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RESEARCH PAPER

Testimonials to reconstruct past abundances of wildlife populations

David Bolduc[a,*], Dominique Fauteux[a,b], Catherine A. Gagnon[c], Gilles Gauthier[a], Joël Bêty[d], Pierre Legagneux[a,e]

[a]*Département de Biologie & Centre d'Études Nordiques, Université Laval, 1045 Avenue de la Médecine, Québec, QC G1V0A6, Canada*
[b]*Canadian Museum of Nature, P.O. Box 3443 Station D, Ottawa, Ontario, Canada*
[c]*Cabinet-conseil Érébia, 300 ch. De la Pointe-aux-Anglais, Québec, Canada*
[d]*Département de Biologie & Centre d'Études Nordiques, Université du Québec à Rimouski, 300 allée des Ursulines, Rimouski, Canada*
[e]*Centre d'Études Biologiques de Chizé (CEBC), Université de LaRochelle, UMR 7372- CNRS, Villiers-en-Bois 79360, France*

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Abstract

Long-term monitoring of wildlife populations has greatly contributed to our current understanding of population dynamics and ecosystem functioning. Despite tireless field campaigns, however, only a fraction of the biodiversity has been monitored to date and the dynamics of potential key species have yet to be understood.

Here, we propose a method based on testimonials of observations from field workers to reconstruct past abundances of unmonitored populations and fill data gaps.

We contacted scientists who conducted field work at the Bylot Island field station, Nunavut, in the Canadian Arctic between 1991 and 2019 and collected 205 testimonials of past observations from 131 participants. We scored each testimonial based on its content and derived annual abundance indices for three highly fluctuating taxa, being lemmings, snowy owls and ermines. These indices were compared to standardized abundance estimates based on field sampling that were either available between 1993 and 2019 (lemmings and snowy owls) or 2007–2019 (ermines).

Our results show that abundance indices based on testimonials correlate well with those from systematic sampling and can be used to detect ecological phenomena. Moreover, we show that abundance indices were not affected by the effort of participants in the field or the delay between the observations and the collection of testimonials. Finally, we use the received testimonials to generate the longest ermine time series of relative abundance in the Canadian Arctic, spanning 29 years.

Monitoring programs and research stations often have access to a pool of past participants (e.g. field workers, ecotourists) whose observations can be localized in time. As we strive to gain a deeper understanding of ecosystem functioning, tapping the memories of these people can provide valuable information on the past abundances of unmonitored populations and help answer hypotheses that would otherwise require years of systematic monitoring.

Keywords: Monitoring; *Mustela erminea*; Population; Past abundances; Social sciences; Testimonials

*Corresponding author.
E-mail address: david.bolduc.6@ulaval.ca (D. Bolduc).

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Introduction

Repeated estimates of wildlife population abundances over time provide key information on their dynamics, while developing the necessary baselines to detect anomalies and threats caused by environment- or human-induced changes (Harvey et al., 2020; Powell & Steele, 2012; Ranta et al., 1995; Southward, 1995). Over the years, many methods have been developed to estimate abundances using direct observations, proxies (i.e. nests, tracks or feces) or more intensive capture-mark-recapture protocols (Amburgey et al., 2021; Fauteux et al., 2018; Murray et al., 2002; Silveira et al., 2003). Each method is selected in a way to maximize precision while minimizing costs, efforts and biases (Buckland et al., 2015; Camino et al., 2020; Efford, 2004; Fauteux et al., 2018; Hochachka et al., 2000). Still, most systematic monitoring methods require intense field efforts and their applicability remains limited in both time, space and to a small set of species (Buckland et al., 2015; Efford, 2004), especially when the subject is rare or cryptic. Thus, compromises are unavoidable. In addition, while some species were monitored in the past due to economic or conservation priorities, others were ignored or insufficiently monitored. This poses serious challenges when studying species that are now recognized as having prominent roles in ecosystems functioning or facing threats.

Today, as we attempt to refine our understanding of the mechanisms behind population, community and ecosystem functioning (Legagneux et al., 2012; Mellard et al., 2021; Polis & Winemiller, 2013), a number of historically understudied species have become of particular interest. To address this situation, indirect and unconventional methods were developed to reconstruct past abundances of organisms. Dendrochronology, paleolimnology, sedimentary environmental DNA and historical harvest records have yielded precious insights into the past abundance of populations at multiple time scales (Burge et al., 2018; Duda et al., 2020; Elton & Nicholson, 1942; Klvana et al., 2004; Kuwae et al., 2020; Morneau & Payette, 1998). In some cases, decadal relative abundances have been assessed through indigenous and local ecological knowledge (Anadón et al., 2009; Ferguson et al., 1998; Knaus et al., 1950; Peñaherrera-Palma et al., 2018; Reif et al., 2021). Still, reconstruction of abundance time series can only be achieved for populations leaving marks in their environments or for species that are culturally or economically important to local users.

