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Research article

Hunter-engaged monitoring of the Eurasian lynx during the reinforcement process

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Collaborative wildlife monitoring programs involving citizen scientists are an efficient approach for surveying large areas. In Europe, hunters play an important role in wildlife monitoring and act as crucial stakeholders in large carnivore conservation. The Eurasian lynx *Lynx lynx*, an elusive felid, is a species of conservation concern in Europe. In Slovenia, lynx was exterminated and later reintroduced in 1973, but the population has declined during the past decades. A reinforcement program was initiated in 2017, translocating lynx from the Carpathian population to improve the status of the critically endangered Dinaric population. The reinforcement was coupled with an intensive monitoring program, involving local hunters as key participants. In this study, we show how the collaboration between wildlife managers, researchers and hunters resulted in a robust assessment of the lynx population at a national level for a period of five years. Questionnaires distributed to hunting clubs and chance observations were used to define the expected lynx distribution, and guide the extent of systematic camera trapping surveys, involving between 63 and 101 hunters each year. In southern Slovenia, the core of the lynx population, lynx density doubled during the reinforcement period (from 0.66 to 1.30 lynx/100 km^2). In north-western Slovenia where a stepping-stone population in the Alps was established in 2021, the number of lynx increased to seven. Furthermore, all three translocated females reproduced, which represents the first confirmed lynx reproduction in the Slovenian Alps in over 150 years. We discuss the motivation behind the hunters' contribution to the data collection process and the implications of this collaboration. We highlight the importance of maintaining the collaboration and their support for lynx conservation. This study serves as an example for large-scale collaborative monitoring of a recovering population undergoing intensive conservation measures with promising results, involving crucial stakeholders as citizen scientists.

Keywords: camera trapping, citizen science, density, reinforcement, spatial capture recapture

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Introduction

Many populations of large carnivores are threatened as a result of past and/or ongoing persecution by humans and habitat fragmentation in combination with their naturally low densities and large spatial requirements (Woodroffe et al. 2005, Ripple et al. 2014). However, in human-dominated landscapes of Europe, several populations of large carnivores have naturally recolonized parts of their former range, or have been successfully reintroduced (Linnell et al. 2009, Chapron et al. 2014, Tosi et al. 2015, Persson et al. 2023). Regardless if populations are declining or increasing, knowledge of their abundance and distribution, as well as population dynamics, is essential as this constitutes the basis for determining the management measures needed to maintain populations at a favourable conservation status (Reed et al. 2002, Sanderson et al. 2002, Kaczensky et al. 2013). However, their elusive behaviour and low densities make monitoring of such large carnivores difficult (Linnell et al. 1998, Karanth and Chellam 2009, Suryawanshi et al. 2019).

Chance observations, such as reports of direct observations; tracks; genetic samples or opportunistic camera trap records; and questionnaires can be cost-effective methods to survey large areas and are commonly used to determine the presence and distribution of large carnivores (Linnell et al. 2007, Zimmermann et al. 2011, Molinari-Jobin et al. 2012, Melovski et al. 2018, Hočevar et al. 2020), while standardized genetic or camera trapping surveys in combination with capture–recapture modelling are used to infer their abundance, density (O'Connell et al. 2011, Marucco et al. 2012, Bischof et al. 2020, Tourani 2022, Palmero et al. 2023) and population dynamics (Harihar et al. 2020, Palmero et al. 2021, Alves et al. 2024). However, genetic and camera trapping surveys are often costly and require high levels of manpower, making it difficult to obtain the information needed across extensive spatial and temporal scales (Danielsen et al. 2005). Participatory monitoring programs involving local communities may represent an efficient and cost-effective approach for surveying large areas (De Angelo et al. 2011, Zimmermann 2019, Lasky et al. 2021). Furthermore, this approach is particularly valuable in regions where increasing the awareness about endangered wildlife and support for management interventions is important (Danielsen et al. 2005, Sun et al. 2021). In Europe, hunters are key participants in wildlife monitoring and management (Andrén et al. 2002, Singh et al. 2014, Helle et al. 2016, Zimmermann 2019, Bischof et al. 2020, Cretois et al. 2020, Hofmeester et al. 2021, Fležar et al. 2023a). For example, they often collect data on a voluntary basis in compliance with hunting regulations, providing wildlife agencies with harvest data to estimate population trends or the veterinary agencies for monitoring wildlife health (Sun et al. 2021). On the other hand, some hunters can become involved in illegal killing, which can impede the recovery and conservation of large carnivore populations (Liberg et al. 2012, Carter et al. 2017, Heurich et al. 2018, Frauenberger 2023).

The Eurasian lynx *Lynx lynx*, hereafter lynx, is the largest felid in Europe, an elusive apex predator of European forest ecosystems characterized by a territorial and solitary lifestyle (Breitenmoser and Breitenmoser-Würsten 2008). Lynx occur in 11 distinct populations across the continent, including six that were reintroduced following extermination (Linnell et al. 2009, Chapron et al. 2014, von Arx et al. 2021) and two additional occurrences originating from reintroductions which are not yet recognized as populations (Kaczensky et al. 2024). Many of the reintroduced populations show a high rate of inbreeding which, together with high anthropogenic mortality and fragmentation, is reported to be an important threat to their conservation (Kaczensky et al. 2013, von Arx et al. 2021).

