Received: 7 February 2019 | Accepted: 3 June 2019

DOI: 10.1111/1365-2664.13457

RESEARCH ARTICLE

Journal of Applied Ecology | BRITISH ECOLOGICAL SOCIETY

Relating national levels of crop damage to the abundance of large grazing birds: Implications for management

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Funding information
FORMAS, Grant/Award Number: 942-2015-1360 and 215-2014-1425; Swedish EPA, Grant/Award Number: 13/361

Handling Editor: Jörg Müller

Abstract

1. Populations of large grazing birds have increased in Europe during the past five decades, raising conflicts between conservation and farming interests. Managing these conflicts requires knowledge about the currently unknown relationship between population sizes and crop damage levels.
2. We analysed unique data on reported, inspected and compensated crop damage caused by geese, swans and cranes together with data from population surveys in Sweden to investigate how bird abundance is related to damage levels at the national scale between 2000 and 2015.
3. Over the study period, the annual number of damage reports, yield loss and costs for compensation increased. These crop damage levels were positively related to national population indices of common crane, barnacle and greylag goose. The shape of these relationships varied between species and encompassed considerable uncertainty. However, on a year-to-year basis (detrended data) we found no evident association between damage levels and bird numbers.
4. Yield loss and compensation costs per reported damage did not increase with higher population indices of greylag goose, but they did so for barnacle goose.
5. *Synthesis and applications*. We present a novel study of the relationships between different crop damage level indicators (damage reports, yield loss and compensation costs) and population numbers of large grazing birds. We identified a positive relationship with high uncertainty for all cases. We also identified the need to (a) better synchronize the monitoring of damages and bird numbers in time and space and (b) further study the relationships between damage levels and bird numbers at smaller (local and regional) and larger (flyway) spatial scales to reduce the uncertainty of the relationship and to gain a more holistic understanding of the system.

KEYWORDS

agriculture, crop protection, human-wildlife conflicts, INLA, large grazing birds, population trends, wildlife management

1 | INTRODUCTION

Wildlife damage on human livelihoods can unfold into conflicts between human interests such as conservation, agriculture and forestry (Redpath et al., 2013). When managing conflicts arising from human–wildlife interactions, knowledge about the relationship between damage levels and population size is fundamental to understand possible outcomes of different interventions and management strategies, as well as to set relevant goals (Conover, 2002; Madsen et al., 2017).

The need for interventions to mitigate damage by large grazing birds (geese, swans and cranes) on agricultural fields, has recently been accentuated (Fox & Madsen, 2017). Many populations of large grazing birds have increased from threatened to superabundant in Europe during at least five decades (Fox & Madsen, 2017) due to conservation efforts and agricultural intensification (Ebbinge, 1991; Fox, Elmberg, Tombre, & Hessel, 2017; Gauthier, Giroux, Reed, Bechet, & Belanger, 2005) and a warmer climate (Jensen, Madsen, Johnson, & Tamstorf, 2014; Mason, Keane, Redpath, & Bunnefeld, 2018). The increasing numbers of large grazing birds and their preference for agricultural fields over their natural foraging habitats – because crops provide higher quality food (Fox & Abraham, 2017) – cause a loss in harvest yield for the farmers (Fox et al., 2017). For example, in Islay, Scotland, spring grazing barnacle geese reduced harvests on spring grasslands by up to 82% (Perceival & Houston, 1992). Also, annual economic compensation for harvest losses due to barnacle geese ranged from 5,000 euros in Belgium to more than 5 million euros in the Netherlands in recent years (Jensen, Madsen, & Nagy, 2018). As the impact of foraging large grazing birds on agricultural landscapes increases, it fuels the conflict between farming and conservation objectives (Stroud, Madsen, & Fox, 2017). While it is reasonable to assume that agricultural yield losses depend on the number of birds and their grazing pressure (Parrott & McKay, 2001), the annual variation in yields caused by factors other than grazing birds (e.g. weather, soil, crop-type) make specific quantification of damage difficult to assess (Anon, 1970; McKenzie & Shaw, 2017). For instance, plants may compensate for grazing (Van der Graaf, Stahl, & Bakker, 2005; McNaughton, 1979) and under certain conditions intermediate grazing may stimulate plant growth (McNaughton, 1979). Few studies have been able to evaluate the relationship between bird numbers and damage levels and this link has often simply been assumed to be linear (Cusack et al., 2018; McKenzie & Shaw, 2017), especially at the national scale where most political and strategic management decisions are conducted (Fox et al., 2017).

Increasing populations of large grazing birds and damage to agricultural fields have led to recent initiatives to establish adaptive flyway management plans. All states along the flyway for these birds need to reach a consensus in agreeing their goals and measures to tackle this issue (Madsen et al., 2017; Stroud et al., 2017). Several measures to mitigate the damage and conservation conflicts exist and have been suggested within the plans for example, set-aside areas, bird-scaring and population control (Fox et al., 2017). However, the current lack of data linking crop damage with population size creates a challenge when it comes to (a) predicting outcomes of proposed interventions, (b) allocating money for compensation costs and (c) adapt any subsequent goals and recommendations for monitoring and compensation strategies.

In Sweden, farmers can report crop damage caused by large grazing birds to acquire economic compensation from an accredited government compensatory scheme. Reported damages must be approved, species involved identified and yield losses estimated by authorized government inspectors before economic compensations are paid. In addition, estimates of population numbers of large grazing birds are conducted as part of the national monitoring schemes (Nilsson, 2013). We use this available data to (a) investigate the relative importance of the species reported to cause crop damage in Sweden; (b) describe temporal and large scale spatial patterns of damage; (c) reveal the relationships between estimated national population numbers and levels of crop damage across 16 years (2000–2015) and whether these relationships differ among the species; and (d) explore the relationship between the amount of damage, yield loss and compensation costs incurred.

2 | MATERIALS AND METHODS

2.1 | Crop damage data

In 1995, the Swedish Government launched a system to compensate farmers for crop damage caused by large grazing birds. Since then, all farmers can report crop damage to the County Administrative Boards (CABs) to receive compensation. All reported damages are verified according to a standardized procedure by trained and authorized inspectors from the CABs (Månsson et al., 2011). The specific methodology varies slightly between crop types (e.g. potato, cereals, hay) but is in general based on a comparison between damaged and undamaged parts of the same field (or a field in close proximity if the whole field is damaged) to estimate yield loss. If damage occurs during an early stage, the field is visited twice: first immediately after the damage occurs to geo-tag the affected area and to identify the species responsible and then a second time just before harvest, to estimate the yield loss. The inspectors verify the affected crops and identify the species responsible based on established protocols (Månsson et al., 2011). Because the first inspection takes place immediately after the farmer contacts the CAB, we expect the identification of the culprit species to be accurate. Harvest loss due to other factors such as drought, flooding or other wildlife (e.g. wild boar *Sus scrofa*) is also estimated and deducted from the total loss (Månsson et al., 2011). Once the damage is registered, the CABs calculate the economical compensations due to be paid, based on the annual crop market price.