Here, we develop a method based on testimonials of observations to reconstruct past annual abundances and test its validity on three taxa. The species of primary interest was the ermine (*Mustela erminea*), a small and highly cryptic mustelid that is only observed in some years and thought to have a critical role in the High Arctic tundra ecosystem (Gilg et al., 2003). We were also interested in lemmings (brown, *Lemmus trimucronatus,* and collared, *Dicrostonyx groenlandicus*, lemmings) and snowy owls (*Bubo scandiacus*), both taxa being systematically monitored since the early days of the project. We collected testimonials of past observations from researchers, graduate students and field assistants conducting field work for the long-term ecosystem monitoring program of the Bylot Island field station, Nunavut, Canada (Gauthier et al., 2013), between 1991 and 2019. For each taxon, a score was given to each testimonial depending on the reported observations, and an annual abundance index was created by averaging scores of same-year testimonials. We then assessed the reliability of this method by comparing the testimonial-based abundance indices to abundance estimates obtained from field sampling. The overlap between methodologies was 13 years for ermines and 28 years for lemmings and snowy owls. Finally, we verified if well-known ecological phenomena, such as predator-prey interactions and cyclic population dynamics, could be detected using testimonial-based abundance indices.

Materials and methods

Study area

Our study area (73°08′N, 80°00′W) lies in the Qarlikturvik Valley on Bylot Island, Nunavut. The valley bottom is a mosaic of mesic tundra covered by herbs, graminoids and shrubs, and of wetlands, mostly covered by graminoids and mosses (Gauthier et al., 2011). Ermines are the only mustelid on the island and their populations are known to fluctuate in abundance in relation with lemmings, their main prey (Bilodeau, 2013; Gilg et al., 2003). On Bylot Island, all rodents are either brown or collared lemmings that fluctuate in abundance according to 3- to 5-year cycles, with the brown lemming having the highest amplitude fluctuations (Gauthier et al., 2013). The snowy owl is a migratory predator specialized on lemmings and fluctuates in abundance in response to that prey (Therrien et al., 2014). In general, observing wildlife species is relatively easy in the High Arctic tundra due to the absence of erect vegetation, the 24-h daylight in summer, and the fact that several mammals and birds are curious and bold (e.g. ermines may come <10 m from people). Moreover, due to the relatively low species richness compared to temperate or tropical systems, vertebrate species identification in the field is straightforward except when distinguishing between the two lemming species at a distance.

Ethics statement

This research was approved by the Comité de Protection des Animaux de l'Université Laval (CPAUL; Current License for lemmings 2019−253, avian predators 2019−245) and Parks Canada (Current License SIR-2021−39,399). The collection of testimonials did not require special permission as our participants are currently or were formerly employed by the Bylot Island monitoring program. Their free, prior and informed consent was confirmed at the beginning of the interview or questionnaire.

Selection of participants and survey method

A total of 353 potential participants composed of students, employees or researchers who took part in the ecosystem monitoring program at our study site from 1991 to 2019 was available. Among the people enrolled for fieldwork, we contacted 259 participants who satisfied the criteria listed below, following a single stage sampling design (Creswell, 2009), and eventually sent a reminder to participants that did not respond within two weeks. We asked participants to fill a questionnaire for every field season they participated in.

Attributing observations to the wrong year is a risk when collecting testimonials of past observations from participants who were involved for multiple field seasons. We assumed that participants visiting the site multiple times would find it easier to assign observations to their first field season (a memorable event due to novelty) and their last (the most recent) than to field seasons falling in between, especially if there were more than one. Thus, because we assumed that the risk of misattributing observations would increase for participants with more than three field seasons, only potential participants with one to three field seasons were initially contacted. However, if less than three testimonials were collected for a given year, we contacted additional participants that spent more than three field seasons until either three testimonials were collected, or all potential participants were contacted for that year.

Questionnaires were filled either directly by participants or through a structured interview on the phone or via videoconference. Self-completed questionnaires can easily reach large numbers of participants but can be of lesser quality if questions are confusing to the participant (Bryman, 2016). Structured interviews with a fixed set of predetermined questions (i.e. identical to the self-completed questionnaire) can alleviate the problems caused by confusing questions due to the presence of the interviewer, but are more time-consuming (Bryman, 2016; Creswell, 2009). We assumed that participants involved in more than one field season would find it easier to be interviewed than to fill multiple questionnaires. Additionally, there were typically fewer participants in the years of 1991−2010 than later, increasing the importance of each testimonial in those years and making it logistically feasible to proceed by interview. All other participants who worked in the field between 2011 and 2019 for a single season received the self-completing questionnaire via email. If the questionnaire was filled incorrectly (e.g. unclear location of observations, missing information), we contacted the participant for an interview. A figure summing our selection of participants and survey method is available in Appendix A.

Testimonials

We built a 14-question, closed-format (i.e. with a predetermined set of answers) questionnaire on Microsoft Forms to collect testimonials of opportunistic observations of ermines, lemmings and snowy owls between 1991 and 2019 at our study site (Table B1). Brown and collared lemmings were pooled as “lemmings” as they are hard to distinguish at a distance. The questionnaire was pre-tested by four experienced ecologists who have in-depth knowledge of the study area and wildlife species. Questions were directed towards whether the participants observed one, several or no individuals of the above-mentioned species and at which frequency. Considering the studied species, their high amplitude fluctuation of abundance and their ease of detection, we considered that no academic or professional training in wildlife biology was needed to properly answer the questionnaire. Answers were collated into scores that represent a hierarchical level of abundance (Table 1). For ermines, the scores reflected four different levels of abundance: no ermine < one individual < many sightings of lone individuals < presence of at least one family. For lemmings, questions were directed towards distinguishing low, intermediate and high abundance years (i.e. 3 possible scores). Because snowy owls typically nest at our site only when lemmings are highly abundant (Therrien et al., 2014), we used binary scores. We averaged testimonial scores across participants for a given species and year providing an annual relative abundance index. These abundance indices differ from the ones derived from systematic or standardized protocols in several ways: they were not obtained by the same observers (i.e. there were many more people providing testimonials than people participating in the systematic sampling) and were not always covering the same time scale during the summer (i.e. lemming trapping and owl nest searching were done at specific periods whereas testimonials were based on the whole field season). Such indices were only calculated for the Qarlikturvik Valley, where most of our participants spent their time. Testimonials that originate from other regions of Bylot Island were not considered.

