Agriculture, Ecosystems and Environment 300 (2020) 107001

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Spatio-temporal patterns of crop damage caused by geese, swans and cranes—Implications for crop damage prevention

Teresa Montràs-Janer[a,*], Jonas Knape[b], Marianne Stoessel[c], Lovisa Nilsson[a], Ingunn Tombre[d], Tomas Pärt[b], Johan Månsson[a]

[a] *Grimsö Wildlife Research Station, Department of Ecology, Swedish University of Agricultural Sciences, SE-730 91 Riddarhyttan, Sweden*
[b] *Department of Ecology, Swedish University of Agricultural Sciences, Box 7044, Uppsala 75007, Sweden*
[c] *Department of Physical Geography, Stockholm University, SE-106 91 Stockholm, Sweden*
[d] *Norwegian Institute for Nature Research, Arctic Ecology Department, The Fram Centre, P.O. Box 6606, Langnes, N-9296 Tromsø, Norway*

ARTICLE INFO

Keywords:
Agriculture
Crop protection
Conservation conflicts
Wildlife damage management

ABSTRACT

European populations of geese, swans and cranes have increased considerably since the 1970s raising conflicts between conservation and farming interests. Crop damage caused by geese, swans and cranes across the national scale needs a trans-boundary approach that captures the site-specific characteristics of crop damage at a more refined spatial scale, to deal with the high spatio-temporal variation inherent in the system and to avoid conflict displacement. In the present study we use long-term crop damage data (2000–2015) in Sweden to evaluate seasonal and annual patterns of crop damage. We show that crop damage increased over years but followed a fairly consistent seasonal pattern during the later parts of the study period. We show how these seasonal patterns differ across the country such that trans-boundary regions with similar patterns of crop damage, relating to different nuisance species and damaged crops, can be identified. These findings about spatio-temporal variation of damage can be used to find appropriate scales of management units (e.g. areas with similar conditions), and to adapt damage mitigation strategies to temporal and spatial-specific conditions, e.g. guidance of when and where certain crop may be suitable as sacrificial crops.

1. Introduction

Management of wildlife damage caused by mobile and widely distributed species requires coordination over large spatial scales (e.g. national, flyway) to avoid displacement of the conflict (Béchet et al., 2003) and to achieve mutual conservation and conflict mitigation goals (Madsen et al., 2017). Since environmental conditions may vary over such large distribution ranges, knowledge about when and where damage occurs at more refined scales (e.g. local and regional), becomes necessary to achieve tailored decisions and actions to prevent damage to human livelihoods (Forsyth et al., 2000; Conover, 2002).

Geese, swans and cranes (hereafter ‘Large Grazing Birds’ - LGBs) are mobile and widely distributed species, migrating over large areas during their annual cycle. Geographically, the occurrence and abundance of the different species of LGBs vary seasonally, according to consistent migratory routes and regular phenology patterns (Madsen et al., 1999; Shah and Coulson, 2018). During migration, LGBs match timing of migration with the spatio-temporal variation in the nutritional properties of plants (Wei et al., 2019), spring growth and onset of spring at each staging site (i.e. green-wave hypothesis; Drent et al., 1978; Owen, 1980; Si et al., 2015); as well as show high degree of fidelity for stopover, breeding and wintering grounds (Warren et al., 1992; Kruckenberg and Borbach-Jaene, 2004). Additionally, human land use and landscape characteristics also vary across large ranges, in relation to climate zones (Kottek et al., 2006), soil and topographic characteristics (Statistics Sweden, 2013); while agricultural farmland is subjected to a regular annual cycle of tillage, sowing and harvesting. Consequently, because wildlife damage depends on the species causing damage and the crop availability (Conover, 2002) and, because LGBs and farming practices follow regular seasonal patterns, it is reasonable to assume a more or less consistent seasonal pattern of crop damage within a given area across years.

