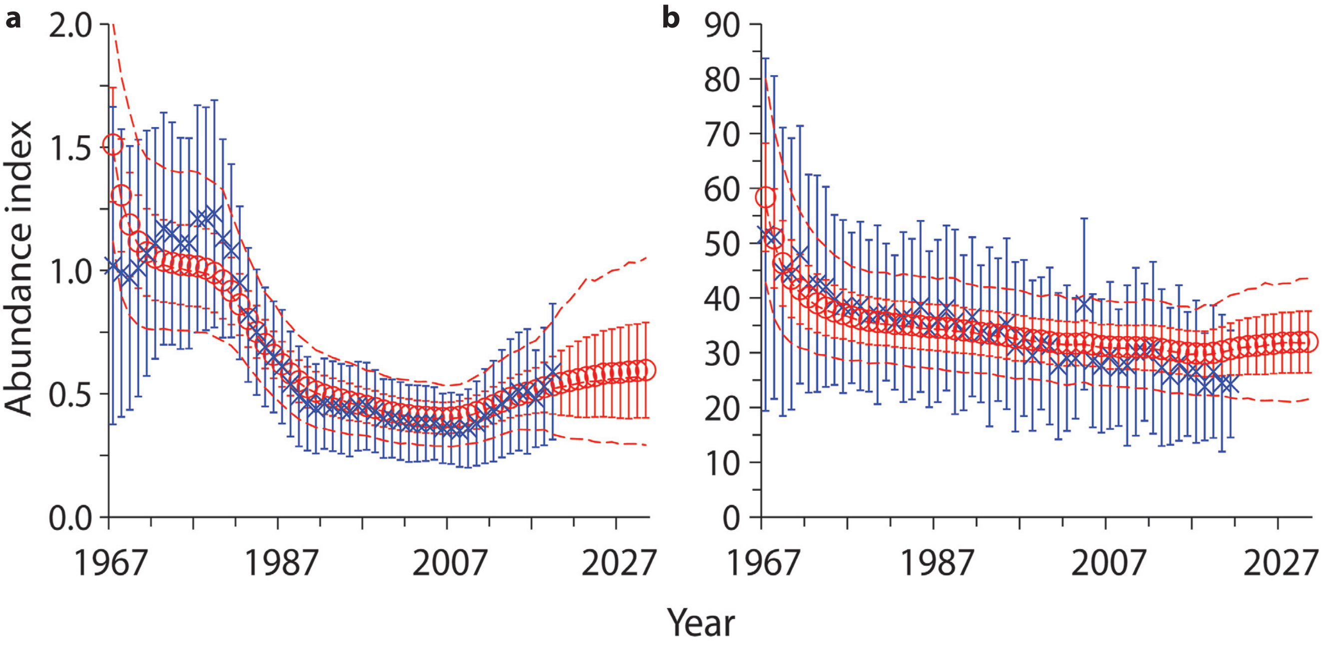

Fig. 1. Survey-wide abundance indices for Lesser Yellowlegs on **(a)** the Breeding Bird Survey during 1967-2019 and **(b)** Christmas Bird Count during 1967-2021; blue X = mean; vertical line = SD. Bayesian state-space logistic model posterior abundance indices during 1967-2030 are indicated by red circles (mean) and vertical lines (SD); dashed lines indicate 2.5th, 50th, and 97.5th percentiles).

Table 2. Mean Prescribed Take Levels (PTL), with standard deviations and percentiles for Lesser Yellowlegs, and using the Breeding Bird Survey and Christmas Bird Count mean r_{max} (0.328, SD = 0.084), flyway and total population size ranges, and management objectives of $F = 0.1$ (high conservation concern), 0.3 (moderate conservation concern), and 0.5 (low conservation concern).

Population size range (individuals)	*F*	Mean PTL	SD	Percentiles 2.5th	 50th	 97.5th
Flyway (200,000-399,000)	0.1	5,000	1,945	1,154	4,982	8,824
	0.3	14,983	5,795	3,883	15,124	26,221
	0.5	25,091	9,873	5,873	25,039	44,632
Total (400,000-527,000)	0.1	7,738	2,626	2,504	7,758	12,892
	0.3	23,346	7,834	8,423	23,318	38,623
	0.5	38,910	13,238	12,699	38,776	64,773

the flyway population size range (Table 2; mean = 282,842, SD = 50,406) and the BBS and CBC mean r_{max}, decreased PTLs of Lesser Yellowlegs from 5,000 individuals, if considered high conservation concern, to 25,091, if considered low conservation concern (Table 2).