We estimated the sensitivity of the testimonial-based annual abundance indices (i.e. averaged scores) to an additional testimonial. To do so, we randomly sampled an additional testimonial from all available testimonials, across all years, combined it to the real testimonials and calculated a

Table 1. Types of observations reported in the questionnaires and associated scores.

Species	Testimonial answer	Score
Ermine	None were seen	0
	One sighting of a lone individual	1
	Multiple sightings of lone individuals	2
	At least one family group sighting	3
Lemmings	None were seen	0
	Some were seen, but rarely	1
	They were often seen	2
Snow owl	None were seen	0
	Nesting snowy owls were seen	1

new abundance index. A 95% confidence interval was built by repeating this process 5000 times (i.e. sampling and calculating the average score). This bootstrapped confidence interval is a simple representation of the sensitivity of each annual index to the recorded values and considers the possibility that years with scores of 0 might be false negatives (i.e. the species of interest was present but not detected).

Two additional sources of data were collected. First, to estimate the impact of time spent in the field on testimonial scores, each testimonial obtained from 2003 to 2019 was associated with the number of days spent in the field by the observer. This information was only available for the period 2003−2019. Secondly, some participants supported their observations of ermine with direct evidence from notebooks (i.e. they had written down their observations at the time) and/or dated photographs. These were recorded as proof of observations allowing us to ground-truth part of the received testimonials (see Statistical analyses). Since lemmings and snowy owls were systematically monitored for the whole period covered by this study, this additional information was only recorded for ermines.

Systematic sampling

To assess the reliability of testimonial-based abundance indices, we compared them with abundance estimates obtained from more systematic field sampling for either a subset (i.e. ermine) or the whole time series (i.e. lemmings and snowy owls). Although a minority of participants trapped lemmings or searched for snowy owl nests during their field work (respectively two and one person per year), questions were directed towards what their general impression of abundance was, not what they had trapped or surveyed, which helped mitigate inter-dependency between the testimonials and systematic indices.

For the ermine, standardized estimates of relative abundance were available from 2007 to 2019 based on incidental observations recorded daily in the field throughout the summer. Past studies reported that systematic recording of incidental field observations provided reliable estimates of relative abundance, especially in species with high-amplitude population fluctuations (Fauteux et al., 2018; Hochachka et al., 2000). Since 2007, a protocol was set to collect incidental wildlife observations on a daily basis from all field workers on Bylot Island along with the observation effort calculated as number of hours spent in the field by each person. Although this method has not been tested specifically for ermines, it provided the most comprehensive dataset available for this species covering the whole summer (i.e. ~1 June until 20 August). The relative abundance of ermines during the summer was derived from the sum of opportunistic observations recorded (i.e. number of observed individuals) divided by total field effort (person-hours).

Summer densities of lemmings were estimated with trapping surveys from 1993 to 2019 in the Qarlikturvik Valley. Two methods were used: snap-trapping (1993−2016) and live-trapping (2004−2019). Abundance estimates obtained with snap-trapping were converted into densities based on the high correlation between snap- and live-trap estimates during the overlapping period (2004−2016) (see Fauteux et al., 2018 for methodological details). Densities of both collared and brown lemmings were summed to obtain a single estimate per year. Only the density estimates from the wetland habitat were used as this habitat was continuously monitored from 1993 through 2019.

For snowy owls, nest densities were available from 1993 to 2019 either on an area of 52 (1993−2000) or 104 km^2 (whole Qarlikturvik Valkley 2001−2019). Owl nests were found by spotting owls flying off a nest at a distance or harassing people intruding into their territory during systematic searches of suitable nesting areas such as ridges along hills or along river embankments (Seyer et al., 2020).

Statistical analyses

Field effort and proof of observations

We investigated if the number of days spent in the field in a given year by participants influenced their testimonial scores. To do so, we used cumulative link mixed models (clmms; Christensen & Brockhoff, 2013). These models estimate if the probability that an observation falls in a certain ordered category (i.e. score) is influenced by external variables (e.g. Gagnon et al., 2020). We built the following model with year and participant as random effects : $Score \sim Number\ of\ days + (1|Year) + (1|Participant)$; and compared its AICc score to a null model : $Score \sim 1 + (1|Year) + (1|Participant)$. We considered that if the ΔAICc between the models was < 2, then the number of days in the field had no influence on a testimonial score (Arnold, 2010).