LGBs, as other wildfowl species in Europe, were declining during the first half of the last century due to overharvesting and habitat destruction (Fox and Madsen, 2017). However, numbers of LGBs have significantly increased in Europe since the 1970s (Fox and Madsen, 2017). Conservation efforts (Ebbinge, 1991; Fox et al., 2017), agricultural intensification increasing the availability of high-quality forage

---

[*] Corresponding author.
E-mail address: teresa.montras.janer@slu.se (T. Montràs-Janer).

https://doi.org/10.1016/j.agee.2020.107001
Received 9 December 2019; Received in revised form 24 April 2020; Accepted 5 May 2020

all year around and thereby extending the effective carrying capacity (van Eerden et al., 1996; Fox et al., 2005; Fox and Abraham, 2017) and a warming climate (Jensen et al., 2014) have fueled this dramatic increase. As monitoring is restricted back in time, there are limitations of historical data (Fox and Madsen, 2017). Nevertheless, the current rapid increase and exponential growth of several LGB populations create a conservation conflicts when foraging birds cause damage to crops and hence a loss of yield for farmers (Hake et al., 2010; Tombre et al., 2013; Fox and Madsen, 2017). This is especially true on farmland near protected wetlands where these species concentrate in high numbers (Fox et al., 2017; Nilsson et al., 2019). Solutions to these conflicts require a cost-effective strategy for both conservation and crop protection. Hence, knowledge about how crop damage varies across time and space, in terms of when it occurs and which species and crops are involved, become crucial for wildlife managers and land-owners in order to design effective strategies for preventive actions (Forsyth et al., 2000).

The administrative jurisdiction of the legislative bodies managing wildlife damage often occurs within administrative boundaries (e.g. counties within the national scale, or countries within the flyway scale), reducing the ecological considerations of the species involved and the spatio-temporal variation of damage patterns (Månsson et al., 2015; Meisingset et al., 2018; Nilsson et al., 2018). This is a challenge when managing widely distributed species moving over large areas. In Sweden, solutions are dealt with at the local scale where farmers can report crop damage caused by LGBs to receive economical compensation for the yield loss, from an accredited governmental compensatory scheme administrated at the county level (Månsson et al., 2011). Reported damages must be approved by authorized inspectors before endorsement of any economical compensation. These data open up unique opportunities to investigate patterns of crop damage in relation to geographical region, crop types and species of LGBs.

We used the approved reports of crop damage in Sweden from 2000 to 2015, to examine the spatial distribution of damage. We investigated monthly patterns of crop damage and how they differ across the country in relation to regional differences in crop types and species causing damage. We expected crop damage to follow a monthly pattern, consistent across the years so that trans-boundary regions with similar patterns of crop damage could be identified. In our study we 1) identified the regions that capture the site-specific variation of damage across the national scale, regardless of administrative borders; 2) identified which crops and species need to be focused on for implementing preventive measures across time and space; and 3) applied our findings to assess current and future management actions for crop protection at different spatio-temporal scales.

2. Methods

2.1. Study area

We analyzed data across all of Sweden, ranging between 55°-70° north and 11°-25° east. This considerable stretch in latitudes includes a significant variation and gradient in climate, vegetation and crop types. Sweden can be divided into four climate zones (oceanic, warm-summer humid continental, subarctic and arctic; Kottek et al., 2006), five distinct vegetation zones (southern deciduous forest, southern coniferous forest, taiga, alpine-birch and bare-mountain zone; Ahti et al., 1968) and eight agricultural productivity areas (Statistics Sweden, 2013). The southernmost part of Sweden has a landscape dominated by agriculture, representing 60 % of all Swedish agricultural land, and a crop production dominated by wheat and ley (i.e., hay and pastures). Here, the production of oil seed across the fertile plains and sugar beets along the coast is the highest in Sweden and the region holds the highest diversity of crops. Potatoes are grown throughout the country (Statistics Sweden, 2013). Towards the north, forest coverage increases and agricultural heterogeneity decreases, with grasslands representing approx. 70 % of the agricultural land (Board of Agriculture, 2019).

Common crane (*Grus grus*), barnacle goose (*Branta leucopsis*) and greylag goose (*Anser anser*) caused 90 % of the reported damage, yield loss and costs for compensation in Sweden between 2000 and 2015, while bean goose *Anser fabalis* and whooper swan *Cygnus cygnus* combined represented 8 % of the reported damage (Montràs-Janer et al., 2019). Common crane occurs all over Sweden, breeding primarily in wet forest habitats, using wetlands as stopover sites while foraging in the surrounding agricultural landscape (Nilsson et al., 2016). Greylag goose is mostly present in south and mid Sweden, extending northwards along the coast, while whooper swan occurs mostly inland (Shah and Coulson, 2018). Both these latter species breed in wetlands and water bodies, which they also use as stopover sites, foraging on the surrounding agriculture fields during breeding, moulting and migration. Barnacle goose has a more southern distribution, predominantly along the coast as stopover sites when migrating, although some sites also have breeding populations, foraging on the surrounding agricultural land (Ottosson et al., 2012; Shah and Coulson, 2018). Bean goose crosses Sweden during migration and only a small part of its population breeds in the north of the country (Ottosson et al., 2012). Overall, and because of the climate differences, northern Sweden has a shorter grazing period compared to southern Sweden - where there are also wintering geese and swans (Nilsson, 2013).