The species included in the compensation scheme are bean goose *Anser fabalis*, barnacle goose *Branta leucopsis*, brent goose *B. bernicla*, greylag goose *A. anser*, greater white-fronted goose *A. albifrons*, mute swan *Cygnus olor*, whooper swan *C. cygnus* and

common crane *Grus grus*. Canada goose *B. canadensis* is a non-native species and is not compensated for since conditional shooting is permitted for this species throughout the year (i.e. farmers can shoot geese outside the open hunting season on fields where they cause damage). In 2009, the hunting regulations for greylag geese changed, allowing for conditional shooting. Hence, farmers were allowed to perform lethal scaring as soon as greylag geese were feeding on unharvested crops independent of season (Månsson, 2017). As a consequence, the CABs decided to cease compensation for crop damage caused by greylag geese (see Figure S1), except for in regions of high concentration of geese like Scania (the southernmost Swedish province) and local areas where shooting was prohibited to avoid disturbance, for example in the vicinity of wetland reserves.

We used three indices to quantify damage level: the number of approved reports of damage (damage reports), registered kilos of yield loss (yield loss) and the amount of compensation paid (compensation costs). Information about the compensatory scheme was spread by information campaigns via CABs and farmer associations. It is reasonable to assume that the awareness about the compensation scheme among farmers was low immediately after it was introduced. To decrease the risk of such a bias, we excluded the first 5 years of data before the year 2000 ($n_{1995–1999}$ = 21 damage reports).

Since geese often occur in mixed flocks (Table S1), one damage report may include several species. When investigating species-specific crop damage, we included *all* damage reports (i.e. involving single and mixed flocks). Consequently, the number of species-specific reports ($n_{2000–2015}$ = 2,851) is greater than the actual number of damage reports ($n_{2000–2015}$ = 2,194 reports). To calculate yield loss and compensation costs for each species, we weighted yield loss and compensation costs according to the species' contribution to each reported damage (i.e. the proportion of each species in the flock).

2.2 | National indices of bird numbers

We used the total number of birds registered during the annual national autumn counts in September for greylag geese, and October for barnacle and bean geese (Nilsson & Haas, 2016). These counts are conducted mainly by volunteers in the vicinity of roosting sites, mainly in southern Sweden (<61° North) and are designed to cover all main stopover sites (Nilsson, 2013). The number of surveyed sites has basically been constant for the October counts, whereas the range of September counts has expanded as greylag geese have been found further north (Nilsson, 2013). For common crane, we used the maximum number of birds counted during the second half of September at the four major autumn stopover sites: lakes Tåkern, Hjälstaviken, Kvismaren and Hornborgasjön (Lundin, 2005; Nilsson, 2016). The timing of the crane and geese monitoring periods match the species' peak numbers at Swedish autumn staging sites. These estimates of population numbers should be viewed as estimates of national numbers and do not provide detailed information about local abundances and within-year variation (Nilsson, 2013). Autumn counts for whooper swan involved very poor coverage (<200 individuals/year) and were not analysed.

Common cranes arrive in Sweden in March and leave early October. Barnacle geese peak in April–May and September–October. Greylag geese arrive in February and March and the vast majority leave in September–October. Whooper swans arrive in February–March and leave in October–November. Bean geese arrive in March and leave in November (Shah & Coulson, 2018) (see Figure 1d for details on number of migrant individuals). All these species, except common crane, winter in southernmost Sweden during mild winters. The Swedish breeding populations are estimated (figures are number of breeding pairs) at 30,000 cranes; 4,900 barnacles; 41,000 greylags; 5,600 whoopers and 850 beans (Ottosson et al., 2012).

2.3 | Crop availability and market prices

Since 2000, ley is the most abundant crop in Sweden (40% of the agricultural land) followed by wheat (14%) and barley (13%) (84% of wheat corresponds to winter crops while 92% of barley, to spring crops; Anon, 2018a). The south and central areas of Sweden have an agricultural-dominated landscape fragmented with urban settlements and boreonemoral forests. Ley is the major crop (>37%), followed by wheat (15%), barley (14%) and a mosaic of rapeseed, potatoes, legumes, carrots and beets (<5%). In the north, forest cover increases and agricultural heterogeneity decreases with ley and barley as the major crops (c. 70% and 12% respectively). The availability of crops at the national scale did not show any distinct trends from 2000 until 2015 (Figure S2). Similarly, market prices (corrected for inflation), did not show any tendency over the study period either (Figure S3). There is considerable variation in the market price between crops, for example, higher for rapeseed and potato (14–34 euros/100 kg) and lower for barley and wheat (8–17 euros/100 kg) (Anon, 2018a, 2018b).

2.4 | Statistical analyses

2.4.1 | Modelling relationships between population indices and damage levels

To analyse the broad relationship between damage reports and population indices we fitted, for each species, a Negative Binomial Generalized Linear Mixed Model (GLMM), with a natural logarithm link-function. The number of damage reports acted as the response variable and population index as the explanatory. To analyse how yield loss and compensation costs are related to population indices, we fitted a Gamma GLMM with natural logarithm link-function for each species, using yield loss and compensation costs as the response variables and population index as the explanatory. In all models we log-transformed the explanatory variables. The use of