We also attempted to ground-truth ermine observations with proof of observations when available, such as dated pictures or field book notes. Thus, we calculated two metrics: the proportion of years for which ermines had been reported by testimonials and at least one proof of observation exists, and the proportion of testimonials that provide such proofs. A high proportion of ground-truthed observations provided high confidence in the testimonials since no standardized sampling data existed on ermines for most of the 1991−2019 period.

Comparison between testimonial-based and systematic sampling abundance indices

We investigated if testimonial-based and systematic sampling abundance indices correlated positively using Spearman ranks correlation. Significant correlation coefficients (ρ) of ≥ 0.7 were considered as high. We computed a bootstrapped 95% CI on the correlation coefficient to assess significance.

Additionally, for lemmings and snowy owls, we tested if the time since the reported observations had an effect on the correlation score of testimonial-based and systematic sampling time series. To do so, we computed the Spearman correlation scores across the time series in sliding windows of 9 years (i.e. a third of the time series) by 1-year increment. We built three generalized linear models (family Gamma, link = log), each with a single covariate, to investigate which one best explained the Spearman correlation scores. The covariates were the delay in years between field observations and completion of the questionnaire (represented by the year in the middle of the window), the average number of testimonials per year in the considered window, or the intercept (i.e. null model). All fixed effects were in interaction with the term species, as both lemmings and snowy owl data were used. We then proceeded with a model selection based on AICc. We considered that the model with the lowest AICc score and a ΔAICc < 2 with the next model would indicate which parameter had the stronger effect on the Spearman correlation scores (Arnold, 2010), i.e., on the relationship between testimonial-based and systematic sampling-based estimates of population sizes.

Ecological relevance

To be of any use in deciphering ecosystems dynamics, testimonial-based abundance time series should be able to account for ecological processes. We verified if well-known ecological phenomena, either already documented at our study site or elsewhere, could be detected with the testimonial-based time series. First, we attempted to detect the known predator-prey relations between snowy owls and lemmings (Therrien et al., 2014) by testing the Spearman correlation coefficient between their respective testimonial time series. Abundance of snowy owls is known to be positively related to lemming density in the Arctic (Gilg et al., 2006; Therrien et al., 2014).

Secondly, the population dynamics of lemmings and ermines were analyzed by testing for the presence of cycles in testimonial-based abundance time series. For lemmings, we compared those results with the ones obtained using systematically estimated densities. Lemming populations are known to fluctuate according to 3- to 5-year cycles, and ermines tend to do the same in the Arctic (Bilodeau, 2013; Gilg et al., 2003; Gruyer et al., 2008; Sittler, 1995). Clear, unnoisy cycles can be easily detected with autocorrelation coefficients or autoregressive models, but ecological time series influenced by stochasticity often violate assumptions of these methods (Cazelles et al., 2008; Menyushina et al., 2012). Wavelet analyses are designed to handle such non-stationary time series that may be affected by stochasticity and vary in periodicity over time (Cazelles et al., 2008). Ermines and lemming time series were detrended with local Loess polynomial regression to ensure stationarity. We used a 10-year detrending window to encompass at least two cycles.

To determine the robustness of the results from the wavelet analyses, we used the same methodology on 500 testimonial-based time series that were previously generated by bootstrapping abundance indices with testimonials randomly sampled from all testimonials (see Testimonials section). For each iteration, we extracted the power average (i.e. the strength of detection for a given periodicity) and its significance compared to white noise at $\alpha < 0.05$ and $\alpha < 0.1$. All wavelet analyses, as well as the resulting periodicity, were fitted to our data with the R package “WaveletComp” (Roesch & Schmidbauer, 2018).

Results

Testimonials

Overall, among the 259 contacted people, 131 participants either answered the questionnaire or were interviewed. Collected answers from both methods for a single field season and participant are hereafter called a testimonial (Fig. 1; Table 2). A total of 205 testimonials were collected with half of them obtained from interviews, the other half from self-completed questionnaires. We obtained multiple testimonials from 46 participants and participants spent an average of 1.4 (mode of 1.0) field seasons at the study area. One participant, who was involved for 10 field seasons, was exceptionally interviewed to increase sample size in the first year of the project (1991). Participants reported 70 observations of ermines, 126 of lemmings and 87 of snowy owls in total. Testimonials allowed the reconstitution of relative abundances time series in all taxa for the whole study period (Fig. 2). As expected, relative abundance showed large inter-annual variations, ranging 0−2.9 for ermines, 0−2 for lemmings and 0−1 for snowy owls.

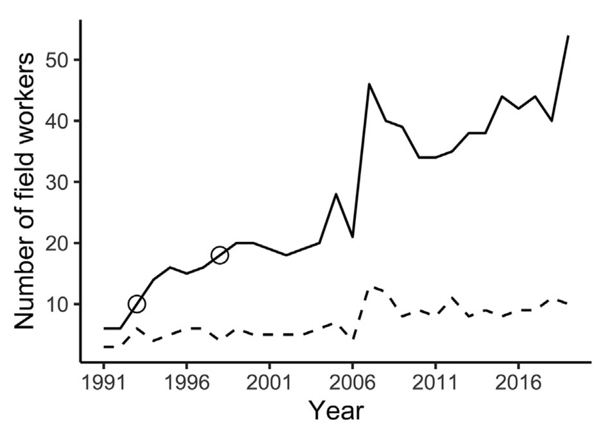

Fig. 1. Number of field workers present annually at the Bylot Island research station (solid line) and number of participants to our questionnaire (dashed line) per year. Empty dots in the solid line in 1993 and 1998 are years when the total number of people who were present at the field station is unknown.