2.2. Swedish compensatory scheme for crop damage

In 1995, the Swedish government implemented a compensatory scheme for crop damage caused by LGBs. Since then, farmers that want compensation for the loss of yield due to foraging LGBs can report crop damage to the County Administrative Board (CAB). Authorized inspectors will then visit the farms and, following standardized protocols, approve and certify the reported damages, identify culprit species and damaged crop types, and estimate harvest loss before any compensation is granted (for details about inspection method see Månsson et al., 2011; Montràs-Janer et al., 2019). To evaluate the within-year and between-year patterns of crop damage occurrence, we used the number of certified reports of damage (hereafter ‘damage reports’) from 2000 to 2015 (n = 2194). LGBs often occur in mixed flocks and therefore one damage report often included more than one species (Montràs-Janer et al., 2019). Because the inspectors of the CAB identified culprit species, we could now account for species-specific reports of damage.

2.3. Statistical analysis

2.3.1. Spatial distribution of damage patterns

To capture the spatial variation of monthly patterns of crop damage we used clustering analysis. We first extracted the GPS location for each one of the 2,194 damage reports and computed the Euclidean distance matrix between all individual locations, with QGIS version 2.14. We then ran an Agglomerative Hierarchical Clustering (AHC), using a complete linkage method over the distance matrix to lump the individual locations by proximity. The idea was that closer locations would likely have more similar crop damage characteristics (i.e., time of damage occurrence, culprit species and damaged crop type) than locations further apart. The goal was to group the locations by the similarity of their crop damage characteristics and not by the administrative borders of their locations (e.g. using Swedish provinces). We extracted 21 units of crop damage from the resulting dendrogram (Figs. A1, Supporting information). Two of the units were excluded due to low sample size (1 and 5 data points) (Fig. B1, Supporting information).

Thereafter, we computed a composition table where, for each unit of crop damage, we calculated the total number of damage reports each month across all years, and their percentages in relation to the total number of damage reports of the unit (Table B1, Supporting information). We then ran a second AHC over the composition table, using Euclidean distance and Ward’s linkage method (Ward D2), with the aim of grouping the units of crop damage into a bigger clusters (to define regions of crop damage). The Ward's linkage method uses the minimum variance criterion. This criterion minimizes the total distance variance within clusters and at each step of the AHC, the pair of clusters that leads to the minimum increase in this variance are merged. The uncertainty of this analysis, and thus the strength of the resulting regions of crop damage, was assessed by calculating probability values for each cluster (the probability to obtain the same clusters if we would run the AHC multiple times). We used Approximate Unbiased (AU) p-value, calculated by multiscale bootstrapping resampling with 10,000 bootstrap replications (Suzuki and Shimodaira, 2004). AU offers a better approximation to unbiased p-value than the Bootstrap Probability (BP) p-value, calculated by ordinary bootstrap resampling (Suzuki and Shimodaira, 2006).

2.3.2. Temporal consistency of damage patterns

To determine if monthly patterns of damage reports were consistent over the years, from 2000 to 2015, and to investigate annual tendencies of crop damage, we used Generalised Additive Models (GAM) (Wood, 2004). For each region obtained from the AHC analysis, we modelled damage reports as response variable over time and month. A time covariate was added as a dummy variable representing the number of months passed since the start of the study (vector from 1 to 192 as January 2000 is accorded a value of 1; February 2000, value of 2 and so on until December 2015, with value of 192). The variable month refers to the number of the month (vector from 1 to 12). The dummy variable time was introduced in the model as a penalized cubic regression spline, with 30 regularly spaced knots to model slow, smooth, changes over the years. The variable month was introduced in the model as a cyclic cubic spline, a penalized cubic regression spline whose ends match up to the second derivative, with 9 knots. In order to correct for overdispersion, we used a Negative Binomial response distribution. The optimum degree of smoothing was estimated as part of the model fitting procedure. Goodness of fit was examined using randomized quantile residuals (rq-residuals) (Dunn and Smyth, 1996) via the R-package nmixgof (Knape et al., 2018). Rq-residuals are normally distributed under the correct model. To check for normality in rq-residuals we used quantile-quantile plots (qq-plots). To assess for remaining trends in the residuals, we plotted rq-residuals against predictors and fitted values. We checked for remaining trends in the residuals within each year across the different months, and also within each month across the different years. We audited the rq-residuals for temporal dependency by computing Autocorrelation Function (ACF). For details, see Figs. C1 and C2 in Supporting information.