Slovenia represents an important connection between the Dinaric and the Alpine lynx populations and could play a crucial role in reaching the long-term goal of establishing a viable central European metapopulation (Breitenmoser et al. 2021). Lynx were extirpated in Slovenia in the beginning of the twentieth century, and the Dinaric lynx population originates from a reintroduction to the Slovenian Dinaric Mountains in 1973 (Čop 1990). This reintroduction was at first considered to be one of the most successful in Europe (Breitenmoser-Würsten and Breitenmoser 2001), with the lynx expanding to the southeastern Alps in the north and to Croatia and Bosnia and Herzegovina in the south (Čop and Frković 1998). However, largely due to inbreeding depression and possibly to legal hunting, a decrease in the lynx distribution was observed in the 2000s (Kos et al. 2012, Huber et al. 2013, Sindičić et al. 2013, Fležar et al. 2021) and, until recently, the Dinaric lynx population was considered one of the most endangered lynx populations in Europe (von Arx et al. 2021). Consequently, a reinforcement program was launched in 2017 (LIFE Lynx project, www.lifelynx.eu), where wild lynx from the Carpathian Mountains (Romania and Slovakia) were translocated to southern Slovenia and Croatia in 2019–2023 to decrease the level of inbreeding of the Dinaric lynx population (Fležar et al. 2021). Furthermore, within the same program, lynx were reintroduced to the Slovenian Julian Alps in 2021–2023 where no lynx presence had been confirmed since 2014 (SCALP 2014), to create a stepping-stone promoting long-term connectivity between the Dinaric and the Alpine lynx populations (i.e. in Switzerland, Italy and Austria; Fležar et al. 2021, Molinari et al. 2021).

In Slovenia, hunters regularly participate in monitoring and management of wildlife, including large carnivores (Skrbinšek et al. 2019, Rot et al. 2022). For example, hunters collected non-invasive genetic samples for brown bear *Ursus arctos* abundance estimation (Skrbinšek et al. 2019), reported observation data for brown bears from artificial feeding sites (Jerina et al. 2019) and participated in grey wolf *Canis lupus* howling surveys (Ražen et al. 2020, Bartol et al. 2023). Starting in 2017, with the onset of the lynx reinforcement project, hunters were also invited to collaborate in a large-scale lynx monitoring program, combining questionnaires, chance observations and systematic camera trapping (Fležar et al. 2023a). While monitoring of lynx across most of Europe is often conducted by trained technical staff (Duľa et al. 2021, Palmero et al. 2021, Iosif et al. 2022, Port et al. 2024), the Slovenian program is based on a citizen-science approach with voluntary participation by hunters, resembling the practice used in Switzerland (Zimmermann 2019) and Scandinavia (Andrén et al. 2002, Helle et al. 2016, Bischof et al. 2020, Hofmeester et al 2021).

In this study, we present the process of establishment, participation and maintenance of the hunter-engaged lynx monitoring program in Slovenia, and assess the changes in the lynx populations in 2018–2023, following the reinforcement program. Specifically, we first used information from questionnaires and chance observations to define the expected lynx distribution, which guided the spatial extent of the following camera trapping surveys. We used camera trapping data to assess the yearly minimum count of independent lynx (subadult and adult) and minimum number of reproductions in two regions: 1) the southern region, where the Dinaric lynx population resides, and 2) the northern region, where the stepping-stone population in the Julian Alps was established (Fig. 1). Lastly, we provide changes in annual density and abundance estimates for the Slovenian part of the Dinaric lynx population (the southern region) in connection with the reinforcement effort.

Material and methods

Study area

This study was conducted in the south-eastern to north-western part of Slovenia (44°31′N, 15°15′E), encompassing the Dinaric, Alpine and Mediterranean macroregions (Perko 1988, Fig. 1). The Dinaric macroregion consists of high forest cover, low habitat fragmentation (i.e. small patches of agricultural land and human settlement) and low human density (average 100 persons/km^2) (Skrbinšek et al. 2019, http://www.luminocity3d.org). The forests are dominated by a mix of beech *Fagus sylvatica* and fir *Abies alba*, growing in a typical karstic, rugged and hilly terrain, reaching up to 1800 m a.s.l. (Čonč et al. 2022). The Alpine macroregion contains the Julian Alps (hereafter: Alps) with peaks reaching up to 2864 m a.s.l. At lower altitudes (≤ 1000 m a.s.l.), the landscape is characterized by mixed forest (predominantly beech and spruce *Picea abies*), coniferous forests (predominantly spruce) at higher altitudes (1000–1400 m a.s.l.) and mountain pine *Pinus mugo* or herbaceous plants above the tree line (Poljanec et al. 2023). In both the Alpine and Dinaric macroregions, large human settlements are limited to valleys and foothills. The Mediterranean macroregion contains of hilly karst plateaus or flysch low hills with high forest cover, where winter temperature stays above zero (Perko