DISCUSSION

We used the BBS and CBC survey-wide abundance indices of Lesser Yellowlegs to fit a simple but flexible Bayesian state-space logistic model grounded in harvest theory (Wade 1998, Runge *et al.* 2009). With the model, we generated posterior estimates of carrying capacity (K) and intrinsic rate of growth (r_{max}) and made survey-wide abundance index predictions for the BBS during 2020-2030 and CBC during 2022-2030, assuming a range of annual take rates. We also assumed that the BBS and CBC survey-wide abundance indices were directly related to annual changes in the Lesser Yellowlegs population size. In the model, the posterior estimates of K are representative of the BBS and CBC survey-wide abundance indices above which the Lesser Yellowlegs population tends to decline, because of linear density-dependent factors (Runge *et al.* 2009) such as limited foraging resources at breeding sites. The posterior estimates of r_{max} are representative of the exponential rate of increase of the Lesser Yellowlegs population at low density and under optimal conditions (e.g., in the absence of additive mortality from natural and anthropogenic disturbances and with adequate foraging resources to maximize annual reproductive output; Rivera-Milán *et al.* 2022). To estimate r_{max} with the demographic invariant method, α and S should also be estimated at low density and under optimal conditions (Niel & Lebreton 2005). Although empirical values of α and S for the Lesser Yellowlegs population at low density and under optimal conditions are lacking (Bird *et al.* 2020, COSEWIC 2020, Tibbitts & Moskoff 2020), our estimate of r_{max} using the demographic invariant method at low density and assuming optimal conditions (α = 1 year and S = 0.80–0.90) was comparable (within 14%) to our Bayesian model-based estimates, based on the combined BBS and CBC survey-wide abundance. In addition, our posterior estimates of r_{max} were comparable to the estimate of Watts *et al.* (2015), which also used the demographic invariant method with slightly different values for α and S. Therefore, the abundance indices and Bayesian state-space logistic model were adequate to estimate r_{max} and apply the PTL framework.

The BBS and CBC posterior estimates of r_{max} were sensitive to the annual take rates (0.035-0.235) specified in the Bayesian state-space model. Take rates are dependent on information on Lesser Yellowlegs population size (N) and total take levels (T). We admit that knowledge of the total harvest of Lesser Yellowlegs is incomplete, but we used the best available information from published articles, unpublished reports and data, and personal communications with colleagues and partner organizations working in the eastern Caribbean and northern South America. In the Bayesian model, we assumed that mortality was equally distributed among age and sex classes (Rivera-Milán *et al.* 2022). We also used the best available information on population size of Lesser Yellowlegs (COSEWIC 2020), which is rooted in periodic reviews of population sizes of North American shorebirds (e.g., Andres *et al.* 2012). The framework provided here will allow rapid revisions to parameter estimates as new information accumulates on population sizes and harvest levels.

The mean PTL estimates representative of total population size and all conservation concern (F) levels were lower than the PBR estimate of 79,450 (SD = 20,562) generated by Watts *et al.* (2015), although there was overlap in confidence limits at the low conservation concern level. Based on our analysis and considering that a minimum of 18,316-46,940 individuals are harvested annually in Martinique, Guadeloupe, Barbados, Guyana, and

Suriname, and an unknown number killed elsewhere in the Americas (Watts & Turrin 2016), we suggest that overharvesting has contributed to the decline in abundance of Lesser Yellowlegs. Reed *et al*. (2018) and McDuffie *et al*. (2022) indicated that the eastern Canada breeding segment of the Lesser Yellowlegs population had a greater exposure to harvest in the eastern Caribbean and northern South America than the western Canada and Alaska breeding segments, which would require additional information to refine our PTL estimates (e.g., proportional allocation of take levels, based on breeding segment, country, or harvest zone population estimates). If we assume, however, an Atlantic Americas Flyway population size of 50-76% of the total breeding population of Canada and the USA (COSEWIC 2020), then the PTL estimates were reduced by 35% from those estimated for the entire population. So, with a Lesser Yellowlegs population that is declining across most of its breeding range, the current annual harvest is likely unsustainable in some of the eastern Caribbean and northern South American countries for which data are available.