GAM models were implemented using R package mgcv (Wood, 2006) version 1.8-22. AHC and the sensitivity analysis were computed with the R package pvcluster (Suzuki and Shimodaira, 2006). All statistical analyses were conducted with R version 3.3.3 (R Core Team, 2017).

2.4. Crop availability and crops at risk

Data on crop availability is available on an annual basis (Board of Agriculture, 2019). We computed the region-specific crop availability using a yearly raster crop dataset at 25 m resolution, available from 2001 to 2014 (www.smed.se). This raster grouped all different crop types in the following crop categories: rye, spring barley, oat, autumn and spring wheat, autumn and spring rapeseed, corn, pastures, silage and hay, sugar beets and small scale crops (i.e. leguminous, sunflower, buckwheat, white mustard, millet) (see http://www.smed.se/wp-content/uploads/2016/05/SMED-Rapport-186-2016_GIS_PLC6.pdf, Appendix F in Widén-Nilsson et al., 2016 for details).

To identify which crops could be at higher risk when certain species are present, we calculated for each region obtained from the second AHC, species and crop, the ratio between the proportion of damage reports and the proportion of crop availability, averaged over all years (first ratio analysis, Table 1). To identify the crops with the highest damage in relation to their availability, we explored for each region and crop, the ratio between the proportion of damage reports for the crop and the proportion of crop availability, over all species and averaged over all years (second ratio analysis, Fig. 6). In the first analysis, a ratio > 1 would suggest potential selection of a species for certain crops, identifying crops at risk. The opposite holds for ratios < 1. In the second analysis, if the ratio between damage reports and crop availability equals 1, it means that the impact of foraging LGBs in general was in average proportional to the availability of the crop. A ratio > 1, would suggest an overuse in relation to availability of the crops and a ratio < 1, an underuse.

Crops providing higher income such as rapeseed or potatoes (mean market price$_{2000\text{-}2015}$ 27 and 21 euros/100 kg respectively) may be prone to be reported more than crops providing less income, for example barley (11 euros/100 kg) (Board of Agriculture, 2019). Because market prices showed no annual tendency since 2000 (once accounted for annual inflation; Statistics Sweden, 2019) we expect no temporal changes in crop-specific reporting.

3. Results

3.1. Spatial distribution of damage patterns

The statistical clustering (AHC) identified six different regions with distinct monthly patterns of crop damage separated in two major groups: Southeast and East Sweden (regions IV, V and VI; Fig. 1) and West and North (regions I, II and III; Fig. 1). A seventh cluster was excluded due to low sample size (n = 17; Fig. 1). Damage reports came from south to north with the highest densities in the south. Regions IV and V had the highest number of damage reports (562 and 557 respectively), followed by regions VI (396), I (301), III (254) and II (101; Fig. 1).

3.2. Crop availability

Ley dominated the agricultural landscape in all six regions (40 % in southern regions, up to 70 % in the north). Barley and wheat were also dominant crops. But while the availability of barley remained relatively constant throughout the country (about 14 % for all regions), wheat was more abundant in the south (around 16 %) and less in the north (down to < 3 %) and region IV (ca 10 %). Rye, beets, mixed crops, oat, potatoes and rapeseed represented < 5 % of the agricultural land in all six regions, except for oat in region I where it represented around 13 %. No distinct annual tendencies on crop availability were detected for any of the six regions, except for regions II and III where barley decreased by half through the study period (Fig. D1, Supporting information for details).