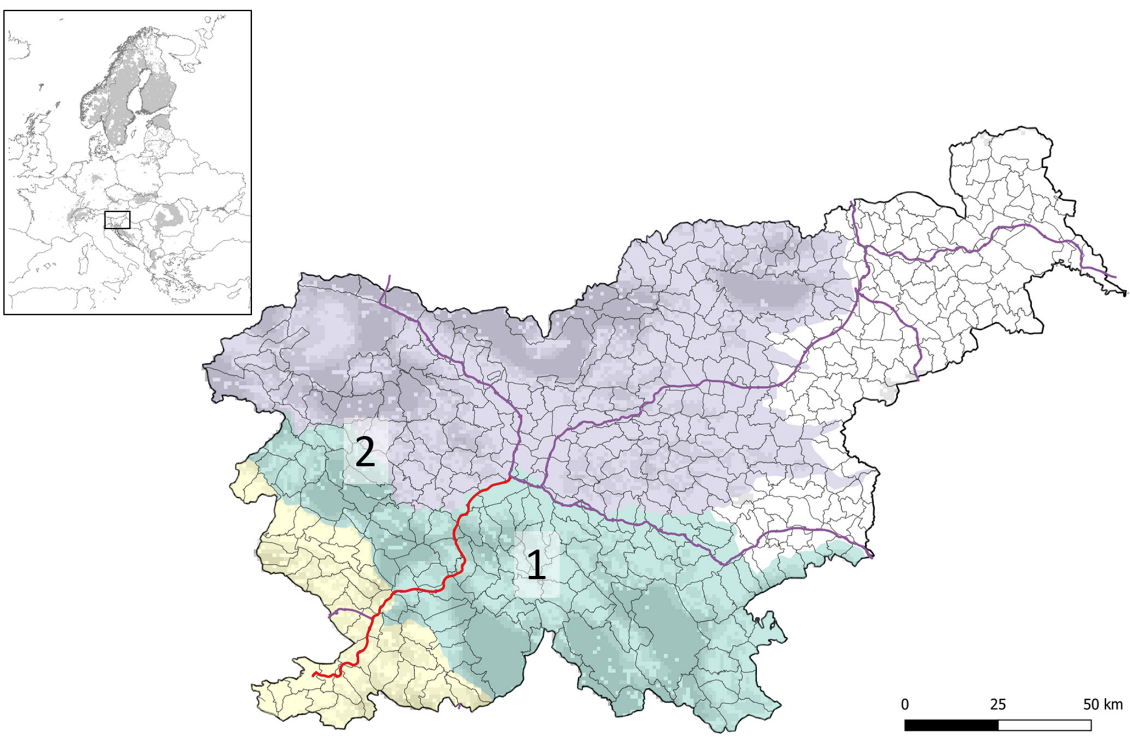

Figure 1. The study area in Slovenia, including the southern study region (1) and the northern study region (2), which are separated by the A1 (Ljubljana-Koper) highway (red line). The macroregions of Slovenia are shown in violet (Alpine), blue (Dinaric), and yellow (Mediterranean) (Perko 1998). Lynx habitat suitability is shown as shaded, darker areas indicating more suitable habitat (Skrbinšek and Krofel 2008). The borders of the hunting grounds are shown as grey lines, and other highways in violet.

1998). The Dinaric and the Mediterranean macroregions are intersected by the A1 highway, with very limited opportunities for wildlife crossing, creating a barrier for the connectivity (Fig. 1). The effect of this barrier appears strong for lynx as GPS-tracking showed that despite suitable habitat, no lynx from the southern Dinaric region established a territory overlapping the highway, and several dispersing individuals were stopped by this highway (Krofel 2012, Fležar et al. 2024a). Moreover, the core distribution of lynx in Slovenia was historically limited to the southern Dinaric region (Čop and Frković 1998, Staniša et al. 2001, Koren et al. 2006, Kos et al. 2012). Due to this barrier, and the current and historic lynx distribution, we divided our study area into two study regions: 1) the southern study region, encompassing the Dinaric and Mediterranean macroregions south-east of the A1 highway, and 2) the northern study region, encompassing the part of the Dinaric, Mediterranean and Alpine macroregions north-west of the A1 highway (Fig. 1). Both study regions include large areas of land that are highly suitable habitat for lynx (Skrbinšek and Krofel 2008, Oeser et al. 2023).

Lynx monitoring in Slovenia

Network of collaborating hunters, questionnaires and chance observations

Slovenia is divided into hunting grounds with two main management types: 1) state-owned hunting grounds (n = 12, ~40–400 km^2, encompassing 25.5% of the country) managed by professional hunters/rangers employed by the central national wildlife management institution (Slovenia Forest Service) or the Triglav National Park, and 2) hunting grounds managed by local hunting clubs (n = 411, average size ~ 50 km^2, 74.5% of the county) (Fig. 1). Hunting clubs consist of amateur hunters who have undergone the necessary education to obtain a hunting licence and become member of a hunting club (Wild Game and Hunting Act 2004). Following the initiation of the lynx reinforcement program in 2017, questionnaires regarding lynx presence/absence were distributed to hunting clubs in autumn and spring each year (Fig. 2). In addition, independently from the questionnaires, chance observations were reported to Slovenia Forest Service by hunters, foresters, scientists and the general public (Čop

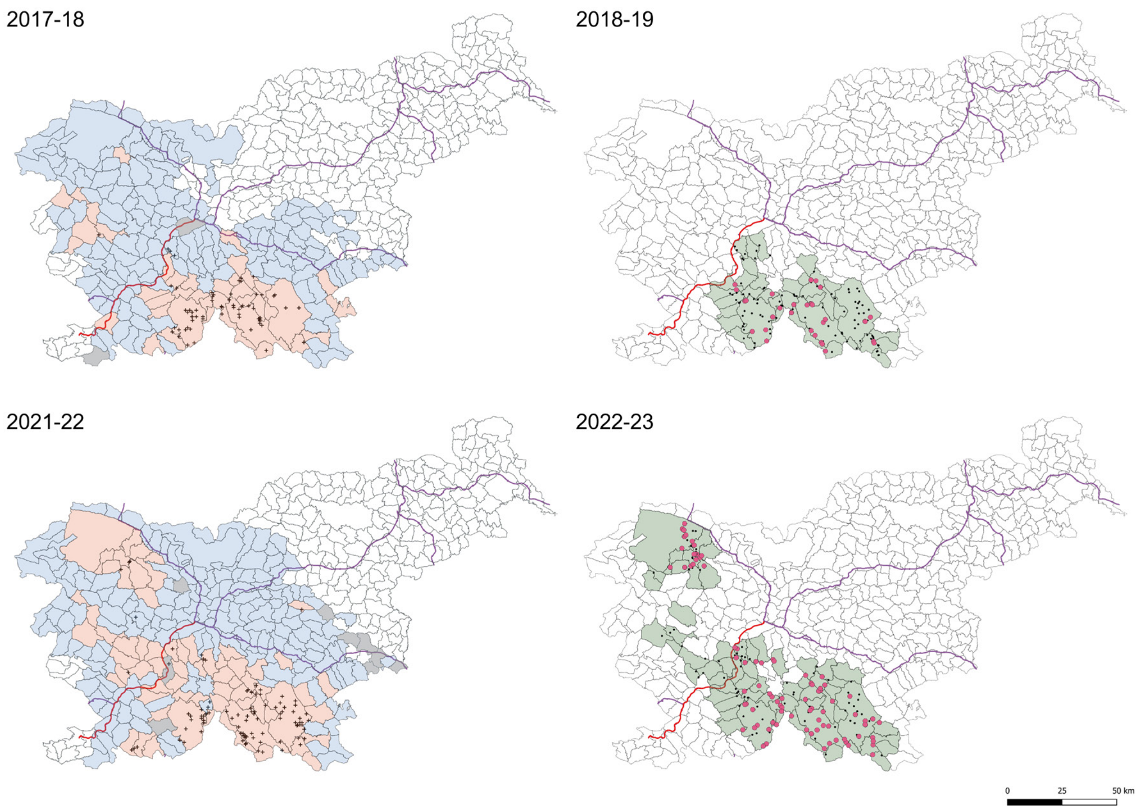

Figure 2. Panels to the left show hunting grounds where the questionnaires were distributed and the lynx presence (red) or absence (blue) was reported, or no response was received (grey), and the locations of verified chance observations (black dots). Panels to the right show the hunting grounds participating in the following camera trapping survey (green), the locations of camera trapping sites recording lynx presence (pink dots) and camera trapping sites not recording lynx (black dots). The first and the last two surveys are shown here. For the remaining survey years see the Supporting information.