Table 2. Summary of the information reported in the testimonials reported for the Qarlikturvik valley, Bylot Island, NU. A testimonial includes the observations of a participant for a single year.

Criteria	Statistics
Number of participants	131
Number of testimonials	205
Number of testimonials reporting sightings of lemmings	126
Number of testimonials reporting sightings of snowy owls	87
Number of testimonials reporting sightings of ermines	70
Proportion of ermine sightings supported by photographs or field book notes	0.44
Mean, mode and maximum number of seasons spent at the study area per participant.	1.38, 1, 10
Proportion of testimonials issued from interviews	0.5
Mean, minimum and maximum number of testimonials per year	7.1 [3,13]

Field effort

We found no evidence that the number of days spent at the study area influenced the testimonial score for all three species as null models were either preferred or showed a ΔAICc < 2 compared to the model including time (Table 3). The term Participant was dropped from all models as comparison between the full model and models without either Participant or Year as random effects showed that only Year was a significant factor. The *p*-values of the LRT tests between full models and those without Participant were respectively 0.98, 0.99 and 0.90 for the ermine, lemmings and snowy owl models.

Comparison between testimonial-based and systematic sampling abundance indices

For all taxa, testimonial-based and systematic or standardized sampling abundance indices were significantly

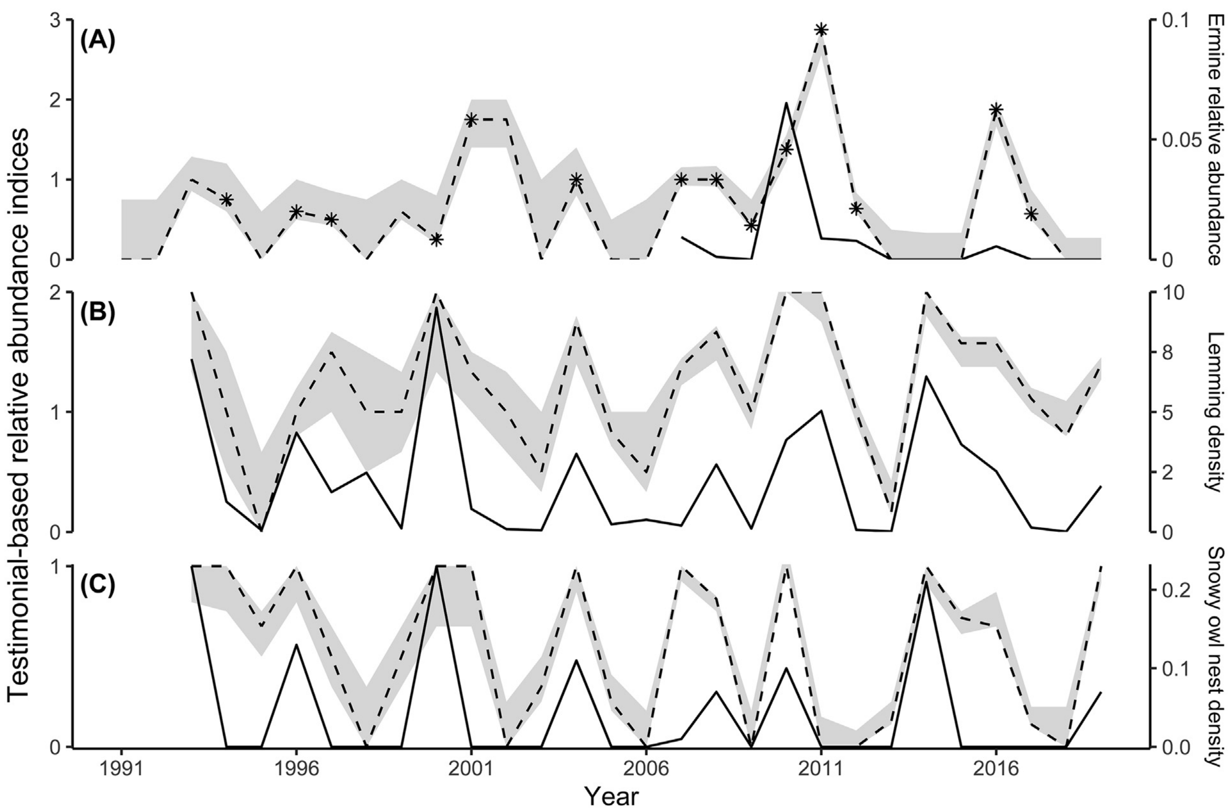

Fig. 2. Annual abundance estimates based on testimonials (dashed line) and systematic sampling (solid line) of three sympatric taxa on Bylot Island, Nunavut, Canada. The 95% confidence intervals (gray ribbon) of annual indices are calculated with an additional random testimonial sampled from all testimonials (see methods for details). (A) Ermine. Asterisks represent years where at least one proof (i.e. dated photograph or field book notes) of observation was reported. Abundance is estimated by dividing the number of opportunistic observations recorded by annual field effort. (B) Lemmings. Density is measured as individuals/ha (densities of both brown and collared lemmings were summed). (C) Snowy owls. Density is measures as number of active nests per km^2.