3.3. Temporal damage patterns

Monthly patterns of damage reports differed among regions. In regions I-III, damage reports peaked in August and to some extent September. Almost all damage involved common cranes (Fig. 2) causing damage in barley fields (Fig. 3). However, damage also occurred in potato fields in region II, and wheat and ley in region I (Fig. 3). Region IV showed a peak of damage reports in April-May (Fig. 2), almost exclusively involving barnacle geese in ley fields (Fig. 3). Region V showed a bimodal pattern of damage, with one peak in March-May equally involving barnacle and greylag geese, and another in July caused by greylag geese (Fig. 2). Half of the reports by barnacle geese were in ley, while up to 84 % of the reports by greylag goose were in barley. Region VI recorded the most damage in June-September: 60 % caused by common cranes in July-September and 30 % by greylag geese in July-August (Fig. 2). While reports of common cranes were mainly in barley (40 %) and potato fields (26 %), greylag geese registered most of

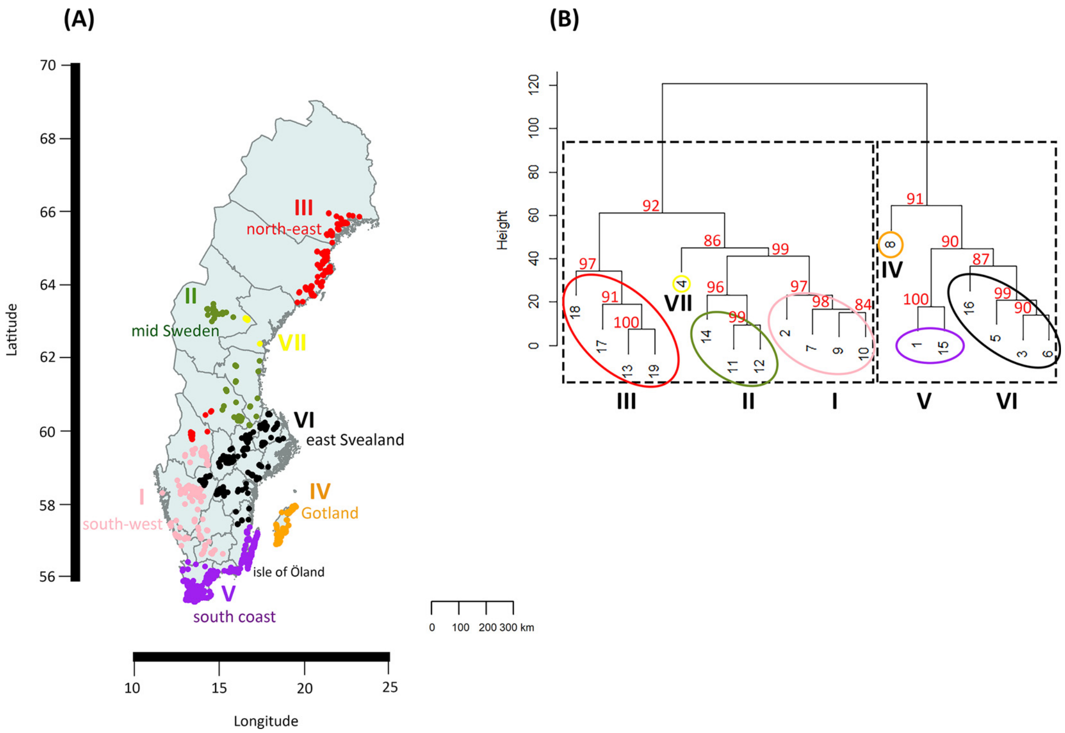

Fig. 1. Spatial distribution of crop damage caused by large grazing birds between 2000 and 2015, across the 21 Swedish counties (A). Dendrogram of the Agglomerative Hierarchical Clustering (AHC) analysis identifying six regions with similar patterns of crop damage (B). The dendrogram identifies two areas (black dashed frames) in which the regions appear aggregated. Each region (I to VII) is represented by circles on the dendrogram matching the colors in the map. Each dot in in the map represents an individual damage report. The yellow dots indicate a region with only 17 damage reports (excluded from the analysis) and relates to region VII in the dendrogram. The black numbers in the dendrogram refer to each one of the units of damage used to build the dendrogram (Fig. B1, Supporting information for details). The red numbers, represent the Approximately Biased (AB) p-values (in percentage), i.e. probability values for each cluster using multiscale bootstrap resampling.

