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Learning from long time series of harvest and population data: Swedish lessons for European goose management

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Goose management in Europe is faced by multiple challenges, as some species are declining and in need of conservation actions, while other populations have become very abundant, resulting in calls for increased harvest. Sweden has long-term series of harvest data and counts of breeding and autumn-staging geese. We used national data (indices) for greylag goose, bean goose and Canada goose to study shifts in temporal trends and correlative patterns, and to infer possible causal links between harvest and population trends. Our study provides an opportunity to guide management given the data collected within the present monitoring, as well as to suggest improvements for future data collection. The populations of greylag and Canada geese increased in Sweden 1979–2018, but this long-term trend included a recent decrease in the latter species. Bean goose breeding index decreased, whilst staging numbers and harvest varied with no clear long-term trend. For Canada goose, our analysis suggests that harvest may affect population growth negatively. For bean goose and greylag goose we could not detect any effect of harvest on autumn counts the following year. We find that the present data and analysis of coherence may suffice as basis for decisions for the current management situation in Sweden with its rather unspecific goals for greylag (very abundant) and Canada goose (invasive species) populations. However, for management of bean geese, with international concerns of over harvest, data lack crucial information. For future management challenges, with more explicit goals, for all goose species we advocate information that is more precise. Data such as hunting effort, age-structure of goose populations and mark–recapture data to estimate survival and population size, is needed to feed predictive population models guiding future Swedish and European goose management.

Keywords: conservation, goose populations, harvest, management, monitoring programs, population trajectories, time series

Interest in European goose management has grown in recent decades. This is largely due to some goose populations growing so abundant that they impact ecosystems and cause conflicts within conservation and wildlife management (Buij et al. 2017, Fox and Madsen 2017). At the same time, geese provide ecosystem services (Green and ElMBERG 2014, Widemo et al. 2019) and support a long tradition of hunting representing high recreational values (Kear 1990). Following over-exploitation and population decline of many goose populations in previous centuries, increased regulation of hunting has been a cornerstone in their manage-

ment since World War II (Cooch et al. 2014). The rapid recent growth of some populations has been linked to milder winters and a shift in foraging sites from traditional natural habitats to intensively managed agricultural fields (Van Eerden et al. 1996, Madsen et al. 1999, Abraham et al. 2005, Fox et al. 2005). After decades of successful conservation efforts, goose management in Europe now faces new challenges, including calls to increase harvest rates of very abundant species (Madsen et al. 2015, Jensen et al. 2016, Fox and Madsen 2017). Given this rapid and recent change in mind-set, i.e. from a conservation focus to problems associated with high abundance, it is not surprising that studies relating harvest effects to goose population dynamics in Europe are relatively scarce (Williams et al. 2019). Yet, such knowledge is essential to understand how different harvest strategies may influence population dynamics and management.

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Managing geese at the flyway level has a long history in North America (Walters 1986, Williams and Nichols 1990), whereas the first similar effort for a European population (pink-footed goose *Anser brachyrhynchus*) was launched only recently (Madsen et al. 2017). There are additional European flyway plans forthcoming, concerning rapidly increasing species for which the aim is to reduce population growth. Conversely, for declining or endangered species/subspecies the challenge is instead to facilitate population recovery (Marjakangas et al. 2015). In North America, studies based on mark–recapture models are widely used to estimate harvest effects on waterfowl populations (Calvert and Gauthier 2005, Alisauskas et al. 2011), but such comparative data from European geese are very limited (Johnson et al. 2018). Another approach to study effects on population dynamics is to relate monitoring and harvest data, preferably when long time series exist (Niel and Lebreton 2005). Such studies can provide knowledge needed to guide management, and to pinpoint strengths and weaknesses in present management systems.

Goose harvest in Sweden concerns three species with quite different management needs; greylag goose *Anser anser* (very abundant), Canada goose *Branta canadensis* (introduced) and bean goose *Anser fabalis* (with concerns of over-exploitation). Whereas the demographic knowledge about these populations is limited, there are three independent long-term indices available. Two are based on count data and reflect changes in population size, and one estimates the annual harvest. This study aims to investigate correlations between the three indices and whether harvest has an effect on the growth rate of the populations, given the data currently available for management. We used a breakpoint analysis to identify possible temporal shifts in trends of these indices, and to what extent such shifts coincided in time between time series. We also examined correlative patterns among the three indices. Further, we calculated a relative harvest rate to search for possible harvest effects on coming years count data. Based on these analyses we discuss plausible mechanisms behind the patterns found. Further, our analysis provides a critical review of Swedish data and we aim to identify and describe desired improvements in data collection that will facilitate future management of goose populations.