Table 3. Model selection testing the effect of the number of days spent at the study area (Time) on the testimonial scores for ermines, lemmings, and snowy owls. K = number of parameters, LL = Log-likelihood, ΔAICc = the difference between the current model and the one with the lowest AICc value, AICcwt = AICc weight. Models followed by an * were selected on the basis that they had the lowest number of parameters and a ΔAICc <2.

Species	Model	K	LL	ΔAICc	AICcWt
Ermine	Null*	4	−105.57	0	0.73
	Time	5	−105.48	1.97	0.27
Lemmings	Time	4	−73.63	0	0.62
	Null*	3	−75.21	1.00	0.38
Snowy owl	Null*	2	−38.19	0	0.73
	Time	3	−38.14	2.00	0.27

correlated, highly for ermines and lemmings, and to a lesser extent for snowy owls (Table 4, Fig. 2). For the standardized monitoring of ermine, total field effort spent recording incidental observations ranged from 680 to 3712 observer-hours per year, and the total number of ermine sightings annually ranged from 0 to 34. It is worth noting that 82% of the years when an ermine observation was reported in testimonials, at least one proof (dated photograph or field book notes) was provided by a participant (Fig. 2).

The time since the reported observations and the average number of testimonials per year were strongly negatively correlated (ρ = −0.96). Our model selection suggests that the average number of testimonials is the main determinant of the Spearman correlation score but that the effect of time cannot be excluded (Table 5).

Ecological relevance

Testimonial-based abundance time series of snowy owls and lemmings were significantly correlated, although slightly less than between time series obtained from systematic sampling (i.e. nest and trapping densities, Table 4).

Wavelet analyses based on testimonial-based abundance time series suggests that the ermine population of Bylot Island was cyclic over the study period (Fig. 3). The average periodicity detected in the time series (without error) at α < 0.05 was 2.9 years (CI 95% [2.7; 3.0]). However, analysis of bootstrapped time series, which considered the 95% CI of the scores, suggests a slightly longer periodicity around 3.3 years (CI 95% [2.6; 4.8]). Significant periodicity was also detected in lemming time series based on both testimonial-based abundance (average periodicity of 3.3 years, CI 95% [2.0; 3.85) or systematically sampled densities (average periodicity of 3.8 years, CI 95% [3.6; 4.0]).

Table 5. Model selection of parameters impacting the Spearman correlation coefficient between testimonial-based and systematic sampling abundance estimates based on eighteen 9-year sliding time-windows subsets of the original time series (27 years). Lemmings and snowy owls are considered. Parameters are the delay between field observations and the completion of the questionnaire (Delay), the average number of annual testimonials during the time window (ANT), and the species. K = number of parameters, LL = Log-likelihood, ΔAICc = the difference between the current model and the one with the lowest AICc value, AICcwt = AICc weight. Models followed by an * were selected on the basis that they had a ΔAICc < 2 with the second best model.

Model	K	LL	ΔAICc	AICcWt
ANT×Species*	5	52.02	0	0.93
Delay×Species	5	49.48	5.08	0.07
Intercept×Species	2	28.83	38.74	0

Discussion

Our results showed that the relative population abundance of highly fluctuating arctic small mammals and snowy owls can be reconstructed over almost three decades from testimonials of field workers. Specifically, we have shown that abundance indices generated from our testimonial-based method were (1) not affected by the field effort of participants (number of days spent in the field), but mainly related to the number of testimonials obtained, (2) highly correlated to abundances estimated with systematic or standardized sampling, and (3) insightful to characterize the population dynamics of species and predator-prey relationships. These

Table 4. Spearman rank correlations between testimonial-based and systematic sampling abundance time series. Correlation coefficients (ρ) and their 95% bootstrapped confidence interval (C.I.) are presented. Coefficients in bold are significant (i.e., 95% C.I. does not include zero).

	Ermine testimonial	Ermine opportunistic observations	Lemming testimonial	Snowy owl testimonial	Lemming density
Ermine opportunistic observations	**0.84 [0.56, 0.95]**				
Lemming testimonial	**0.50 [0.13, 0.78]**	0.43 [−0.14, 0.84]			
Snowy owls testimonial	−0.21 [−0.19, 0.60]	0.13 [−0.58,0.69]	**0.53 [0.19, 0.77]**		
Lemming density	0.29 [−0.09, 0.61]	0.31 [−0.28, 0.782]	**0.83 [0.63, 0.94]**	**0.47 [0.10, 77]**	
Snowy owl nest density	0.14 [−0.22, 0.51]	0.21 [−0.42, 0.79]	**0.65 [0.35, 0.85]**	**0.69 [0.49, 0.85]**	**0.69 [0.40, 0.88]**