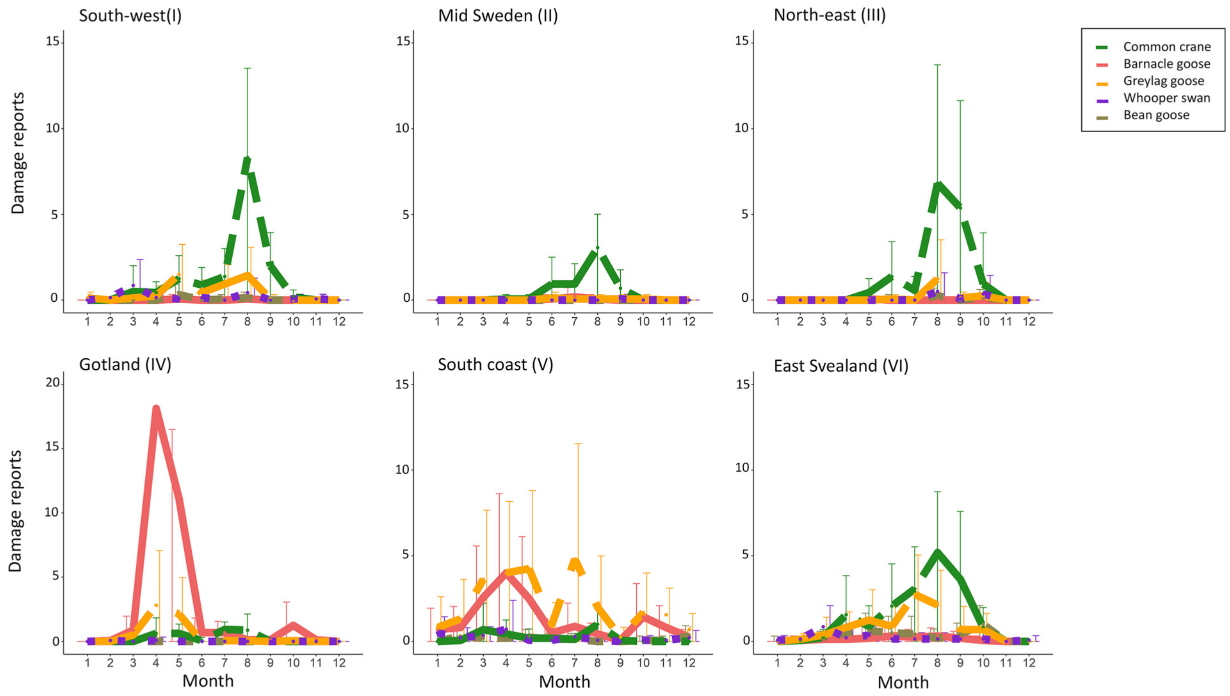

Fig. 2. Number of damage reports per month (mean ± standard deviation) concerning five species of large grazing birds, for six different regions with similar monthly patterns of crop damage in Sweden, from 2000 to 2015. Note the different scale on the y-axis for Gotland.