Material and methods

Study populations and regulation of harvest

Greylag geese breeding in Sweden typically spend the winter in western Europe. Analyses thus far do not suggest a large influx of individuals from breeding populations in other countries to Sweden during the migration periods (Andersson et al. 2001, Fransson et al. 2008, Bacon et al. 2019). Despite an open hunting season over entire Sweden, a long period of growth has made the greylag goose population very large and a main culprit in crop damage (Montràs-Janer et al. 2019). Hence, hunting of this species is rarely controversial.

The non-native Canada goose was introduced and has been widely translocated in Sweden, starting in the 1930s in response to declining native goose populations at the time. These efforts have continued until the 1980s at least

(Ottosson et al. 2012). Today it is locally regarded as a problematic species by farmers and considered a nuisance in some urban environments (Fox 2019). Canada geese breeding in the north of the country are long-distance migrants, but Swedish breeders normally do not leave the country. Minor occasional exchange with other countries has been reported in winter, e.g. movements to northern Germany and influx by Norwegian breeders (Fransson et al. 2008).

The bean goose is a scarce breeder of boreal fens and mires in the northern half of Sweden. In contrast to greylag and Canada geese, the majority of bean geese present in Sweden in autumn and winter comes from breeding populations in other countries; likely only a fraction of the Swedish breeding birds spend the winter within the country (i.e. western management unit, Marjakangas et al. 2015). The majority of bean geese migrating through and wintering in Sweden is of the taiga subspecies (*A. f. fabalis*) breeding in western Russia and Finland, but the tundra subspecies (*A. f. rossicus* or *serrirostris*) from more northern and eastern breeding grounds seems to be increasing in numbers (Nilsson 2017). The bean goose is harvested in Sweden, but the open hunting season has been questioned as the *fabalis* subspecies population is relatively small and its trajectory debated (Marjakangas et al. 2015).

Breeding pairs of one or more of these three species are found throughout Sweden, but only in low densities in the boreal north (Ottosson et al. 2012). Typically, goose migration in northern Europe is along a southwest–northeast axis, in our study represented by greylag and bean geese. Greylag and Canada geese have an open hunting season during autumn throughout the country, whereas hunting of bean geese is geographically restricted to the two southernmost counties. Legislation also permits on-site derogation shooting to prevent crop damage (Månsson 2017). For bean goose derogation shooting is restricted to certain time periods and areas; outside these, a permit is needed from the county administrative boards. Derogation shooting of greylag and Canada geese is allowed regardless of season and site, as long as birds are causing damage. Hunting of waterfowl in Sweden, as in many other European countries, has thus far not been regulated by bag limits or quotas.

Population indices and harvest data

We based this study on data from three independent long-term monitoring programs in Sweden, providing annual data of: 1) breeding season abundance (1998–2017), 2) autumn staging counts (1978–2017) and 3) national harvest estimates (1978–2017). These datasets are here used as indices for breeding and autumn staging population development and changes in harvest levels respectively, and represent the available nation-wide monitoring of goose populations in Sweden.

Breeding index

The breeding population index stems from a national monitoring programme called ‘fixed routes’ (Ram et al. 2017, Green et al. 2020), that is, 716 routes distributed systematically over Sweden in a 25 × 25 km grid. The sampling design ensures a representative coverage of all widespread habitats in Sweden. Each route is a pre-determined 8 km

line transect in the shape of a 2×2 km square. Censuses are carried out by foot, from mid-May (southernmost Sweden) to early July (alpine areas in northern Sweden). A route starts 04 a.m. daylight saving time and includes all birds of all species heard and seen, except for obvious young-of-the-year. Thus, goose data from this source refer to adult individuals only. When interpreting goose trends it is important to know that aggregations of adult birds add somewhat to the variation in yearly indices. Such aggregations include local breeders, especially greylags and flocks of failed breeders and non-breeders. On average, 413 routes were surveyed per year in 1998–2017, ranging from 165 in 1998 to 585 in 2008. This is equivalent to, on average, 3000 km of yearly line transects. The program is hosted by Lund University and data are public at <www.fageltaxering.lu.se>.

Autumn counts of staging geese

Hosted by Lund University this program started in 1977, with special efforts for greylag goose starting in 1984, and it has been based on the same methodology since (Haas and Nilsson 2019). All geese of all species are counted at monitoring events in September, October, November and January, and centred in time around the mid-weekend of each month according to the standards set by Wetlands International. Counts are synchronized (all sites in the same weekend), performed by volunteering ornithologists, and birds are determined to species but not age (for more details, Nilsson 2013, Nilsson and Kampe-Persson 2020). The exact survey procedure varies among staging areas but, importantly, does not change between years for a given area. In some areas counts are made when geese are feeding, whilst in other areas arriving (evening) or departing (morning) geese are counted at roost sites. The network of counted sites is concentrated to the southern third of the country (north to 60°N). Initially this program covered most major staging (and all wintering) sites. However, during the latest 15 years, the distribution of greylag and Canada geese in September and October has shifted and an increasing proportion is now found in coastal areas of northern Sweden. Monitoring has adapted accordingly by a geographical northward expansion of surveys (Haas and Nilsson 2019).