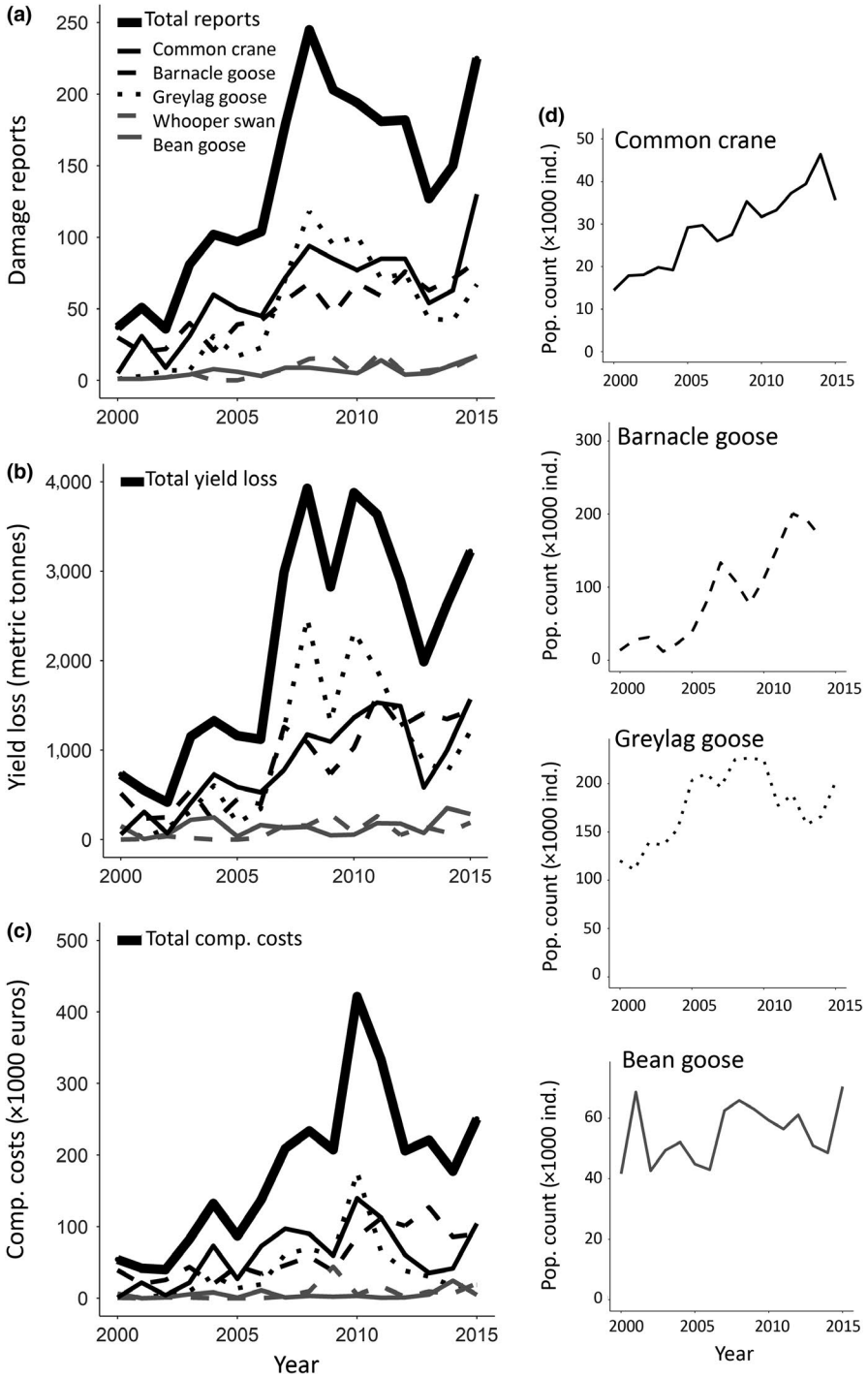


FIGURE 1 Development of total annual damage reports (a), yield loss (metric tonnes) (b), compensation costs (euros) (c) and population count (d) for different species of large grazing birds in Sweden from 2000 to 2015

log-log models satisfies the restriction that damage levels would be zero when population index is zero, if the exponent, beta, is positive.

We accounted for temporal autocorrelation by assuming that regression residuals follow a random walk (i.e. Rw1) process. Our model for damage reports is expressed as.

$$\begin{aligned} D_t &\sim \text{NegBin}(\text{mu}_\wedge D_t, \text{theta}) \\ \log(\text{mu}_\wedge D_t) &= \text{Intercept} + \beta_1 \times \log P_t + u_t \end{aligned} \quad (1)$$

and the models for yield loss and compensation costs are expressed as.

$$\begin{aligned} Y_t &\sim \text{Gamma}(\text{mu}_\wedge Y_t) \\ \log(\text{mu}_\wedge Y_t) &= \text{Intercept} + \zeta_1 \times \log P_t + z_t \end{aligned} \quad (2)$$

$$\begin{aligned} C_t &\sim \text{Gamma}(\text{mu}_\wedge C_t) \\ \log(\text{mu}_\wedge C_t) &= \text{Intercept} + \delta_1 \times \log P_t + w_t \end{aligned} \quad (3)$$

where, mu$_\wedge$ refers to the mean; D_t the number of damage reports in year t; P_t population index (×1,000 birds) in year t; Y_t yield loss (in metric tonnes) in year t; and C_t compensation costs (×1,000 euros) in year t. u_t is the Rw1 residual defined by the formula $u_t = u_{t-1} + V_t$; where u_t is the trend of the response variable at time t; u_{t-1} the trend at time $t - 1$; and V_t the noise component. V_t follows a Normal distribution ($V_t \sim N(0, \sigma_V^2)$) and σ_V^2 is the variance of the noise component. The same applies for the Rw1 residuals z_t and w_t in Models 2 and 3 respectively. These models refer to the broad association (over the study period) between covariates and response due to a common trend. All three models are log-log models. Hence, the relationship between covariates will be a power law of the type $P^{\wedge} \beta_1$ (Model 1), $P^{\wedge} \zeta_1$ (Model 2) and $P^{\wedge} \delta_1$ (Model 3) and linear if β_1 (ζ_1 or δ_1) = 1.

To evaluate how inter-annual fluctuations of population indices are related to inter-annual fluctuations of damage reports, yield loss and compensation costs, we ran Models 1, 2 and 3 including a drift term into the random walk. A random walk Rw1 with a drift term is equivalent to a non-drift random walk plus a linear effect of time, which can be simply added as an ordinary covariate. This is a model-based variant of detrending the response and covariate to examine the annual association between the variables when trends in both variables are accounted for. Our models are expressed as.

$$D_t \sim \text{NegBin}(\text{mu}_\wedge D_t, \text{theta})$$
$$\log(\text{mu}_\wedge D_t) = \text{Intercept} + \beta_2 \times \log(P_t) + u_t + \Omega_1 \times \text{drift term} \quad (4)$$

$$Y_t \sim \text{Gamma}(\text{mu}_\wedge Y_t)$$
$$\log(\text{mu}_\wedge Y_t) = \text{Intercept} + \zeta_2 \times \log(P_t) + z_t + \psi_1 \times \text{drift term} \quad (5)$$

$$C_t \sim \text{Gamma}(\text{mu}_\wedge C_t)$$
$$\log(\text{mu}_\wedge C_t) = \text{Intercept} + \delta_2 \times \log(P_t) + w_t + \pi_1 \times \text{drift term} \quad (6)$$

where, drift term = t − RT and RT is a reference time, accounting for the first year of our dataset (i.e. 2000). So, if time variable t is a vector from year 2000, 2001… to 2015, the drift term will be a vector 0, 1, 2… to 15. These are also log-log models and, therefore, the relationships between covariates will also be a power law of the type $P^{\wedge} \beta_2$ (Model 4), $P^{\wedge} \zeta_2$ (Model 5) and $P^{\wedge} \delta_2$ (Model 6); linear if β_2 (ζ_2 or δ_2) = 1.