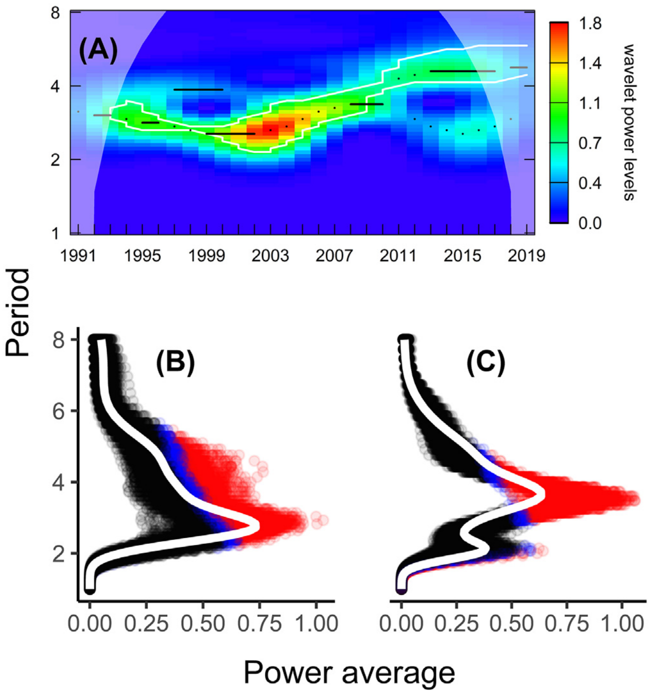

Fig. 3. Wavelet analysis results of the relative abundance of ermines and lemmings at Bylot Island, Nunavut, Canada, based on testimonial. (A) Wavelet power spectrum of the relative abundance of ermines. Colors indicate the wavelets power level, black lines or dots are the detected periods and the white line delimits the area where the cyclic pattern is significant. The pale colored area on the edges of the power spectrum are outside the cone of influence. (B) Ermine and (C) Lemming: Power average of each period for 500 simulated testimonial-based time series. Blue dots represent periods that differ significantly from white noise at $\alpha < 0.1$ and red dots at $\alpha < 0.05$. Black dots are not significantly different ($p > 0.1$). White line represents the observed power averages in (B) the original ermine testimonial-based time series and (C) the lemming density time series.

claims were supported in three different taxa, for which the overlap between systematic sampling and testimonial-based time series varied between 13 and 27 years. This suggests that we can confidently reconstruct the abundance of ermines over a 29-year period, which is more than twice the length of the abundance time series derived from standardized sampling for this cryptic and potential key predator of the High Arctic tundra. Our method differs from other methods based on interviews of land-users (i.e. indigenous and local ecological knowledge) seeking to reconstruct past abundances (Anadón et al., 2009; Ferguson et al., 1998; Knaus et al., 1950; Peñaherrera-Palma et al., 2018; Reif et al., 2021) by its aim to create annual abundance indices. It appears as a promising avenue to reconstruct abundance time series of species recently considered in ecological monitoring projects where field workers can provide testimonials of past observations. It may be particularly useful to reconstruct past abundances of highly fluctuating species, such as those with outbreak dynamics.

Reliability of testimonials, ecological relevance and limitations

Abundance indices based on testimonials may have great potential, but they have inherent caveats calling for caution when interpreting them. The field effort, which can vary tremendously between participants, could affect the number of reported sightings (Hochachka et al., 2000) and ultimately the abundance scores associated to testimonials. Yet, in all cases, we have found no link between time spent at the study area (i.e. field effort) and the score associated with a testimonial. However, such result does not dismiss lack of precision of scores when effort is low, and participants who spent no time in the field were not part of the analysis. Our result can be explained by our use of abundance categories instead of an exact number of sightings, as observations of participants with different field efforts can easily fall into the same category. In fact, considering the landscape at our study site (flat, treeless tundra) and the behavior of the concerned taxa, the answers to the questionnaire should be obvious to any observer who spent some time in the field during a given year. Moreover, participants who have been in the field for a shorter period (e.g. one week) overlapped with those staying for longer periods (e.g. several weeks), and thus could share information about their observations while in the field, again reducing the potential impact of field effort.

Interestingly, the correlation coefficients of testimonial-based and systematic abundance indices observed here (i.e. > 0.7) are of the same magnitude than those reported by Fauteux et al. (2018) and Hochachka et al. (2000), who, respectively, compared standardized incidental observations to lemmings live-trapping densities ($r = 0.90$) and to common raven (*Corvus corax,* $r = 0.60$), coyote (*Canis latrans,* $r = 0.65$) and spruce grouse (*Falcipennis canadensis,* $r = 0.80$) abundances based on systematic nest searching and transects. Hence, although testimonial-based and systematic or standardized abundance indices may have different origins (i.e. different observers, protocols) and cover different spatial or temporal scales, both can be proxies of the abundance of a given species.

Correlations between abundance indices from testimonials and from systematic or standardized sampling were higher for ermines and lemmings than for snowy owls, possibly due to the higher number of testimonial scoring possibilities (respectively 4, 3 and 2), which could have allowed a better categorization of true abundance. Differences between the systematic sampling protocols of snowy owls and the behavior of our participants can also explain this result. Our systematic monitoring protocols only records breeding pairs observed within a specific area, while testimonials from participants could also have included non-breeding individuals or pairs observed outside the systematically sampled area.