We chose to use data from the October counts, since these include high numbers of all species and reflect the populations early in the hunting season. There is a strong correlation between goose numbers in October and those in other months for greylag and Canada goose (Supplementary material Appendix 1). For bean goose, on the other hand, October numbers correlated with January numbers but not with those from November.

From earlier comparative studies it is known that count data tend to underestimate true population size (Alisauskas et al. 2009). Nevertheless, it is reasonable to assume that the standardized Swedish monitoring schemes provide representative indices that can be used to describe temporal trends of population sizes and relative harvest rate.

Harvest data

Data on estimated annual harvest (both open hunting season and derogation shooting) of all game species except those hunted by pre-determined quotas (such as moose *Alces alces*, red deer *Cervus elaphus* and large carnivores) are collected on

a voluntary basis in Sweden, i.e. hunters are not required by law to report their bags. Since 1938 the Swedish Association for Hunting and Wildlife Management (SAHWM) is commissioned by the Swedish Government to collect data on game populations. Data on harvest are made public online (<www.viltdata.se>) and reported to the Swedish Government. Hunters are encouraged via information meetings, social media and magazines to report their harvest to the organisation. Today, most reports are collected via web-based platforms, but until the end of the last century most data were reported by standardized forms provided to regional coordinators at each reporting unit. Sweden has continuous series of harvest estimates since 1939 for many species. These data are presented by 'hunting years' (from July to June).

According to Swedish legislation hunting rights belong to the landowner. Almost all land suitable for hunting is used by hunting teams, comprising landowners and/or hunters leasing hunting rights. The turnover of participants in hunting teams is generally low over time, and they are therefore suitable units for harvest reporting (Bergqvist et al. 2015).

Hunting teams comprising hunters with hunting rights (given by landowners) on one (or several) estates are organized under a hunting management precinct (in total 305 precincts in Sweden in 2018/2019, illustrated in Fig. 1). Bag data are collated collectively covering all hunters participating in a hunting team and are reported at team level. Reports from hunting teams within a management precinct are used to estimate a mean harvest density for each species (i.e. bag per 1000 ha). The derived mean harvest density is applied to cover non-reporting hunting teams within the management precinct, resulting in a total harvest estimate for each species and precinct. Estimates from all management precincts are then summed to obtain a countywide, and in the end, a nationwide estimate for each species.

The area covered by reporting hunting teams has varied slightly over time, averaging $29.5 \pm 2.7\%$ (mean \pm SD) of the total area available for hunting in Sweden during the period 1995/1996 to 2018/2019. Regional coordinators at SAHWM make a quality check of the incoming reports (on average 5600 year⁻¹) to identify typos, possible erroneous reporting and sometimes to verify data by communicating with persons responsible for reporting. Until the hunting year 1995/1996, data were collected at the county level, but after that replaced by hunting management precinct, in order to enable analyses with higher geographical resolution. This moderate change in methodology made the indices for most species shift somewhat relative to earlier years. Bergqvist et al. (2015) analysed this pattern, but the exact mechanisms behind the shifts remain unknown, and no significant effects on long term trends were found.

Statistical analyses

Temporal trends (finite growth rates) based on breeding season counts along the fixed routes, were analysed using TRIM (Trends and Indices for Monitoring data, ver. 3.53, Van Strien et al. 2004), taking into account that not all routes were done every year. The statistical model in TRIM builds on Poisson log-linear regression, estimating site and time (year) effects on species abundance (counts) as well as an overall linear trend (log-scale). The basic TRIM model