Bean goose was excluded from the analysis because of the small number of damage reports, yield loss and compensation costs they represented. We ran the temporal regression analysis using Integrated Nested Laplace Approximation (Rue, Martino, & Chopin, 2009) (Bayesian approach) with R-INLA for model execution (www.r-inla.org) as described in Zuur Ieno and Saveliev (2017). All statistical analyses were conducted with R version 3.3.3 (R Core Team, 2017).

2.4.2 | Diffuse priors

Because we used a Bayesian approach, priors are required for the parameters in the models: the size of the NegBin distribution (k) for Models 1 and 4; precision of the Gamma distribution (Ø) for Models 2, 3, 5 and 6; and intercepts, slopes and variance σ_V^2 from the noise component V_t of the random walk for all models. We used vague priors in all cases. Priors for the fixed parameters, intercepts, k and Ø were set to default settings in R-INLA. For σ_V, we used Penalised Complexity prior distributions, recommended for time series with no available prior information (Simpson, Rue, Martins, Riebler, & Sorbye, 2014). For details on prior specification see Appendix S1.

3 | RESULTS

3.1 | Crop damage in Sweden

Between 2000 and 2015, inspectors of the Swedish CABs surveyed and approved 2,194 damage reports, resulting in 34,500 metric tonnes of yield loss. Of these, 88% were compensated with a total cost of 3.4 million euros. The remaining 12% were not compensated because there was no evident damage when the final inspection was conducted, for example, due to compensatory plant growth. About 90% of all damages were caused by common cranes, barnacle and greylag geese (Table 1). The remaining 8% was due to whooper swans and bean geese. Barley, ley (hay and pastures) and wheat were the most reported crops to be damaged (41%, 27% and 14% respectively) while rapeseed, potatoes and legumes were less often reported (5%, 3% and 2% respectively). All other crops represented <2% of the total damage reports.

TABLE 1 Number of damage reports, yield loss (metric tonnes T), compensation costs (euros) and percentages (in parentheses) for five species of large grazing birds in Sweden from 2000 to 2015 (see Table S2 for detailed damage levels in North, mid and South Sweden)

	Barnacle goose	Bean goose	Greylag goose	Common crane	Whooper swan	Others[a]
Damage reports	804 (28.2)	106 (3.7)	772 (27.1)	976 (34.2)	114 (4.0)	79 (2.8)
Yield loss (T)	11,531 (33.5)	902 (2.6)	9,157 (26.6)	11,620 (33.7)	774 (2.2)	460 (1.4)
Compensation costs (×1,000 euros)	1,154 (34.3)	93 (2.8)	738 (22.0)	1,136 (33.8)	144 (4.3)	97.5 (2.9)

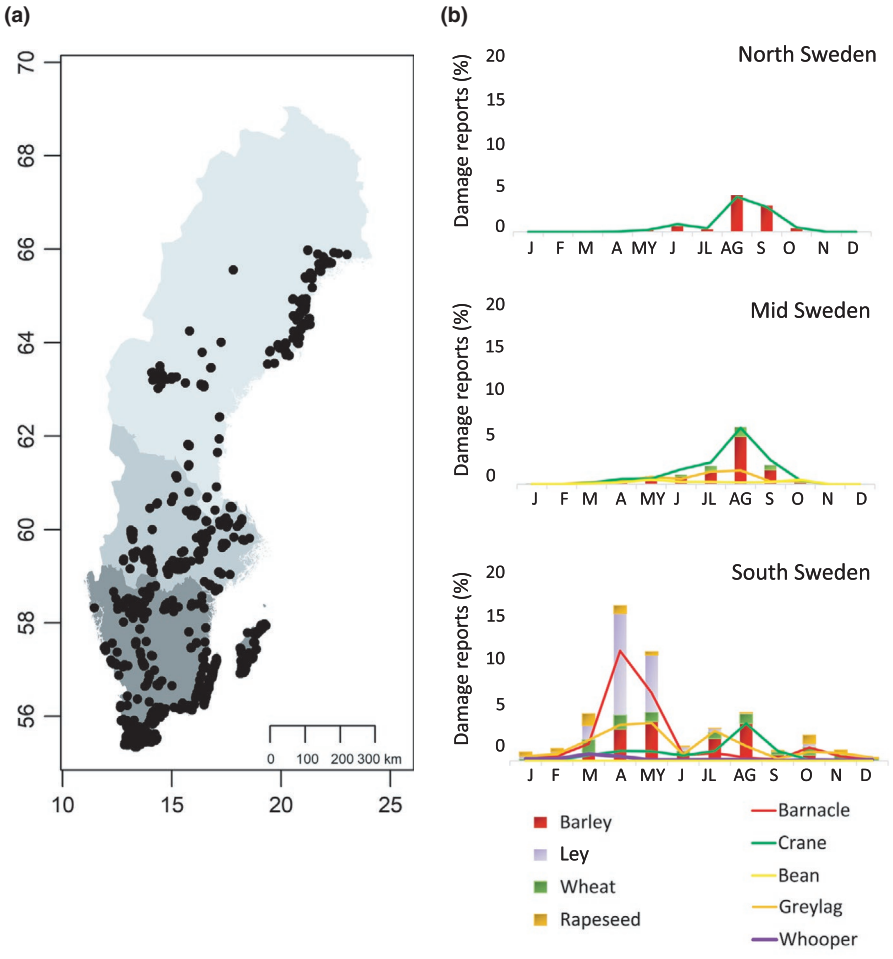
Note: The category 'others' includes Canada goose, mute swan, greater white-fronted goose, brent goose and unidentified geese.
[a]Canada goose = 197 T and 11,500 euros; mute swan = 8 T and 2,600 euros; greater white-fronted goose = 105 T and 60,200 euros; brent goose = 21 T and 2,400 euros; unidentified = 129 T and 20,500 euros.