and Frković 1998, Fležar et al. 2024a) (Fig. 2). The observations are divided into three categories according to their significance and verifiability (i.e. C1: hard facts, e.g. lynx photos, lynx captures, dead lynx, lynx genetic samples; C2: objective proofs of lynx presence, e.g. observations of lynx tracks, kills and scats by people who attended special courses; C3: signs that cannot be verified, e.g. direct observations without proof, unconfirmed kills, tracks, scats, vocalizations; Molinari-Jobin et al. 2003).

Camera trapping monitoring program

Lynx monitoring with camera traps (i.e. camera trapping) has been conducted since 2018 within the expected lynx distribution in Slovenia. The expected lynx distribution for each camera trapping survey was defined based on the questionnaires (i.e. hunting grounds where lynx presence was reported in at least one of the questionnaires), and the verified chance observations (C1 and C2 records) from the previous lynx-year (1 May–30 April, as lynx generally start to give birth in late May; Mattisson et al. 2022, Mináriková et al. 2023). The camera trapping survey started in early–mid August each year and continued until the following spring. All state-owned hunting grounds within the expected lynx distribution were involved in camera trapping. Hunting clubs were invited to participate in the monitoring program if they met all of the following criteria: 1) they reported lynx presence in questionnaires, 2) verified chance observations (C1 and C2 records) were available from the hunting ground, 3) the hunting ground included suitable lynx habitat over at least half of its extent (based on Skrbinšek and Krofel 2008) and 4) the hunting ground was adjacent to other hunting grounds fitting the criteria 1–3). Furthermore, a hunting ground that did not report lynx presence, but was adjacent to more than one other hunting ground where lynx presence was confirmed, was also invited. Also, if a hunting club expressed a wish to participate in camera trapping despite not being invited, it was included if it at least met criteria 3) and 4). Each collaborating hunting club assigned at least one contact person as the main camera operator. Local coordinators, i.e. professionals from Slovenia Forest Service and University of Ljubljana, met each of the camera operators in person at the beginning of each camera trapping survey, to provide necessary training on the use of different camera trap models, and to set up camera traps at the optimal camera trapping sites based on the local knowledge of the hunters and experiences of lynx behaviour, and camera trapping, of the local coordinators. At least one camera trapping site was selected in each participating hunting ground and deployment information (coordinates, site characteristics, contact of the camera operator, number of camera traps per site, date) was collected by the local coordinator. Between 79 and 110 camera trapping sites had one camera trap installed, between nine and 48 had two and up to six had three or four camera traps installed. Camera traps were set up exclusively in forested areas, the optimal habitat of lynx (Skrbinšek and Krofel 2008), using three types of locations with distinct characteristics: lynx scent-marking sites, roads and other types of locations (i.e. located at various karstic habitat features; for details see Fležar et al. 2023a). Camera operators retrieved the SD cards from camera traps and checked battery levels on at least a monthly basis, reporting problems (e.g. stolen or malfunctioning cameras) and handing the SD cards to the local coordinators. In the southern study region, the set-up of the camera traps followed the requirements for spatial capture–recapture (SCR) modelling (i.e. each individual should have a probability > 0 of being detected; Royle et al. 2014), ensuring at least one camera trapping site was placed within the home range of any individual in the study area (Tobler and Powell 2013). The mean smallest (female) home-range size is 114.4 km^2 (range 42.2–176.6 km^2, $n = 9$) in the study area (MCP 95%; Krofel et al. 2024). Given only recent establishment of the stepping-stone in the northern study area, the data were too scarce to enable SCR modelling over the study period. For more information regarding camera trap set-up, see the Supporting information.

We used cameras with white flash (CuddeBack X-Change Color Model 1279; Reconyx HyperFire 2 Professional White Flash Camera HP2W) or cameras with black (940 nm light wave) or regular infrared light (850 nm light wave; CuddeBack X-Change Color Model 1279; StealthCam STC-G42NG; Moultrie M40-i; Browning Spec Ops Elite HP4), respecting the best-practice guidelines for selecting the appropriate model for the given location type (Stergar and Slijepčević 2017).

Camera trapping data processing, annual minimum count and reproductions

All camera trapping data were processed, sorted and annotated using Camelot software (Hendry and Mann 2017), where approximately 300 000 annotated wildlife recordings, including 2157 photos of lynx, were entered during the five-year camera trapping monitoring period. Images of humans were removed to conform to the General Data Protection Regulation (Directive (EU) 2016/679), but information on their passing was kept. For this study, we used data collected from 15 August to 15 February in each survey (2018–2019 to 2022–2023), to avoid including the mating season and the peak in dispersal (Zimmermann et al. 2005, Breitenmoser and Breitenmoser-Würsten 2008). The number of camera trapping sites, total camera trapping days and other details about the camera trapping effort are provided in the Supporting information. In cases where there were > 1 camera trap per site (defined as all camera traps within a 100-m radius), we pooled all camera trapping data and accounted for the number of camera traps per site in the modelling process (section SCR modelling in the southern study region).