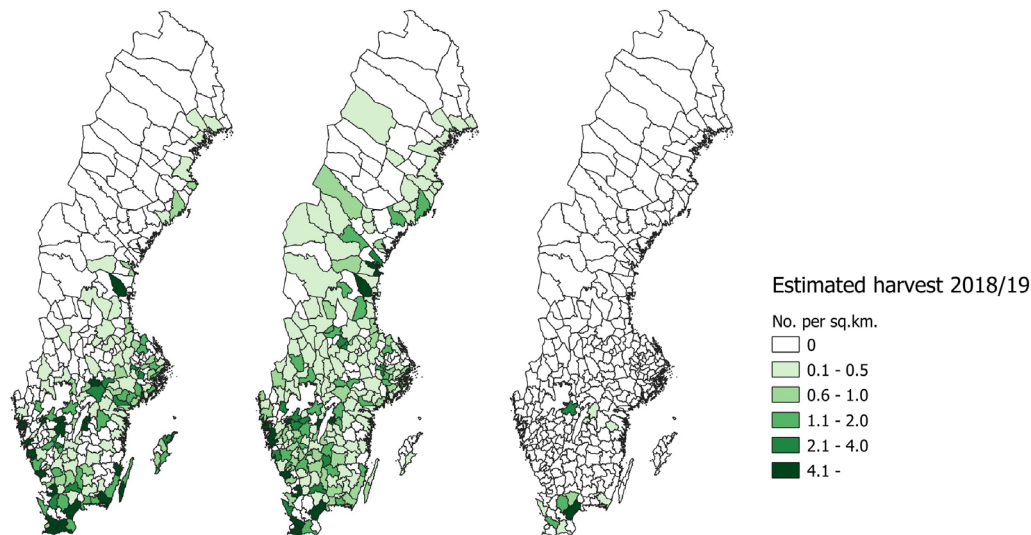


Figure 1. Maps showing estimated harvest per km² for greylag goose (left), Canada goose (middle) and bean goose (right) per management precinct (n = 305) in Sweden in the hunting year 2018/2019.

is: expected count = year + site, where both year and site are fixed effects. Effects are estimated using maximum likelihood and generalized estimating equations, the latter to handle potential overdispersion and serial (auto) correlation. For autumn counts and harvest estimates, the finite

rate of increase was calculated according to Caughley and Sinclair (1994).

To identify possible changes in trends, we performed a breakpoint analysis using the package *strucchange* for all three species and all three indices (Fig. 2, Kleiber and Kotz 2003).

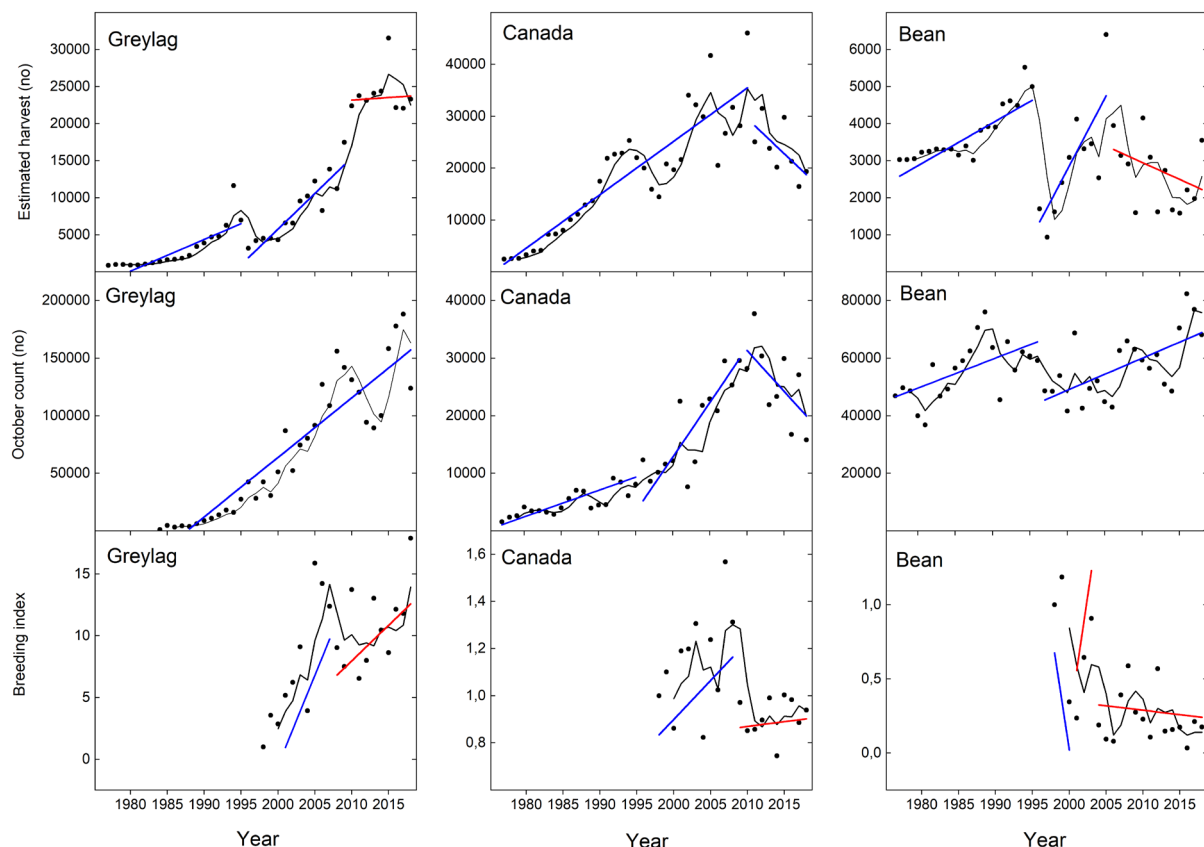


Figure 2. Estimated harvest (top), October counts (middle) and breeding index (bottom) for greylag goose (left), Canada goose (middle) and bean goose (right). Dots represent actual values for harvest and October counts while breeding population is given from TRIM-indices. The undulating lines show moving three-year means and the straight lines show regression lines. Blue lines show statistically significant regression lines and red lines represent non-significant. Breakpoints and regression estimates are found in Supplementary material Appendix 2. Note differences in y-axis scales.