Damage reports increased by a factor of five from 2000 to 2008, when maximum levels of damage reports were recorded for cranes, barnacles and greylags. From 2009 to 2013, the total number of damage reports decreased. During the same time period, greylag goose damage reports also decreased, while crane damage reports levelled off and barnacle damage reports increased. From 2014 to 2015, the total number of damage reports increased again (Figure 1a). A similar temporal pattern was found for yield loss (Figure 1b) and compensation costs (Figure 1c). However, there was a mismatch between peaks of compensation costs and those for damage reports and yield loss.

More damage reports were registered in southern than northern Sweden. Similarly, yield losses and compensation costs were higher in the south and involved more species and crops (Figure 2). South Sweden showed a bimodal pattern of damage, with peaks during spring and late summer to autumn. In mid and northern Sweden damage was concentrated in late summer and autumn. (Figure 2b). In southern Sweden, 64% of the spring damage was due to barnacles (two thirds on ley and 16% on barley), 25% to greylags (half on ley, 20% on barley and wheat and 9% in rapeseed) and 7% to cranes (half on barley, a quarter on wheat and 12% on legumes). From the autumn damage reported in south Sweden, 42% was caused by greylags in July (half on barley, 14% on leguminous, 12% on wheat and 7% on ley, beets and carrots) and 46% by cranes in August (two-thirds on barley and 18% on wheat). As for mid Sweden, 75% of the autumn damage was due to cranes (two-thirds on barley, 13% on wheat and potatoes and 7% on leguminous) and 18% to greylags (half on barley, 15% on wheat and 12% on leguminous and carrots). In northern Sweden, 74% of all registered damage was due to cranes foraging on barley fields (Figure 2).

3.2 | Relationships between population indices and damage levels

Damage levels (damage reports, yield loss and compensation costs) were positively related to population indices for common crane,



(c)

	Damage reports (2,198 damages)	Yield loss (34,500 metric tonnes)	Compensation costs (3.4 Million euros)
North Sweden	12.0%	4.7%	10.8%
Mid Sweden	24.8%	28.1%	23.1%
South Sweden	63.2%	67.5%	66.1%

FIGURE 2 Spatial distribution of damage reports (a); intra-annual distribution of damage reports for five species of large grazing birds and the four most damaged crop types) (b); percentage of total damage for three regions in Sweden (c) from 2000 to 2015. The division north, mid and south Sweden is for illustration purposes only and follows the historical division of Norrland, Svealand and Götaland respectively

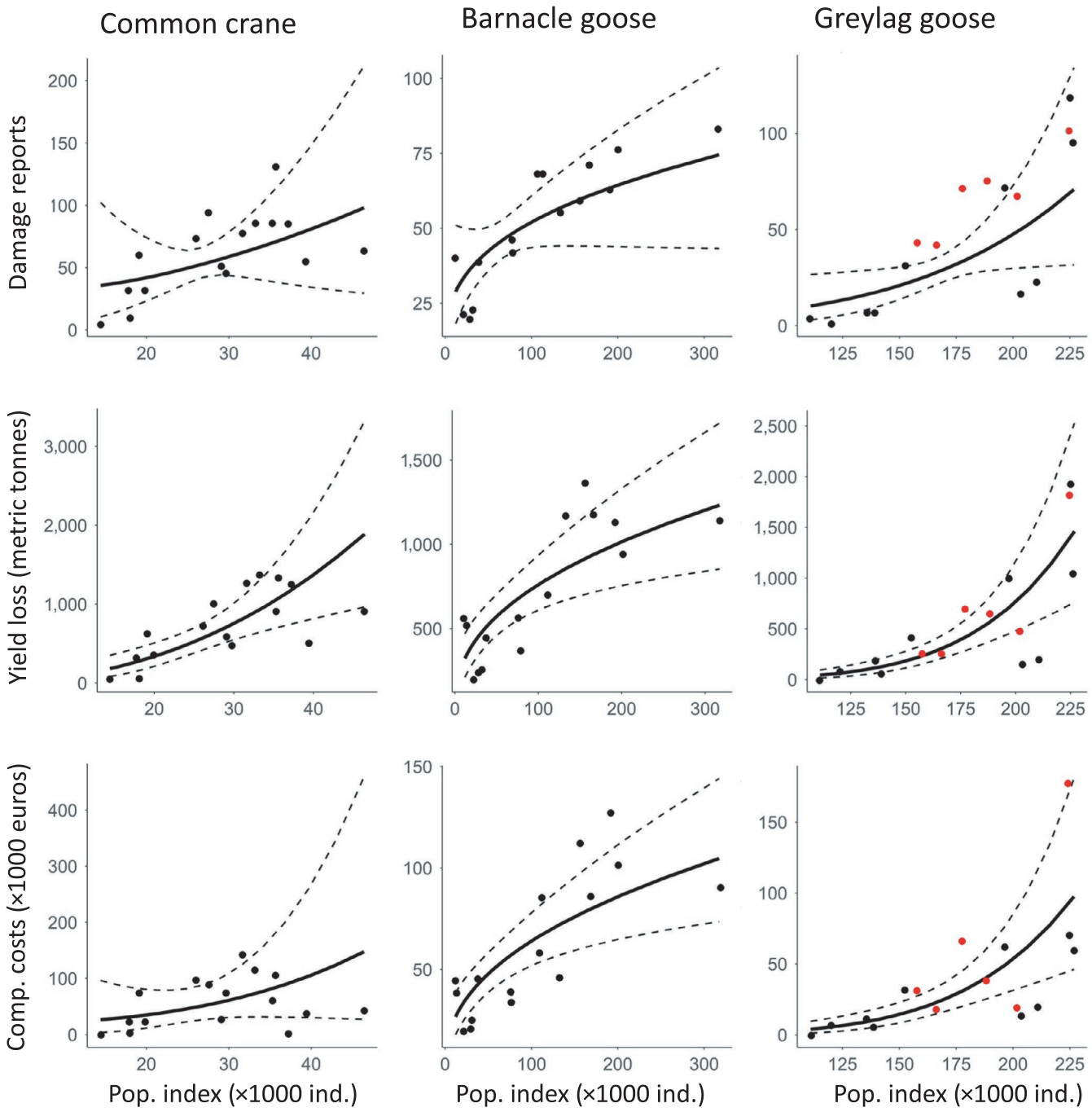


FIGURE 3 Relationship between damage reports, yield loss and compensation costs, and population indices for the three main species of large grazing birds causing crop damage in Sweden from 2000 to 2015, based on regression model (1), (2) and (3) respectively; as described in Methods. Solid lines represent the estimated curves based on the slope coefficient for the effect of population index over the response variables. Dashed lines, the 95% credible interval. Black dots, the observed values. Red dots in the greylag goose graphs represent observed values after 2009 when compensation rules changed for this species

barnacle and greylag goose (Figure 3). However, the broad relationships contained a high level of uncertainty (Table 2). Linear relationships could not be ruled out for common crane and greylag goose (Table 2). However, a nonlinear relationship appeared to fit best for greylag goose (Figure 3). Under the log-log model, a linear relationship (beta = 1) did not appear compatible with the data for barnacle goose (Table 2).