Lynx photos were annotated with status, individual identity and sex. Status was defined based on lynx size: full-grown animals (i.e. adults or subadults) were defined as 'independent', kittens less than one year old were defined as 'juveniles' and if the status could not be determined, they were labelled as 'unknown'. Each photo of lynx was subjected to identification based on the animal's unique pelage pattern by trained observers ($n = 4$), following the established guidelines in Choo et al. (2020). In the few cases of photos of individuals where only one flank was available (one left- and two right-flanked individuals in 2018–2019 and two left- and three right-flanked individuals in the 2022–2023 survey), only the right-flanked animals were considered for further analysis, and photos of poor quality were not subjected to identification. Sex was determined if the genital area was clearly visible on at least one of the recordings of a given individual, or for females accompanied by kittens; thus individuals were defined as females, males or of unknown sex. Among 1008 lynx events, 77.1% allowed lynx identification, 73.5% allowed status determination and 78.2% of lynx events allowed for sex determination. For the annual total and sex-specific minimum count of lynx per study region, we used records of individually identified independent (subadult or adult) lynx. For the yearly minimum count of reproductions, we used the records of individual females with kittens.

SCR modelling in the southern study region

For the southern study region, we used records of individually identified independent lynx to build capture histories used for the SCR modelling to obtain annual density and abundance estimates. During the five surveys (15 August–15 February in 2018–2019 to 2022–2023), between 119 and 149 camera trapping sites were active, operating for an average of 14 203 camera trapping days (Supporting information). Annual lynx density, baseline detection rate and spatial scale parameter were estimated with maximum likelihood SCR models (Efford et al. 2004, Royle et al. 2014) using the 'oSCR' package (Sutherland et al. 2019) in R software ver. 4.3.0 (www.r-project.org). We ran multi-session models with five sessions defined as the respective survey. At least 20 spatial recaptures were confirmed for each survey (Efford et al. 2004, Palmero et al. 2023; Supporting information). The distribution of individual activity centres was defined as Bernoulli random trials (Royle et al. 2014) and the spatial model of detection followed a half-normal detection function (Efford and Schofield 2020). We assumed homogeneous distribution of the individuals across space (Royle et al. 2014).

To obtain specific estimates of density and abundance for each survey, we included survey year as a covariate to the density parameter. Furthermore, we included the effect of: 1) local behavioural response to assess if a subsequent encounter of an individual after its capture at a specific trap is increased or decreased for that trap (Royle et al. 2011), 2) sex, to assess the sex-specific variation in density, baseline detection rate and the spatial scale parameter (Sollmann et al. 2011, Goldberg et al. 2015), in which fully or partially observed sex data are included in the likelihood (Sutherland et al. 2019), 3) location type (lynx scent-marking sites, roads and other locations), to assess variation in baseline detection rate due to camera trapping site characteristics (Fležar et al. 2023a), 4) number of camera traps to assess the variation in baseline detection rate due to variation in number of camera traps per site and 5) survey year, to assess the variation in baseline detection rate and spatial scale parameter between the five surveys. This resulted in 41 candidate models (Supporting information), which we ranked based on the Akaike information criterion (AIC; Burnham and Anderson 2004) and their predictive power (AIC weight; Johnson and Omland 2004). We used the highest-ranked model to calculate the annual density and abundance of lynx in the southern study region. We used relative standard error (RSE; Efford and Boulanger 2019, Green et al. 2020, Palmero et al. 2023) as an indicator of precision for density and abundance estimates.

We defined the extent of the effective sampling area, (i.e. the state space) with a buffer width of 15 km and a resolution of buffer cells 2.5 × 2.5 km for each survey year, following the recommendations of Efford and Fewster (2013) and Dupont et al. (2021) and findings for this area in Fležar et al. (2023a). We restricted the state space by removing non-suitable habitat (as described in Fležar et al. 2023a), and limited it to the south-east of the A1 highway, to restrict the modelled activity centres used for density estimation to the southern study region (Supporting information). Finally, to calculate the abundance in the southern study region, we further restricted the state space by the national border of Slovenia, following the approach used for calculating the population size of the Slovenian parts of the transboundary wolf and brown bear populations (Skrbinšek et al. 2019, Bartol et al. 2023). Consequently, the state space used for abundance represented between 71.7% (in 2020–2021) and 73.9% (in 2022–2023) of the state space used for density estimation.

Results

Network of collaborating hunting clubs and camera trapping effort

Over 90% of the hunting clubs receiving the questionnaires responded each year (Supporting information), providing information on lynx presence and which area to target for the camera trapping survey. Prior to the first camera trapping survey (i.e. in May–April 2017–2018), lynx presence was reported in 42 out of 196 hunting grounds (7 out of 80 in the northern study region and 35 out of 116 in the southern study region; Supporting information). During the study period, the number of hunting clubs reporting lynx presence increased in both study regions, although the increase was higher in the northern study region (Supporting information). Prior to the last survey (i.e. in May–April 2021–2022), lynx presence was thus reported in 67 hunting grounds (23 in the northern study regions, 43 in the southern study region and in one outside the study area (i.e. in the eastern part of the Alpine macroregion; Supporting information).

The verified chance observations (C1 and C2) showed a similar trend as the questionnaires. The majority of the records were from the southern study region, where the number of verified lynx records increased from 67 in 2017–2018 to 238 in 2022–2023. From 2017–2018 to 2020–2021, almost all verified chance observations were from the southern study region (in total, 286 in the southern and 5 in the northern region), while after the lynx reintroduction in the

Table 1. The minimum count of identified independent individual lynx (female, male, unknown sex and total) and the minimum number of reproductions per study area for each survey. No camera trapping survey was conducted in the northern study region in 2018–2019.

		2018–2019	2019–2020	2020–2021	2021–2022	2022–2023
Southern study area	Female lynx	7	6	12	11	12
	Male lynx	6	6	8	8	15
	Lynx of unknown sex	0	1	0	1	7
	Total lynx	13	13	20	20	34
	Reproductions	5	2	5	4	5
Northern study area	Female lynx	-	0	0	3	3
	Male lynx	-	1	0	2	2
	Lynx of unknown sex	-	1	0	0	2
	Total lynx	-	2	0	5	7
	Reproductions	-	0	0	1	3

Alps in 2021, the number of records increased in the northern region (in total, 358 in the southern and 16 in the northern region between 2021–2022 and 2022–2023) (Supporting information).