Breakpoint analysis is based on piecewise linear models and it identifies the time of significant shifts in trends (Zeileis et al. 2003). Coherence in timing of changes (breaks) between times series as well as differences in slopes of regression lines before and after breakpoints were used as basis to discuss plausible mechanisms and causality behind shifts in trends.

To analyse the effect of harvest on the population growth rate, we need to relate harvest level to population size. By assuming that our indices provide relative numbers over time we calculated an annual (1977–2018) ‘relative harvest rate’ by dividing the harvest estimate (hunting year *t*) by the autumn count (year *t*). In a second step, relative harvest rate (year *t*) was related to the exponential rate of increase (Caughley and Sinclair 1994, Steidl et al. 1997) based on the autumn count data from year *t* to year *t* + 1, by using linear regression. If harvest affects the population growth rate, we expect a negative relationship between the relative harvest rate (year *t*) and the exponential rate of increase (year *t* + 1). All tests were performed using R ver. 3.3.3 (<www.r-project.org>).

Results

Population and harvest trends over the study period

Greylag goose

The breeding season population index increased 1998–2018 by an average finite growth rate of 8.0% year⁻¹ (TRIM, *p* < 0.001, Fig. 2). October count data showed a positive finite growth rate (13.1% year⁻¹, *p* < 0.001) for the period 1977–2018. In 1984, 1096 greylag geese were counted in October while the highest number, 188 200 individuals, was recorded in 2017. Greylag goose harvest increased by 9.0% year⁻¹ (*p* < 0.001).

Canada goose

The breeding season population index decreased during the period 1998–2018, by 1.1% year⁻¹ (TRIM, *p* < 0.05, Fig. 2), but this includes an increase up to 2008, and much lower index values thereafter. The yearly growth rate in October counts 1977–2018 was positive (6.6% year⁻¹, *p* < 0.001), but note the negative trend for the latest 10 years (Fig. 2). The number of birds counted in October ranged from 8700 in 1997 to a peak of 37 000 individuals in 2010. Canada goose harvest increased over the study period with a finite rate of 5.1% year⁻¹ (*p* < 0.001).

Bean goose

The Swedish breeding population index decreased by 8.1% year⁻¹ (TRIM, *p* < 0.01, Fig. 2) during 1998–2018. Staging data showed a moderate rate of increase (0.60% year⁻¹, *p* = 0.02) over the period 1977–2018. Counts varied between 36 800 (in 1981) and 82 300 (2016). Estimated harvest, on the other hand, showed a slight decrease over the study period with the finite rate of growth being –1.0% year⁻¹ (*p* < 0.05).

Correlations between data sets during the study period

For greylag goose all three indices were correlated to each other (Table 1). While October counts and estimated harvest were correlated for Canada goose, the relationship between

Table 1. Spearman rank correlations (*r_s*) showing the strength of the relationship between estimated harvest, October counts and breeding index for greylag goose, Canada goose and bean goose. Significant relationship in bold. *n*-values followed by *p*-values in brackets.

	Estimated harvest		October count	
Greylag goose				
October count	0.85	(35, < 0.001)		
Breeding index	0.52	(21, 0.016)	0.56	(21, 0.010)
Canada goose				
October count	0.77	(42, < 0.001)		
Breeding index	0.29	(21, 0.209)	−0.24	(21, 0.298)
Bean goose				
October count	−0.03	(42, 0.850)		
Breeding index	−0.14	(21, 0.535)	−0.14	(21, 0.550)

breeding index and the other indices was not significant. For bean goose, the three indices did not show any significant relationship during the study period.

Species-wise breakpoints in trends

Greylag goose

We found breakpoints in 1995/1996 and 2008/2009 in the greylag goose harvest data (Fig. 2). Before and after the first breakpoint, regression lines had positive slopes (regression line statistics are found in Supplementary material Appendix 2). After the second breakpoint, no significant linear regression was found. For October count data no breakpoint was identified, implying a steady population increase over the period (Fig. 2). For the breeding season index, one breakpoint in 2007/2008 was identified, with a positive slope of the regression before, and a statistically non-significant increase thereafter.