As population indices and damage levels displayed a general increase during the study period (Figure 1), we also investigated whether annual changes in population indices were associated with annual changes in crop damage (detrended data). We found no evident relationship between annual estimates of population indices and damage levels when data was detrended (Figure 4; Table 2).

TABLE 2 Population parameter estimates for the broad and detrended association analysis between damage reports, yield loss and compensation costs, and population indices for the three main species of large grazing birds causing crop damage in Sweden from 2000 to 2015

	Broad relationship				Detrended relationship		
	β_1				β_2		
Model (1)	***M***	***SD***	**95% CI**	**Model (4)**	***M***	***SD***	**95% CI**
Damage reports – Population index							
Common crane	0.9154	0.9173	−1.0529, 2.5283		−0.2643	1.0635	−2.3178, 1.9104
Barnacle goose	0.2935	0.1405	−0.0473, 0.5142		0.0523	0.2020	−0.3633, 0.4385
Greylag goose	2.8337	1.2554	0.284, 5.2101		2.2136	1.2789	−0.4537, 2.2726
	ξ_1				ξ_2		
Model (2)	***M***	***SD***	**95% CI**	**Model (5)**	***M***	***SD***	**95% CI**
Yield loss – Population index							
Common crane	1.5728	0.9152	−0.5298, 3.1282		0.2957	1.3191	−2.2923, 2.9440
Barnacle goose	0.3643	0.1417	0.039, 0.6056		0.0405	0.2861	−0.5597, 0.5812
Greylag goose	4.6955	1.1586	2.2109, 6.8398		3.9848	1.8103	0.0563, 7.3265
	δ_1				δ_2		
Model (3)	***M***	***SD***	**95% CI**	**Model (6)**	***M***	***SD***	**95% CI**
Compensation costs – Population index							
Common crane	1.3850	1.4700	−9.7528, 9.6404		−0.7877	2.8865	−6.4099, 5.0425
Barnacle goose	0.2027	0.2148	−0.2625, 0.5524		−0.1436	0.2382	−0.6236, 0.3237
Greylag goose	3.9254	1.4924	0.6283, 6.6056		3.3200	1.9026	−0.6903, 6.9580

Note: Rcex (×1,000 individuals). See Tables S5 and S6 for details.
Abbreviation: CI, credible interval.

4 | DISCUSSION

Knowledge about the relationship between population size and damage levels is crucial for wildlife damage management (Conover, 2002; Madsen et al., 2017). However, this knowledge is lacking for large grazing birds, especially at large spatial scales (Fox et al., 2017), and the relationship is often assumed to be linear (Cusack et al., 2018; McKenzie & Shaw, 2017). In this manuscript we investigated this important knowledge gap in the ecology of wildlife damage management. We assessed the relationship between national numbers of staging large grazing birds and national levels of reported crop damage, yield loss and compensation costs in Sweden, described how national temporal patterns of damage differs across the country and discussed how further information about spatiotemporal patterns of damage is crucial to provide guidance for when and where preventive actions should be prioritized and how to monitor the system.

We showed that crop damage has increased in Sweden since 2000. Common crane, barnacle and greylag goose caused the majority of yield losses and costs for compensation (c. 90%). It is reasonable to assume that damage levels are related to bird numbers and grazing pressures (Parrott & McKay, 2001). Our results broadly supported this assertion as when estimated populations sizes of large grazing birds increased, so did the levels of crop damage. We also showed that relationships between population numbers and damage levels seem to differ among species. Although a linear relationship could not be ruled out for common crane and greylag goose, barnacle goose showed a curvilinear relationship with all three damage level indicators (damage reports, yield loss and compensation costs) increasing at a lower rate when population numbers increase. For barnacles, this pattern could be explained by a tendency for the flocks to aggregate more than the other two species (Nilsson, 2013), that is concentrating the impact of damage. This is further supported by an observed increase of yield loss per reported damage at higher population indices (Figure 5). For greylag goose we found no such increase, suggesting that more fields could be damaged when population index increase. However, the lowered, but still increasing rates of yield loss as barnacle numbers increase, suggest additional factors are at play, for example, October counts not mirroring the actual culprit population. Most of the damage caused by barnacles occurred in April–May, implying a mix of Swedish and Russian breeders. If October counts contained a higher proportion of the Russian population (exponentially increasing; Fox & Madsen, 2017) versus the Swedish population (not increasing; Ottosson et al., 2012) this could mask the relationships. Regardless, awareness of potential nonlinearity is important because predicted outcomes for damage levels could change quite dramatically when population numbers change. The new compensation policy for greylag