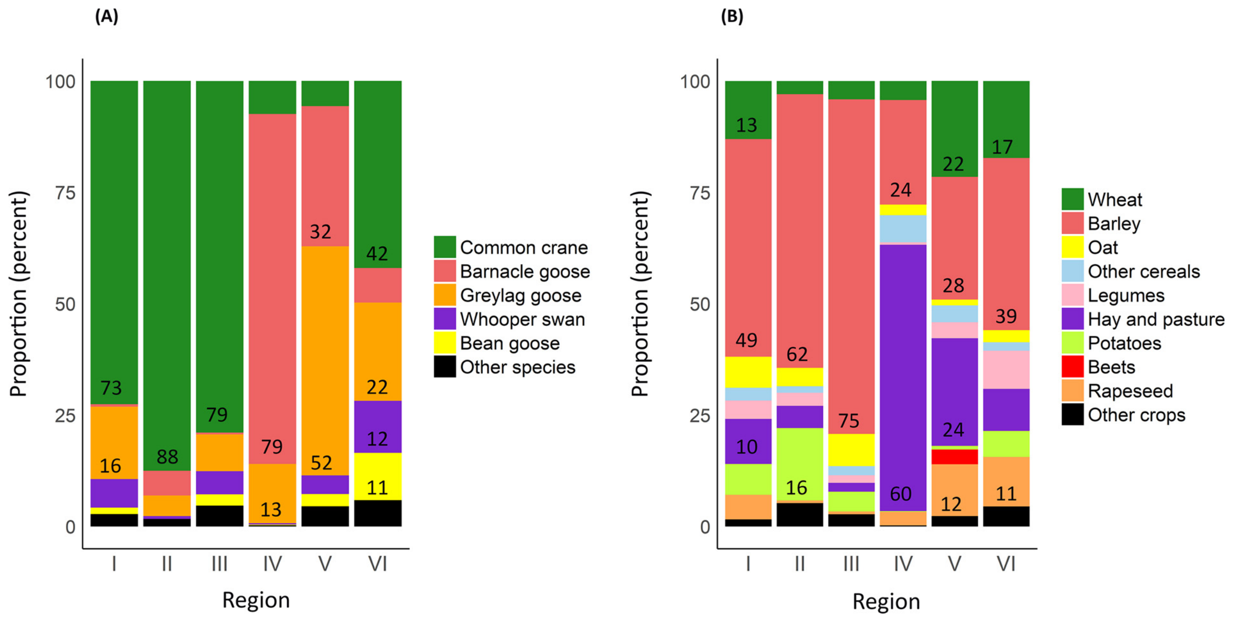

Fig. 3. Proportion values (in %) of the species of large grazing birds reported to cause crop damage (A) and the affected crop types (B), for six different regions (I – VI) with similar monthly patterns of crop damage in Sweden, summarized between years 2000 to 2015. Percentage values are given only for cases ≥ 10 % from the total regional number of damage reports." Other species" includes Canada goose, mute swan, greater white-fronted goose, brent goose, unidentified goose and other grazing bird species. "Other crops" includes carrot, strawberry, sunflower or other unmentioned crops where damage never reached > 5 % of the total damage per region, and diversionary fields.

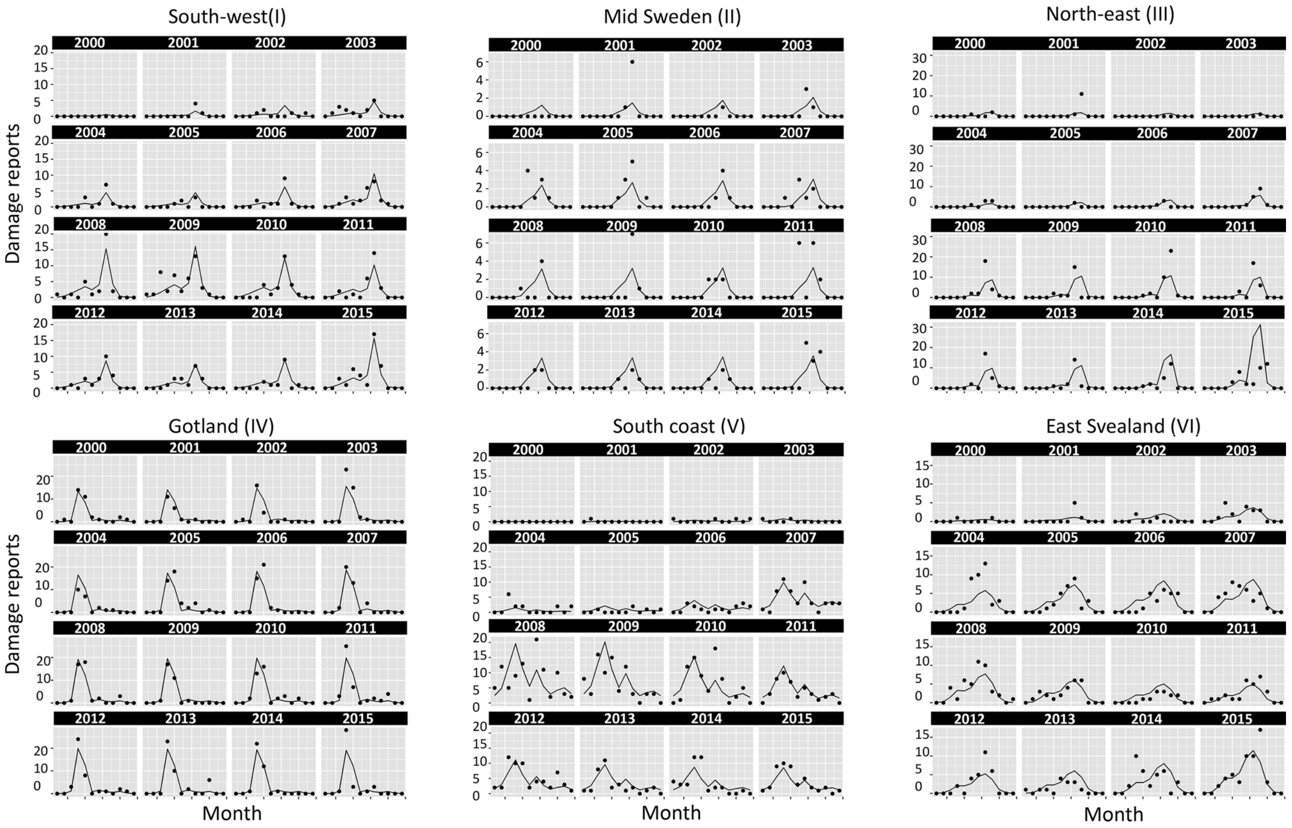

Fig. 4. Predicted number of damage reports (per month and year) caused by large grazing birds in Sweden from 2000 to 2015, identifying six different.

the damage in barley (40 %) and wheat, carrot and small scale crops fields (15 %). Region VI was the only region where whooper swan and bean goose represented > 10 % of the overall damage reports (Fig. 3), occurring in March and October respectively, with almost all of them in rapeseed for whooper swans and wheat, barley and carrots for bean geese.