Canada goose

Harvest increased until the identified breakpoint in 2009/2010 (Fig. 2), after which it decreased (regression line statistics in Supplementary material Appendix 2). In October count data positive regression slopes were found before and after the breakpoint in 2002/2003. A negative regression line followed the last breakpoint in 2010/2011. For the Swedish breeding population of Canada goose, a breakpoint was identified for 2007/2008. Before that shift in trend a positive regression was found, followed by a non-significant moderate increase. Note however, that the population index values were notably lower after than before the breakpoint, suggesting a strong drop in population size in recent years.

Bean goose

We found no apparent overall temporal trend in harvest data, but nonetheless our analysis identified two breakpoints; in 1995/1996 and in 2005/2006. The regression lines (statistics in Supplementary material Appendix 2) before and after the first breakpoint both indicate increasing numbers, but with different intercepts (Discussion). The negative slope of the line after the last breakpoint was non-significant. In October count data our analysis identified a breakpoint for 1995/1996. The slopes of the regression lines before and after it were both positive (Fig. 2, Supplementary material Appendix 2). For the small Swedish breeding population two breakpoints were identified in index values: 2000/2001

and 2003/2004. The first regression line (1998–2000) was negative while the slopes of the two other lines were non-significant.

Relationship between harvest and population growth rate

For greylag goose, we did not find any relationship between exponential rate of increase in October counts and relative harvest rate in the preceding year (Fig. 3, regression estimates; $a=0.152$, $b=-0.014$, $p=0.970$, Adj. $R^2=-0.03$). For Canada goose, however, the exponential rate of increase in October counts was negatively related to relative harvest rate in the preceding year ($a=0.275$, $b=-0.120$, $p=0.026$, Adj. $R^2=0.10$). We found no such relationship for bean goose ($a=0.115$, $b=-2.16$, $p=0.19$, Adj. $R^2=0.02$).

Discussion

During the study period, staging and breeding greylag and Canada geese have increased substantially from very low numbers, albeit with a decline in Canada geese in more recent years (Fig. 2). In contrast, bean goose was the most numerous species in the beginning of the study, followed by fluctuating staging numbers, high annual variation in harvest, and a clear decrease in the breeding season index. The potential effect of harvest also seems to differ among the three species. We did not find any indication of harvest affecting growth rate in greylag geese. The population of the less numerous Canada goose, however, seemed to be negatively affected by a relatively high harvest, whereas our results for bean goose in this respect are inconclusive.

The relationship between the three indices differed among species. Harvest levels were more strongly correlated to October count data than breeding season index in greylag and Canada goose. Breeding season index methodology is not explicitly designed for geese and occasional inclusion of larger flocks in the data may add variation that blur the correlation with other indices. Further, the breeding season index does not include young of the year, as do October counts, and annual variation in reproductive success is known to

affect harvest levels significantly (Menu et al. 2002). In bean goose none of the indices were correlated. This may be because bean geese included in the Swedish staging and harvest indices breed outside the country, while Swedish breeders (western management unit, Marjakangas et al. 2015) largely leave the country before hunting starts. Further, bean goose hunting is permitted only in the two south most Swedish counties; as a result flocks moving within the country during the hunting period may affect harvest levels (Marjakangas et al. 2015). For greylag geese, earlier studies have not indicated any major influx to Sweden prior to the hunting season, strongly suggesting that the October counts mainly tally birds breeding in Sweden (Andersson et al. 2001, Bacon et al. 2019). However, changes in migration traditions of greylag geese, due to climate change as observed in the later parts of the study period (Ramo et al. 2015, Nilsson and Kampe-Persson 2020) may affect the Swedish harvest level because flocks spend more time in the country. Even though minor exchange with other countries have been reported for Canada geese, breeding birds in Sweden normally spend the whole life cycle within the country (Fransson et al. 2008). This suggests that the need for and level of international coordination of management differ among the species.

Previous European studies addressing if increased harvest rates may reduce populations have indicated only limited effects (barnacle goose; Van der Jeugd and Kwak 2017, and pink-footed goose; Clausen et al. 2017, Madsen et al. 2017). A majority of North American studies, too, demonstrates weak effects of harvest on population trajectories (greater snow goose; Calvert and Gauthier 2005, lesser snow goose *Anser c. caeruleus*; Alisauskas et al. 2011, Koons et al. 2014, Canada goose; Iverson et al. 2014, Pilotte et al. 2014). Our analysis suggests that population growth in Canada geese may be affected by Swedish harvest, but not in bean goose and greylag goose. In the case of the latter, our results suggest that present harvest levels may instead be outpaced by rapid and continuous population increase (Fig. 2, 3), while the negative trend for bean goose lacks sufficient statistical support for any clear interpretation.