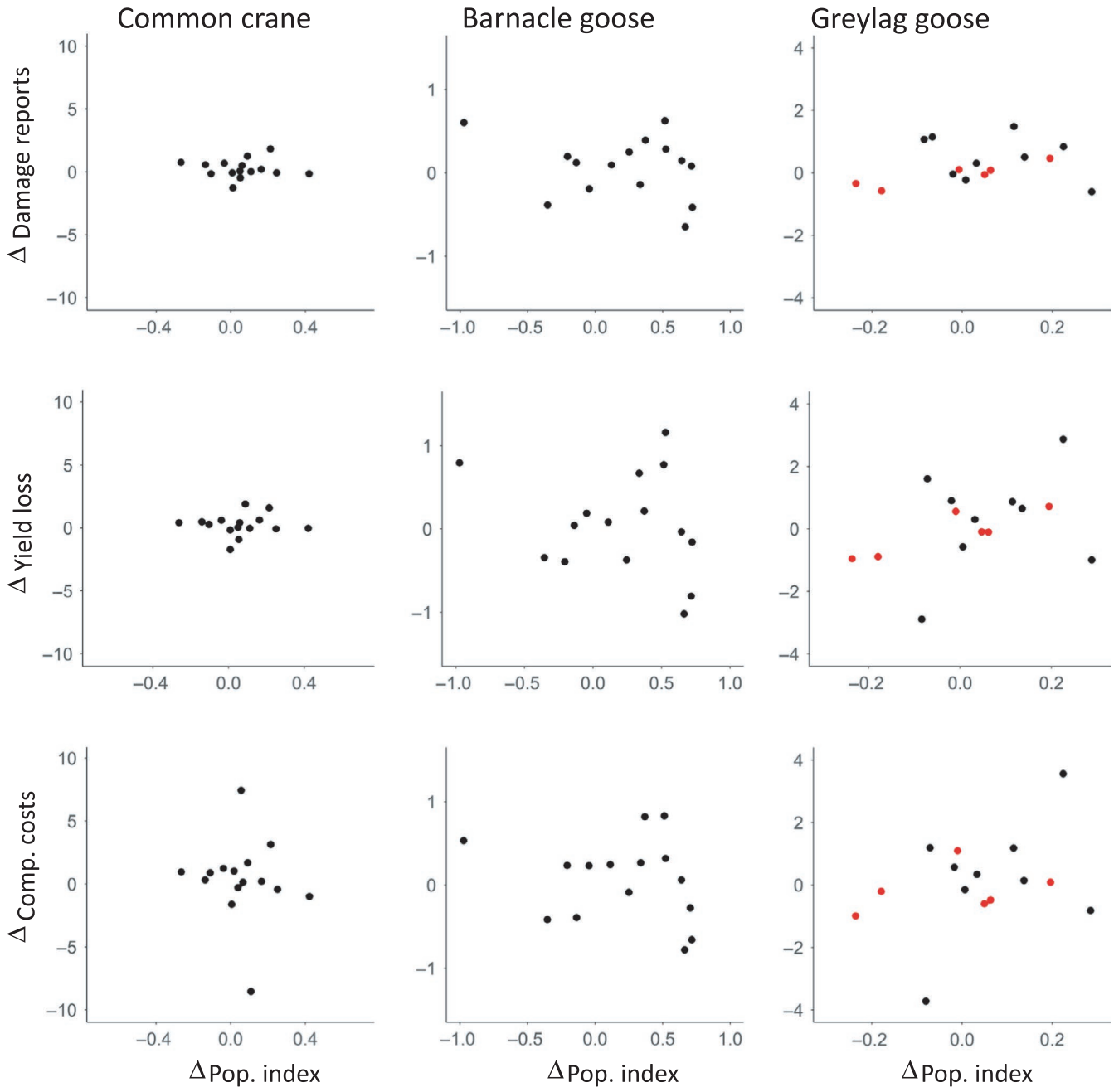


FIGURE 4 Scatterplot of the annual changes of damage reports, yield loss and compensation costs versus the annual changes of population index (in log scale), for three main species of large grazing birds causing crop damage in Sweden from 2000 to 2015. Red dots in the greylag goose graphs represent the data after 2009 when compensation rules changed for this species

goose established in 2009 may have reduced farmers' motivation for reporting greylag damage. Hence, damage levels for greylag goose could be underestimated and the relationships biased.

Regardless of the shape of the relationships, compensation costs seemed on average proportional to yield loss. However, annual peaks of yield loss did not always mirror annual peaks of compensation costs, which seems consistent with the variability of crop types that are damaged (Figure S3). As large grazing birds tend to concentrate in big numbers around wetlands, foraging on the surrounding agricultural landscape (Jankowiak et al., 2015), individual farmers in areas of high concentrations of large grazing birds may be disproportionately affected (Fox et al., 2017).

Our study demonstrated a high degree of uncertainty around the predicted estimates of the relationships between damage levels and population indices. In addition, annual changes in population indices did not relate to detrended inter-annual changes of damage levels. There are several possible reasons. Firstly, national indices of population size were based on monitoring data restricted to specific staging sites during a few weeks in autumn. It is reasonable to assume that the autumn staging monitoring provides a reasonable index of national