While 35 hunting clubs in the southern study region reported lynx presence in 2017–2018, 37 were invited to participate in the first camera trapping survey (in 2018–2019), 36 accepted the invitation and lynx were recorded on camera traps in less than 40% of the hunting grounds (3.3% of all hunting grounds in Slovenia). In the following years, all hunting clubs that were invited in the southern study region participated in camera trapping surveys. In the northern study region, camera trapping was initiated in 2019–2020, where all invited hunting clubs (n = 9) participated. The total number of hunting clubs participating in camera trapping reached its maximum in the final survey (2022–2023) (n = 63; 43 hunting clubs in the southern and 20 in northern study region), when over 60% of them recorded lynx on camera traps (70% in the southern and 40% in the northern study region; 9% of all hunting grounds in the country; Supporting information). Between 63 and 101 hunters annually operated the camera traps and the total area of participating hunting grounds ranged between 2406 and 4364 km^2.

Minimum count of independent lynx and reproductions

In the southern study region, the minimum number of independent lynx increased from 13 (7 females, 6 males) to 34 (12 females, 15 males) from 2018–2019 to 2022–2023. The minimum number of reproductions fluctuated between two and five (Table 1).

In the northern study region, the number of independent lynx increased from two in 2019–2020 to seven in 2022–2023 (Table 1). Following the translocation of lynx to the Alps in 2021, all released lynx (n = 5) were recorded on camera traps in the 2021–2022 survey. The first reproduction in the northern study region was confirmed immediately after the reintroduction, and all three translocated females reproduced in the subsequent year (2022–2023) (Table 1). In 2022–2023, only four of the translocated lynx were detected, while two additional individuals of unknown sex were detected, likely the offspring of the translocated lynx.

Lynx density and abundance in the southern study region

The SCR model with highest support included effects of local behavioural response, sex, number of cameras per site and location type on baseline detection rate, and of sex on the spatial scale parameter (Supporting information). The mean lynx density estimate increased from 0.66 lynx/100 km^2 (95% confidence interval (CI) 0.37–1.18) in 2018–2019 to 1.30 lynx/100 km^2 (0.92–1.83) in 2022–2023, indicating an almost 100% increase over the five-year period (Fig. 3, Supporting information). The mean abundance estimates increased from 21 (12–38) lynx in 2018–2019 to 42 (30–59) in 2022–2023 (Supporting information). Both density and abundance estimates reached a medium precision for the first four surveys (RSE > 0.20), and a high precision (RSE = 0.18) in the last survey year (Supporting information). The change in the size of the state space, for which the estimates of these demographic parameters were produced, was negligible (0.4% larger state space in 2022–2023 compared to 2018–2019) (Supporting information).

The mean densities of females were consistently higher than those of males, although we did not identify more females than males in each survey (Table 1). Females had a consistently lower baseline detection probability and spatial scale parameter compared to males. The baseline detection rate was highest at marking sites, followed by roads and other types of locations, and lower in sites with one camera trap compared to sites with two or three camera traps (Supporting information).

Discussion

We showed that a citizen-science approach to monitoring coupled with professional coordination can yield high-resolution data enabling population estimates for an endangered population of a large carnivore, the Eurasian lynx, at a national level. Our approach can be classified as collaborative monitoring with external data interpretation (Danielsen et al. 2008), focused on involving local people in data collection and decision-making, while the design and data analyses are undertaken by researchers and wildlife managers (for details, see the Supporting information). Contrary to the many

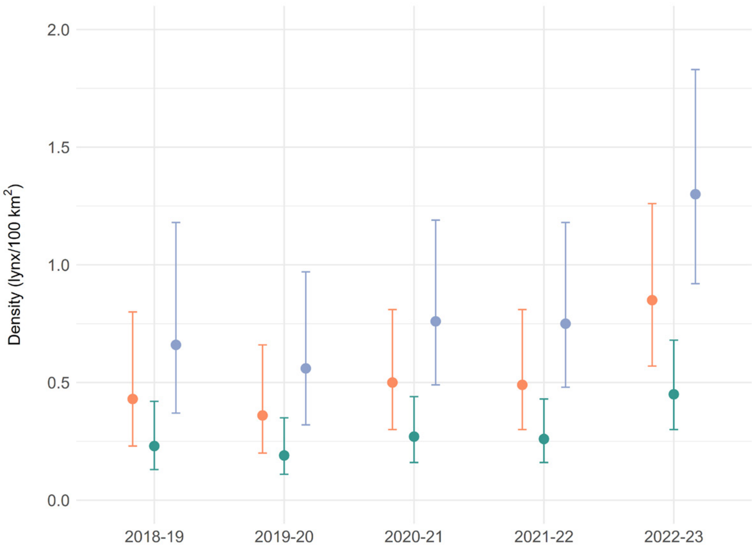

Figure 3. Female (orange), male (green) and total (blue) lynx density over the five-year period in the southern study region in Slovenia (for details, see the Supporting information).

other wildlife monitoring citizen-science programs involving participants from the general public (MacPhail and Colla 2020), our approach adds to the practices used in Switzerland and Scandinavia (Andrén et al. 2002, Helle et al. 2016, Zimmermann 2019, Bischof et al. 2020), which are largely involving a targeted group – i.e. hunters. This contributed to hunters acting as stewards for lynx conservation, which could help maintain, or even increase, positive attitudes towards the species during the reinforcement program (Mavec et al. 2024a).