Counts of geese tend to underestimate population size (Alisauskas et al. 2009) and in our case this is especially true

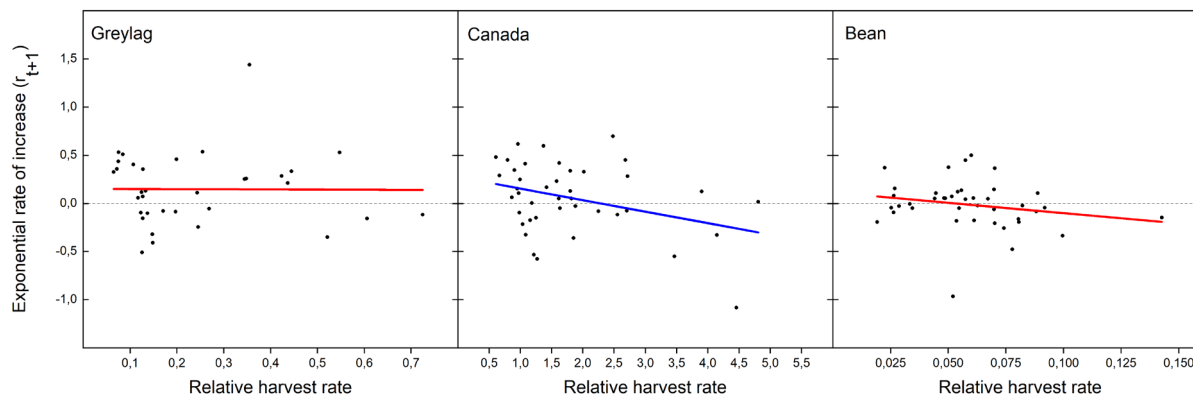


Figure 3. Exponential rate of increase ($t+1$) in relation to relative harvest rate year t for greylag goose (left), Canada goose (middle) and bean goose (right). Relative harvest rate represents estimated harvest divided by numbers in October count the specific year. Dotted lines show the zero values (no change). For Canada goose, the significant regression line in blue and the non-significant regressions for greylag and bean geese are in red. Note differences in x-axis scales.

for autumn counts of Canada geese, since they are spatially less concentrated during this time of the year than are the other species (Haas and Nilsson 2019). This explains why the estimated harvest outsized the number of Canada geese counted in October in several years. In line with this reasoning Fox et al. (2010) presented a population estimate of 90 000 Scandinavian Canada geese for winter 2008/2009, when the October count for Sweden was 25 343 birds. Swedish hunters harvested 30 000–46 000 Canada geese annually 2006–2011 (Fig. 2), suggesting that the annual harvest in Sweden alone amounted to 30–50% of the Scandinavian population. Corresponding figures for greylag goose yield an estimated annual harvest rate of 9–13% (based on an estimated Swedish population of 240 000 birds, Polowny et al. 2018), and 3–6% in bean goose (based on an estimated flyway population of bean geese of approximately 60 000 birds (ssp. *fabalis*, Heldbjerg et al. 2019)).

After 4–5 years of relatively high harvest levels, autumn count data for Canada geese changed from a positive trend to a negative, as indicated by the breakpoint in 2010/2011. Both autumn numbers and harvest levels may be heavily influenced by year-specific variation in reproduction (Menu et al. 2002, Calvert and Gauthier 2005, Madsen 2010). However, also breeding season index (adult birds), shifted from an increasing trend in 2007/2008 to lower indexes (but without clear trend) after that, suggesting that also adult numbers may be affected by the high harvest levels. Earlier studies have shown that adult harvest rates of 11–15% in goose populations can reduce survival and halt population growth (Canada goose; Pilotte et al. 2014, Luukkonen et al. 2017 and greater snow goose; Lefebvre et al. 2017). Unfortunately, the monitoring programs on which our study are based do not separate age classes. This limits the possibility to analyse effects of harvest on population dynamics in depth. Moreover, since our study was correlative, there may be still other factors affecting the decline in Canada goose numbers and harvest. Notwithstanding the limitations of our approach, we find that the hunting pressure on Canada geese in Sweden is very high compared to the other two species, and potentially negatively affecting population growth rate.

In contrast to Canada goose, for which the autumn staging index and harvest estimates show similar trends (slopes in the breakpoint analysis, Fig. 2), greylag goose harvest estimates do not correspond with the positive trends found in breeding and staging count data the last ten years of the study period. In Sweden, hunting of small game species, such as birds, is regulated neither by bag limits nor quotas, as in e.g. North America (Johnson et al. 2012). Earlier studies have shown a strong correlation between national harvest estimates and population size for bird species with open hunting season and without bag limits (Cattadori et al. 2003). Even though such a relationship is typically less clear in migratory species (Holopainen et al. 2018) we expected similar patterns for Canada and greylag goose in our study. One explanation for the contrast between the two species may be that the effectiveness of hunters can reach a plateau resulting in stable harvest numbers not corresponding to a continued population growth (as described for lesser snow goose; Johnson et al. 2012). Simberloff (2012) reported that hunters' efforts reaching a plateau is a general prob-

lem in controlling fast-growing, invasive populations and very abundant species. Furthermore, Williams et al. (2019) found that time devoted to hunting of pink-footed goose was affected by hunters' personal preferences rather than legislative limitations. Consequently, only relying on voluntary efforts by hunters can hinder in the achievement of management objectives.