Our model-based abundance index predictions suggested that with annual take rates of 0.035-0.245, the Lesser Yellowlegs BBS and CBC survey-wide abundance indices will remain below the 2.5th percentiles of carrying capacity (K) during the current decade. In other words, our predictions fall below the minimum abundance targets for setting a conservation objective (Sanderson 2006, Rivera-Milán *et al*. 2018). Increased international collaboration and cooperation among wildlife managers, biologists, and harvesting communities is needed to obtain better estimates of population sizes and harvest levels and to ensure sustainable human-induced mortality limits for the Lesser Yellowlegs across the Americas. To that end, our analytical framework is amenable to the development of an adaptive management scheme (Runge 2011), involving partially-controllable recovery actions (e.g., harvest regulations and allocation per country or zone), recurrent decisions (e.g., five-year revisions of conservation status), and monitored outcomes (e.g., changes in population size and take levels) that can be used to update the Lesser Yellowlegs PTL as more data become available for countries such as Brazil and French Guiana. Our analytical framework can also be used to determine take levels for other shorebirds of conservation concern, such as the Willet *Tringa semipalmata*, that are compatible with the intent of international agreements and domestic laws.

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REFERENCES

Andres, B.A., P.A. Smith, R.I.G. Morrison, C.L. Gratto-Trevor, S.C. Brown & C.A. Friis. 2012. Population estimates of North American shorebirds, 2012. *Wader Study Group Bulletin* 119: 178-192.

Andres, B.A., L. Moore, A.R. Cox, B. Frei & C. Roy. 2022. A preliminary assessment of shorebird harvest in coastal Guyana. *Wader Study* 129: 39–47.

Atlantic Flyway Shorebird Initiative (AFSI) Harvest Working Group. 2020. *Actions for the Atlantic Flyway Shorebird Initiative's Shorebird Harvest Working Group 2020–2025*. Unpubl. report, U.S. Fish & Wildlife Service, Falls Church, VA, USA. Accessed 13 Jan 2023 at: *www.shorebirdplan.org/shorebird-hunting*

Bird, J.P., R. Martin, H.R. Akçakaya, J. Gilroy, I.J. Burfield, S.T. Garnett, A. Symes, J. Taylor, C. Sekercioglu & S.H.M. Butchart. 2020. Generation lengths of the world's birds and their implications for extinction risk. *Conservation Biology* 34: 1252-1261.

Committee on the Status of Endangered Wildlife in Canada (COSEWIC). 2020. *COSEWIC assessment and status report on the Lesser Yellowlegs (Tringa flavipes) in Canada*. Accessed 13 Jan 2023 at: *https://www.canada.ca/ en/environment-climate-change/services/species-risk-public-registry/cosewic-assessments-status-reports/lesser-yellowlegs-2020.html*

Delignette-Muller, M.L. & C. Dutang. 2015. Fitdistrplus: an R package for fitting distributions. *Journal of Statistical Software* 64: 1-34.

Dillingham, P.W. & D. Fletcher. 2008. Estimating the ability of birds to sustain additional human-caused mortalities using simple decision rule and allometric relationships. *Biological Conservation* 141: 1783-1792.

Gelman, A. & J. Hill. 2007. *Data analysis using regression and multilevel/hierarchical models*. Cambridge University Press, New York, USA.

Handel, C.M. & J.R. Sauer. 2017. Combined analysis of roadside and off-road breeding bird survey data to assess population change in Alaska. *Condor* 119: 557–575.

Hope, D.D., C. Pekarik, M.C. Drever, P.A. Smith, C. Gratto-Trevor, J. Paquet, Y. Aubry, G. Donaldson, C. Friis, K. Gurney, J. Rausch, A.E. McKellar & B. Andres. 2019. Shorebirds of conservation concern in Canada – 2019. *Wader Study* 126: 88–100.

McDuffie, L.A., K.S. Christie, A-L. Harrison, A.R. Taylor, B.A. Andres, B. Laliberté & J.A. Johnson. 2022. Eastern-breeding Lesser Yellowlegs are more likely than western-breeding birds to visit areas with high shorebird hunting during southward migration. *Ornithological Applications* 124: 1-16.

Meehan, T.D., G.S. LeBaron, K. Dale, A. Krump, N.L. Michel & C.B. Wilsey. 2022. *Trends in relative abundance for birds wintering in the continental USA and Canada: Audubon Christmas Bird Counts, 1966–2021, v.4.0*. National Audubon Society, New York, NY, USA. Accessed 13 Jan 2023 at: *https://www.audubon.org/conservation/where-have-all-birds-gone*

Niel, C. & J-D. Lebreton. 2005. Using demographic invariants to detect overharvested bird populations from incomplete data. *Conservation Biology* 19: 826-835.