Collaboration with hunters

The leaders of hunting clubs and professional hunting grounds were highly responsive to questionnaires about lynx presence (over 90% responded in each survey; Supporting information), and people increasingly contributed with reporting chance observations. Questionnaires combined with chance observations provided a relative assessment of increasing lynx presence in space and time (Breitenmoser et al. 2006). The coordination of the camera trapping survey required high involvement of experts, especially where the sampling design needed to fit the requirements for estimating lynx density and abundance. Nevertheless, hunters were the key participants in the most labour-intensive part of the lynx monitoring program, operating between 126 and 168 camera trapping sites per survey. This collaboration enabled a large-scale monitoring over a multi-year period, which would be otherwise unfeasible with available funds and personnel.

The lynx is strictly protected in Slovenia by European (Habitats Directive 92/43/EEC) and national law (Nature Conservation Act), and no hunting has been permitted since 2004 (Kos et al. 2012). Consequently, the motivation of hunters to participate in a lynx monitoring program cannot be connected with the benefits of trophy hunting (Bichel and Hart 2023), which could potentially be said for their involvement in the monitoring of brown bear, which is regularly hunted in Slovenia (Skrbinšek et al. 2019). The motivation for participating in lynx monitoring could originate from the hunters' inherent connection with nature, including their interest in the forest ecosystem as a whole (Bell et al. 2008) and the sense of 'psychological ownership' of wildlife (Greving et al. 2020), as well as the lynx reinforcement program. Approximately 80% of Slovenian hunters expressed a positive attitude towards the lynx, and support for lynx conservation at both the beginning and the end of the reinforcement program (Mavec et al. 2024a). Furthermore, there might be a feeling of responsibility to continue the legacy of the hunters who initiated and contributed to the successful lynx reintroduction in 1973 (Čop 1990). In a survey by Mavec et al. (2024b), they also reported to feel pride in having the 'beautiful' felid present in their local environment. Additionally, obtaining photographs of elusive, rare and iconic species by camera trapping can be perceived similarly to a possession of a trophy, which can induce social recognition and prestige (Darimont et al. 2017). Camera traps are an increasingly popular hunting tool (Meek and Pittet 2012, Webb 2020), enabling hunters to obtain various information about wildlife, e.g. the presence of trophy game, such as red deer *Cervus elaphus*, or less known species, such as the European wildcat *Felis silvestris* or golden jackal *Canis aureus*, their habits and individual traits (sex, age, reproduction, etc.). By collaborating in lynx camera trapping, hunters could thus increase their local knowledge about lynx and other wildlife, as well as develop new skills in operating different camera models (Haywood et al. 2016; Supporting information). For more information regarding increasing stakeholder capacity, see the Supporting information.

The hunters' voluntary work was primarily acknowledged through timely, accurate feedback and public recognition of their contribution (Supporting information). Personal meetings between local coordinators and hunters were crucial to exchange and discuss information about the lynx, the monitoring and the reinforcement activities, as well as building trust between the hunters and the governmental institutions (Danielsen et al. 2005), and integration of hunters in the data collection process can help increase hunters' trust in the results of monitoring (Meek and Zimmermann 2016). Furthermore, local consultative groups were formed to identify the benefits of lynx conservation by the local communities (Velkavrh et al. 2024). Also, closed social media groups facilitated by local coordinators were created, and practical lynx-themed items (hunting badges, plaquettes, T-shirts) were distributed among the collaborating hunters to promote a sense of unity and collaboration (Haywood et al. 2016).

Finally, hunters were involved in adapting the national game management plans in such a way that the presence of lynx and other predators was acknowledged, which addresses one of the main sources of conflict between hunters and large carnivores, i.e. the competition for game species (Treves and Karanth 2003, Liberg et al. 2012, Heurich et al. 2018). One of the main goals of adaptive wildlife management is that viable populations of prey species are maintained. Thus, the hunting quotas are adjusted and/or deviation from the proposed hunting quota (including the prescribed sex ratio) is allowed, in accordance with the prey species' local density index and predator presence (Rot et al. 2022). For increasing awareness of the status and conservation of lynx among the wider hunting community, online access to lynx data was provided (Supporting information) and the monitoring results were published annually in the national hunting magazine (Fležar et al. 2022) and presented at various educational or expert meetings (Javornik et al. 2022, Fležar et al. 2023b, 2024b).

Changes in lynx density, abundance and reproduction

The southern study region represents the Dinaric lynx population in Slovenia, located south of the A1 highway (Fig. 2, Supporting information). At the beginning of the reinforcement program, the mean estimated density in this area was one of the lowest reported for lynx populations in central Europe (0.56 (95% CI 0.32–0.97) lynx/100 km^2 in the 2019–2020 survey; Supporting information). This was comparable to the French Jura with an established reintroduced lynx population (from 0.24 $\pm$ 0.02 SE lynx/100 km^2 in the Doubs area in 2011 to 0.91 $\pm$ 0.03 SE lynx/100 km^2 in the Ain area in 2014; Gimenez et al. 2019), or the German Palatinate forest where lynx was recently reintroduced (0.52 $\pm$ 0.18 SE lynx/100 km^2, Port et al. 2024). However, 5 years after the start of the reinforcement, the mean density more than doubled in a constant area of space (1.30 (95% CI 0.92–1.83) lynx/100 km^2 in the 2022–2023 survey), approaching the estimates obtained for the core areas of stable lynx populations, e.g. the Bohemian–Bavarian–Austrian population (1.33, 1.05–1.79 95% highest posterior density interval; Palmero et al. 2021), the Alpine population (1.38 $\pm$ 0.23 lynx/100 km^2; Pesenti and Zimmermann 2013) and the Carpathian population (1.6 $\pm$ 0.39 SE; Iosif et al. 2022). Following the increasing density within the survey area, we could expect that lynx will/might start to expand to suitable habitats in the southern study region and possibly into the northern study region, which was already indicated by the responses to questionnaires and opportunistic lynx records collected in the 2021–2022 survey (Fig. 2). Moreover, the planned construction of a wildlife crossing over the A1 highway (Ministry for Natural Resouces and Spatial Planning 2021), should promote the expansion and enhance the functional connectivity between the southern and the northern study region.