Our results suggest that the correlation scores between testimonial-based and systematic sampling abundance indices were best explained by the average number of testimonials, and less so by the delay between the observations and the questionnaire. Although we cannot completely rule out the effect of time on memories, the high proportion of participants who had access to dated pictures or notebooks likely limited errors in testimonials. Reif et al. (2021) showed that older ornithologists, with their memories and field notes, were able to assess the trends of 75% of the 209 bird populations monitored in the Czech Republic Atlas from 1960 to 2010. Moreover, studies have shown that memories associated with strong emotions, both positive and negative, are clearer for a longer period than memories without emotion (Tyng et al., 2017). This could have had a positive effect on the accuracy of testimonials as most, if not all, participants had strong interest in charismatic arctic wildlife like snowy owls and ermines and, to a lesser extent, lemmings. Thus, even if collected decades after the events, testimonials, and the abundance indices they generate, can be valuable (Reif et al., 2021).

In addition to informing on past abundance, our method can also be used to investigate ecological phenomena. Testimonial-based abundance indices were able to decipher the dependency of snowy owls on lemmings as well as the cyclic dynamics of lemmings and ermines, phenomena observed at our study sites (Bilodeau, 2013; Gruyer et al., 2008; Therrien et al., 2014) and elsewhere (Gilg et al., 2006; Johnson et al., 2000) with systematic sampling. Thus, even when lacking the precision brought by rigorous systematic sampling, testimonial-based abundance time series appears successful in detecting ecological phenomena such as predator-prey interactions and population dynamics of species with high amplitude fluctuations of abundance.

Applications

Research projects where the observations of participants can be relatively precise spatially and temporally can benefit from a testimonial-based approach. Long-term research projects, research stations with regular field workers or national parks often have access to a large population of potential participants (e.g. seasonal workers, ecotourists). The low cost of this approach can be particularly helpful for research questions where the cost of standard sampling techniques is prohibitive, but where potential observers are numerous.

The testimonial-based approach can be complementary to systematic sampling and fills some of its deficiencies. Systematic sampling often yields precise estimates but requires significant effort, both in time and budget, and is valid at a limited spatial or temporal scale (Anadón et al., 2009). Observations from field workers or land-users, on the other hand, are harder to localize but can properly describe abundance variation on a large spatial scale with relatively little effort (Braga-Pereira et al., 2021; Peñaherrera-Palma et al., 2018). They can inform us on long-term populational trends even if estimates are neither quantitative nor as precise as systematic sampling measurements (Anadón et al., 2009; Ferguson et al., 1998; Peñaherrera-Palma et al., 2018). Moreover, to avoid the bias associated with creating an annual abundance index from arbitrarily given scores, cumulative-link mixed models (Christensen & Brockhoff, 2013) can be used to model the probability of a testimonial to fall in an ordered category.

Limits and potential improvements

Our experience with the testimonial-based approach, as well as insights from social sciences and the literature on indigenous and local knowledge, point towards some key aspects to consider if this method is to be used successfully in wildlife ecology. First, the target participant population must be knowledgeable about the species of interest (Anadón et al., 2009; Camino et al., 2020; Gagnon & Berteaux, 2009; Peñaherrera-Palma et al., 2018). Participants need to be able to properly identify species. In our case, we had a relatively large population of knowledgeable participants (field workers) capable of identifying the limited number of species present at the study site and locating them in time. Yet, even under these favorable conditions, within-year testimonial scores differed between participants. The experience of participants in animal identification may be more critical in systems with more biodiversity. As a solution, collecting as many testimonials as possible without increasing the risk of attributing them to the wrong year should make testimonial-based abundance indices more reliable, as suggested by our analysis. However, as observed here, time series based on testimonials from a sufficient number of participants may rarely exceed 30 years due to the increased difficulty of contacting the earliest participants.

Secondly, questions asked to participants need to be precise and able to produce different set of answers that can be ordered in terms of relative abundance (i.e. Table 1). An ordinal scale allows the attribution of scores to answers or to use cumulative-link mixed models if the abundance is to be modelled. Species-specific questions concerning observable proxies of abundance is a key element.

Conclusion

Our testimonial-based approach successfully reconstructed past relative abundances of three Arctic terrestrial taxa and generated the longest ermine time series for the Canadian Arctic. Our results, along with the increasing body of literature on local and traditional ecological knowledge (Anadón et al., 2009; Braga-Pereira et al., 2021; Camino et al., 2020; Ferguson et al., 1998; Gagnon et al., 2020; Peñaherrera-Palma et al., 2018), substantiate the usefulness of testimonials in research and conservation. While one must recognize the limitations of this method, it can unlock the necessary data to address difficult ecological questions in ecosystems where traces of past abundances are left in the memory of knowledgeable field workers or land-users. Further research should focus on calibrating testimonial-based relative abundance indices with systematic sampling data and thus widen the scope of questions for which this type of information can be used.

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Data accessibility statement

All data used in this manuscript will be made available in open access upon request or publication on NordicanaD.

CRediT authorship contribution statement

David Bolduc: Conceptualization, Methodology, Funding acquisition, Formal analysis, Writing – original draft. **Dominique Fauteux:** Conceptualization, Methodology, Funding acquisition, Writing – review & editing. **Catherine A. Gagnon:** Methodology, Writing – review & editing. **Gilles Gauthier:** Funding acquisition, Writing – review & editing. **Joël Bêty:** Conceptualization, Funding acquisition, Writing – review & editing. **Pierre Legagneux:** Conceptualization, Methodology, Writing – review & editing.

Declaration of Competing Interest

We declare no conflict of interest.

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Supplementary materials

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.baae.2022.11.005.

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