Plummer, M. 2003. JAGS: a program for analysis of Bayesian graphical models using Gibbs sampling. In: *Proceedings of the Third International Workshop on Distributed Statistical Computing* (K. Hornik, F. Leisch & A. Zeileis, Eds.). Vienna University of Technology, Austria.

R Development Core Team. 2021. *R: a language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria. Accessed 13 Jan 2023 at: *https://www.r-project.org/*

Reed, E.T., K.J. Kardynal, J.A. Horrocks & K.A. Hobson. 2018. Shorebird hunting in Barbados: Using stable isotopes to link the harvest at a migratory stopover site with sources of production. *Condor* 120: 357-370.

Rivera-Milán, F.F., F. Simal, P. Bertuol & G.S. Boomer. 2018. Population monitoring and modelling of yellow-shouldered parrot on Bonaire, Caribbean Netherlands. *Wildlife Biology* 2018: wlb.00384.

Rivera-Milán, F.F., P.S. Coates, J.B. Cupples, M. Green & P.K. Devers. 2022. Evaluating Common Raven take for Greater Sage-Grouse in Oregon's Baker County Priority Conservation Area and Great Basin Region. *Human-Wildlife Interactions* 15: 1-12.

Runge, M.C. 2011. An introduction to adaptive management for threatened and endangered species. *Journal of Fish & Wildlife Management* 2: 220-233.

Runge, M.C., J.R. Sauer, M.L. Avery, B.F. Blackwell & M.D. Koneff. 2009. Assessing allowable take of migratory birds. *Journal of Wildlife Management* 73: 556-565.

Sanderson, E.W. 2006. How many animals do we want to save? The many ways of setting population target levels for conservation. *Biotropica* 56: 911–922.

Sauer, J.R., W.A. Link & J.E. Hines. 2020. *The North American Breeding Bird Survey, Analysis Results 1966-2019: U.S. Geological Survey data release*. Accessed 13 Jan 2023 at: *https://www.sciencebase.gov/catalog/item/5f1836a482cef313ed843104*

Smith, P.A., A.C. Smith, B.A. Andres, C.M. Francis, B. Harrington, C. Friis, R.I.G. Morrison, J. Paquet, B. Winn & S. Brown. 2023. Accelerating declines of North America's shorebirds signal the need for urgent action. *Ornithological Applications* 125: duad003.

Stubben, C. & B. Milligan. 2007. Estimating and analyzing demographic models using the popbio package in R. *Journal of Statistical Software* 22: 1–23.

Su, J-S. & M. Yajima. 2021. *Using R to run JAGS, version 0.7-1*. Accessed 13 Jan 2023 at: *https://cran.r-project.org/web/packages/R2jags/index.html*

Tibbitts, T.L. & W. Moskoff. 2020. Lesser Yellowlegs (*Tringa flavipes*), v.1.0. In: *Birds of the World* (A.F. Poole, Ed.). Cornell Lab of Ornithology, Ithaca, NY, USA. Accessed 13 Jan 2023 at: *https://doi.org/10.2173/bow.lesyel.01*

United States Fish & Wildlife Service (USFWS). 2021. *Birds of Conservation Concern, 2021*. U.S. Department of the Interior, USFWS, Migratory Birds, Falls Church, VA, USA. Accessed 13 Jan 2023 at: *http://www.fws.gov/birds/management/managed-species/birds-of-conservation-concern.php*

Wade, P.R. 1998. Calculating limits to the allowable human-caused mortality of cetaceans and pinnipeds. *Marine Mammal Science* 14: 1-37.

Watts, B.D. & C. Turrin. 2016. Assessing hunting policies for migratory shorebirds throughout the Western Hemisphere. *Wader Study* 123: 6–15.

Watts, B.D., E.T. Reed & C. Turrin. 2015. Estimating sustainable mortality for shorebirds using the Western Atlantic Flyway. *Wader Study* 122: 37-53.

Wege, D.C., W. Burke & E.T. Reed. 2014. *Migratory shorebirds in Barbados: Hunting, management, and conservation*. Unpubl. report, BirdLife International, Cambridge, UK. Accessed 13 Jan 2023 at: *https://www.shorebirdplan.org/shorebird-hunting*