Despite the substantial increase in the number of detected females in the southern study region, as well as the abundance and density estimations, the annual minimum count of reproductions did not exceed five. However, an increasing number of reproductions was detected within the home ranges of translocated males. For example, in the 2019–2020 survey, only two reproductions were detected, of which one was from late mating of a translocated male and a remnant female (Krofel et al. 2021). In the last survey (2022–2023), three out of five detected reproductions were detected within the home ranges of translocated males (the mixed parenthood was genetically confirmed for one litter; Fležar et al. 2024a), although translocated males represented the minority of all detected independent males (i.e. three out of 15). Thus, the survival of these individuals is of high importance, as their continuous reproduction is crucial for further improvement of the genetic status of the Dinaric lynx population (Pazhenkova et al. 2024).

The minimum count of independent lynx and number of reproductions were the core parameters to assess the status of the lynx in the northern study region, especially after the creation of the stepping-stone in the Alps through reintroduction of lynx from the Carpathian population in 2021. Before the translocations (i.e. between 2018 and 2021), reports of lynx observations were sporadic and limited to the south-eastern part of the northern study region (i.e. just north of the A1 highway; Supporting information). However, after reintroduction of five lynx to the Alps, all translocated females (n = 3) reproduced in 2022–2023. These were the first confirmed lynx reproductions in the Slovenian Alps in over 150 years (Čop and Frković 1998, Staniša et al. 2001, Koren et al. 2006, Kos et al. 2012). The current data show a promising development of the stepping-stone population, as seven independent lynx were detected in the last survey (2022–2023), as well as several juveniles. However, the stepping-stone remains vulnerable due to its small size; therefore, another translocation program was initiated in 2023 in the neighbouring region of Italy, releasing five lynx in the vicinity of the Slovenian border (https://www.progettolinceitalia.it). To track the expansion of the new stepping-stone created in the Julian Alps towards the other lynx populations in the Alps (i.e. Switzerland, Austria), international collaboration including coordinated monitoring methods, transboundary data exchange and effective conservation measures need to be implemented (Bonn Lynx Expert Group 2021).

Implications for conservation and management

Besides the importance for assessing the population status, the annual minimum count of independent lynx and reproducing females has had additional management implications in both study regions, as it was the basis for decision-making during the reinforcement program (Supporting information). For example, the loss of a translocated male in the northern study region area led to the release of another male to this area to improve the likelihood of reproduction with the established female (Fležar et al. 2024a). Similarly, aiming at increasing the number of reproductive females in the southern study region, a female lynx was translocated there at the end of the last survey (2022–2023), and confirmed to have established a home range and reproduced in 2024 (Hočevar et al. 2024).

Both local management authorities as well as international assessments (e.g. EU Habitats Directive, IUCN Red Lists) often rely on the estimates of species abundance to assess the conservation status (Chapron et al. 2014). For Slovenia, it is important to combine the results from the SCR modelling in the southern study region (42 independent lynx, 95% CI 30–59), with the minimum count of independent lynx in the northern study region, as this is the only information available at the moment. Consequently, the current national population size can be estimated to be approximately 50 lynx in 2022–2023.

To follow the future development of the reinforced lynx population, the monitoring program as described in this study needs to continue. Ideally, it should continue to aim at estimating density and abundance of lynx through camera trapping and SCR modelling, aided by hunter involvement, questionnaires and reported chance observations, over the entire range. However, a balance between available funding, manpower and the ongoing changes in the lynx range within the country needs to be found. Since all collared lynx in the southern study region (n = 10, Hočevar et al. 2024) were detected by camera traps, incorporating telemetry data into the SCR models could improve the population density estimate (Linden et al. 2018). Our camera trapping design involves setting up a varying number of camera traps at different types of locations, including scent-marking sites, which is usually not the practice in other study areas (Weingarth et al. 2015, Gimenez et al. 2019, Dula et al. 2021). This is a result of the learning process of both collaborating parties, creating a trade-off between requirements of the scientific method and the camera set-up for optimized lynx detection. Here we show that the number of camera traps per site, and the type of site, should be taken into account as covariates for the baseline detection probability in the SCR analysis (Fležar et al. 2023a; Supporting information).

Timely and accurate data on lynx population status are necessary for informed management decisions. For example, if the number of lynx in the northern study area decreases, additional translocation could be required to avoid extinction of the stepping-stone. Novel information about lynx presence in a certain area also needs to be accounted for in the game management plans in a timely manner (Rot et al. 2022). A disruption of the continuous monitoring and information exchange may also result in decreased motivation among the monitoring network members (i.e. hunters), which can impact the quality of the future monitoring program. Finally, information about the status of lynx should be regularly and transparently provided to stakeholders and the public, to maintain trust in the ability of authorities to monitor and manage the carnivore (Krofel et al. 2024). Without this, trust can deteriorate, which can be followed by a decrease in acceptance of the lynx (von Essen et al. 2014), ultimately undermining the past successful conservation efforts.

Conclusions

The involvement of hunters in the lynx monitoring program in Slovenia is an example of hunters acting as promotors of active conservation of a large carnivore. Hunters contributed to the majority of the data collected within the monitoring program and, by combining the knowledge of local hunters, researchers and managers, we obtained increased knowledge about the lynx distribution range as well as annual estimates of lynx density and abundance during the five-year population reinforcement program. In addition, the continuous data from the lynx monitoring program guided the decision-making process of further translocations during the reinforcement program. We believe that our study represents a good practice example of lynx monitoring, which can be replicated in the future lynx reinforcement or reintroduction projects currently planned across central Europe (Linking Lynx 2023), as well as for other regions facing similar challenges connected to conservation and monitoring of rare, elusive species with large spatial requirements. Our study also highlights the importance of close partnership with hunters in wildlife monitoring programs, which can result in improved trust in the results from the monitoring, and acceptance of conservation measures.

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Data availability statement

Data are available from the Dryad Digital Repository: https://do.org10.5061/dryad.cnp5hqcgm (Fležar et al. 2025).

Supporting information

The Supporting information associated with this article is available with the online version.

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