In studies relating harvest to monitoring data it is essential to consider that harvest size is affected not only by population size, density of prey populations and legislation regulating harvest, but also by hunters' motivation as well as changes in the hunting community. As a case in point, several studies have indicated that using harvest data as a proxy of population trends may be fraught with weaknesses (Ranta et al. 2008, Kahlert et al. 2015). Indeed, many scientists call for caution when using harvest data in management, especially when hunters' effort is not carefully monitored (Moa et al. 2017, Eriksen et al. 2018). Conversely, several critical comparisons of the relationship between harvest data and population change have reported strong correlations (Cattadori et al. 2003, Jarnemo and Liberg 2005). For example, Swedish harvest estimates have been used successfully to explain shifts in spatial and temporal patterns of several hunted populations (Lindström et al. 1994, Carlsson et al. 2010, Elmhagen et al. 2015). Taken together, this suggests that harvest estimates like those produced in Sweden may deliver useful indices, especially in analyses relating them to other data sets based on long time series.

Swedish goose hunting has expanded geographically to also include the northern part of the country when it comes to greylag and Canada geese, but remained the same for bean goose over the study period. Increased legislative opportunities may result in suddenly increased hunting effort (Madsen et al. 2016), but our breakpoint analysis did not detect any such dramatic increases in harvest, suggesting that other factors than allowing hunting over a wider area were more important in these two species. Instead, the only evident abrupt shift found in harvest, revealed as a change in the breakpoint analysis intercept, was in bean goose in 1995/1996. At this time, the methodology for collecting harvest data was slightly altered to increase spatial resolution. For unknown reasons this resulted in slightly lower harvest estimates for all three species, compared to earlier years, but significantly so only for bean goose (Fig. 2).

As demonstrated by Johnson et al. (2018), incomplete or imperfect data may be used to guide wildlife management. Under certain circumstances, such as management of invasive species (e.g. Canada goose in Sweden), fast-growing populations of abundant species (e.g. greylag goose) and conservation of threatened species (e.g. bean goose ssp. *fabalis*), 'perfect data' may not always be at hand, and like Tull- och et al. (2017) we argue it would be unwise to wait for such data before taking action.

For the two species without obvious conservation concerns, i.e. greylag (very abundant) and Canada goose (invasive), we argue that existing data and our analysis provide valuable information under the present goose management paradigm. For the rather non-precise objectives that have characterized management of greylag and Canada geese in Sweden, e.g. not jeopardizing conservation status and reducing conflicts with agriculture, an ad hoc analysis like ours,

may suffice to follow up changes in management practices. For the bean goose population, and the previously voiced risk of overharvesting it (Heldbjerg et al. 2019), our analysis does not provide clear guidance for management. As Stroud et al. (2017) point out, we also foresee a new 'phase' in European goose management, embracing all species, characterized by increasing demands for explicit population targets and flyway-level management. This in turn creates a need to improve and reinforce today's monitoring systems. We suggest that one improvement would be to collect more comprehensive data for the different populations studied, for example joint breeding population trends spanning larger areas, in a manner similar to what was recently carried out for breeding waders in Fennoscandia (Lindström et al. 2019). For more precise predictions about harvest effects on population trajectories, inclusion of age structure in monitoring and harvest data is of the essence. Further, the reliability of current estimates of population size and harvest, based solely on count data and voluntary bag reports, may be increased significantly if comparative studies are added (e.g. mark–recapture) and by adapting monitoring to spatio-temporal distribution of populations and sub-populations, particularly needed for bean goose in this study.

The prerequisites for making goose management sustainable in the wide sense, but also to implement adaptive harvest management, are already in place for some populations and in some European countries, but not for others (Madsen et al. 2015, Polowny et al. 2018). Hence, access to data on population size, survival and harvest, coordinated at flyway level, is a common challenge for all European goose populations. As long as such coordinated international efforts are not in place, single countries may nevertheless improve data for management by introducing ringing campaigns addressing population estimates and survival. Such efforts will also help in delineating management units and coordinating monitoring within the flyway.

Data availability statement

Data available from the Dryad Digital Repository: <<http://dx.doi.org/10.5061/dryad.3bk3j9kjc>> (Liljebäck et al. 2020).

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