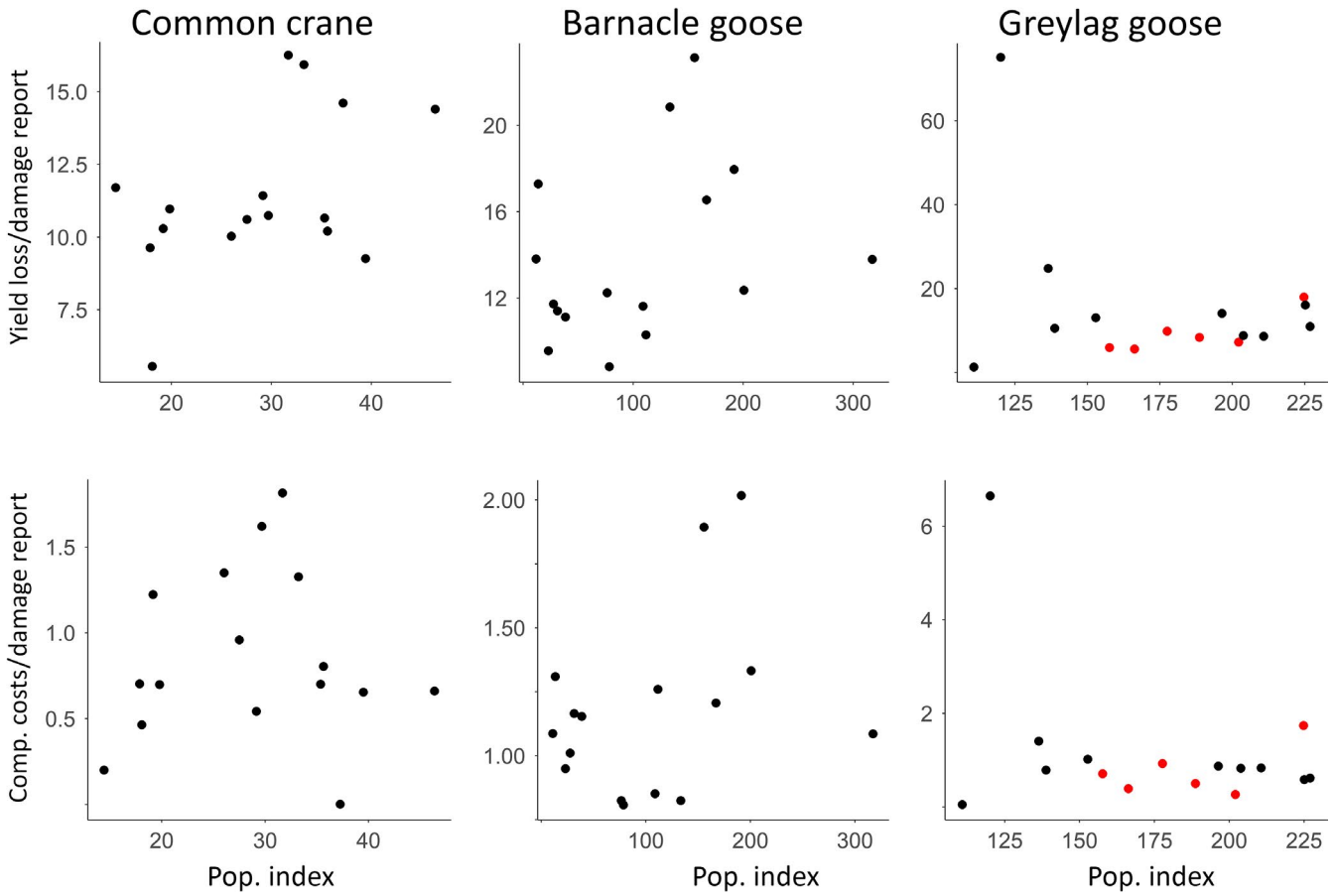


FIGURE 5 Scatterplot of the ratios yield loss (metric tonnes) and compensation costs (thousands of euros) per damage reports versus population indices (thousands of individuals), for three main species of large grazing birds causing crop damage in Sweden from 2000 to 2015. Red dots in the greylag goose graphs represent the data after 2009 when compensation rules changed for this species

population size (Nilsson, 2013) but not necessarily good enough to precisely describe inter-annual fluctuations. Moreover, it involves some spatio-temporal mismatch between estimated population numbers and occurrence of crop damage. Secondly, the present study is based on reported damage, inspected by government personnel. Therefore, the results rely on the farmer's willingness to report. We have no information about any variation in willingness to report, but this may depend on crop type (as they differ in provided income), revenue of the farms themselves and any previous experience of damage. Since availability of different crops and market prices has been stable over the study period (Figures S2 and S3), we assume that willingness to report within crop types, has not changed. Yet, it is reasonable to suspect that willingness to report may increase with increasing levels of damage, that is, tolerance to damage levels may have changed across time and space. Thirdly, the opportunistic foraging behaviour of large grazing birds can lead to sudden bursts of crop damage when local food availability and foraging conditions change (Béchet, Giroux, Gauthier, Nichols, & Hines, 2003; Clausen & Madsen, 2015; Tombre et al., 2008). This spatio-temporal mismatch together with local damage peaks is hard to detect with the coarse data at our disposal.

Wildlife damage depends not only on the presence of species causing damage, but also on resource availability (Conover, 2002), both of which vary across Sweden. The most damage was reported in southern Sweden, with peaks during spring and autumn, comprising a greater diversity of bird species and crop types. In northernmost Sweden, damage was concentrated in late summer and early autumn, three quarters of which took place on barley fields by common cranes. Although barley and wheat had similar availability, barley was more reported than wheat by all species (e.g. in southern and mid Sweden, autumn greylag reports on barley and wheat were 2:1; while crane reports were 3:1). Barley was also more reported than ley for cranes (<7% damage reports on ley even though its availability was four times higher than barley). Ley, the most abundant crop overall in Sweden and suitable throughout spring until late summer, was the most reported crop damaged by geese in spring in southernmost Sweden. Strategies for crop protection, therefore, need to be adapted to regional and seasonal conditions and the species involved.

4.1 | Management implications

Management under uncertainty is a major challenge in all natural systems. Recently developed adaptive goose flyway management plans in Europe suggest population control to reduce damage and conservation conflicts: see for example the adaptive management

plan for the pink-footed goose (Madsen and Williams 2012), and the current work to establish management plans to control the superabundant numbers of barnacle and greylag geese (Jensen et al. 2018; Powolny et al. 2018). The present study suggests that population control may be one possible tool to mitigate damage on a long-term basis (>15 years), especially when populations of large grazing birds continue to increase and crop damage levels are positively related to bird numbers. However, interpretation and guidance should be made with caution as this is a very complex and dynamic system both in time and space. The degree of uncertainty in our estimation demonstrates the difficulty to quantitatively predict specific outcomes of such management actions. Clearly, we need to address the uncertainty around damage–population size relationships and to do so, we need to design monitoring schemes that capture the site-specific variation of crop damage and abundance of wildlife. A possible way to increase the spatiotemporal resolution of data may be to include opportunistic citizen science data or to include observers in new bird monitoring programs in relation to crop protection. Such effort is also compatible with an increased cooperation with farmers, to build upon trust and to increase the understanding of attitudes and effectiveness for managing conservation conflicts (Josefsson, Pärt, Berg, Lokhorst, & Eggers, 2018; Mishra, Young, Fiechter, Rutherford, & Redpath, 2017; Young et al., 2016). Where there are possibilities to receive economical compensation for crop damage (as in Sweden), farmers should be actively encouraged to report damages together with, for example, participation in citizen science-based monitoring of large grazing birds promoted by local conservation organizations.

ACKNOWLEDGEMENTS

FORMAS financial support grant to JM (942-2015-1360) and grant no. 215-2014-1425 (TP) and Swedish EPA grant no. 13/361 (TP). Fredrik Haas, Leif Nilsson for authorizing the use of the geese and the whooper swan counts. Lars Gezelius, Clas Hermansson, Martin Tjernberg for authorizing the use of the common crane counts. David Flumm for the English proof review. Henrik Andrén, Matthew Low, Steve Redpath and three anonymous reviewers whose comments highly improved this manuscript.

AUTHORS' CONTRIBUTIONS

J.M., T.P., T.M.J. and I.T. launched the original idea of the manuscript. All authors contributed in refining the idea and approach. T.M.J. and J.K. developed the modelling analysis. T.M.J. analysed the data. T.M.J. wrote the first draft and led the writing of the manuscript. All authors significantly contributed to the final manuscript and gave final approval for publication.

DATA AVAILABILITY STATEMENT

Data available via the Dryad Digital Repository https://doi.org/10.5061/dryad.6b2c0n3 (Montràs-Janer et al., 2019).

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How to cite this article: Montràs-Janer T, Knape J, Nilsson L, Tombre I, Pärt T, Månsson J. Relating national levels of crop damage to the abundance of large grazing birds: Implications for management. *J Appl Ecol*. 2019;56:2286–2297. https://doi.org/10.1111/1365-2664.13457