The monthly pattern of damage reports in each region was fairly consistent across the years (Fig. 4). These seasonal patterns were relatively stable despite the between-year tendency of the number of increased damage reports in regions I, III and VI, and decrease in damage

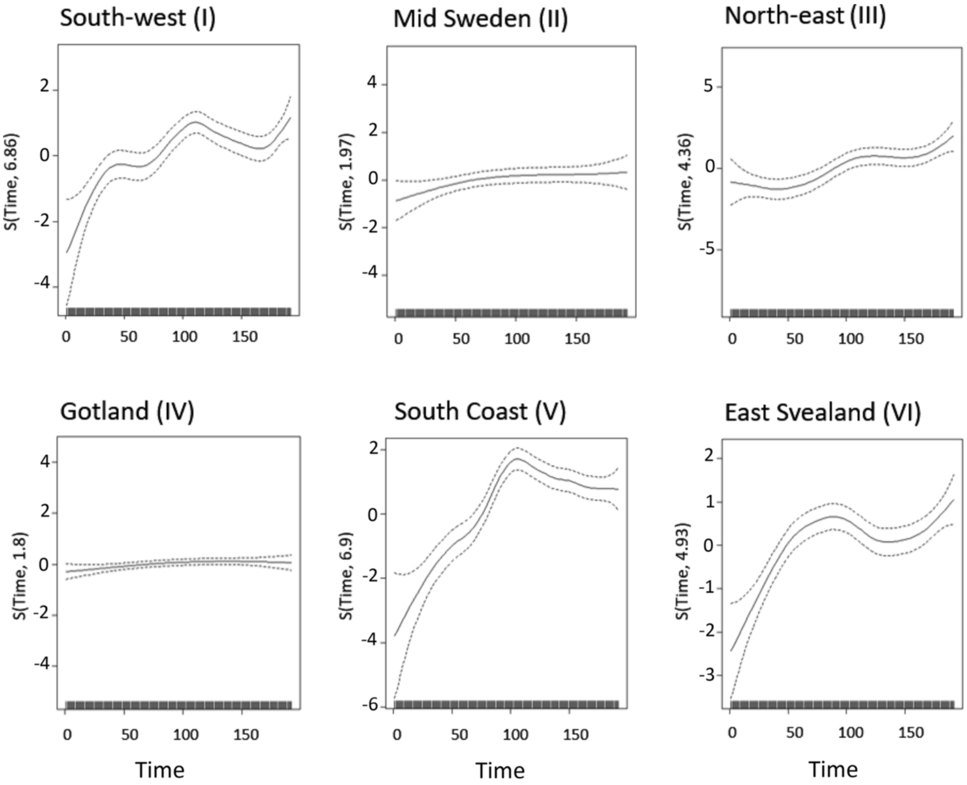

Fig. 5. Variation of damage reports caused by large grazing birds in Sweden across time (represented by the cubic spline of the dummy variable time of the GAM model, as described in methods section), for six different regions with similar monthly patterns of crop damage, from 2000 to 2015.

reports in region V over the last 7 years (Fig. 5 and Fig. E1, Supporting information). In regions II and IV, no strong changes in annual tendency of damage reports were registered during the study period (Fig. 5).

3.4. Species crop selection patterns and crops at risk

Despite the variation amongst regions in species-specific relationship to crop availability and number of damage reports, the ratio analysis suggested broad patterns revealing potential species selection for certain crops. Although the availability of ley was high, no damage reports of cranes were registered for this crop while all other species reported on ley, either matched or were below its availability, except for greylag goose and bean goose in region I (Table 1) (however the latest was dismissed because of only involving two reports of damage; Table D1, Supporting information). Barley seemed to be damaged more than wheat by all species, in relation to its availability, except for barnacle goose in region V and common crane in regions I and III (Table 1). Relationships between crop availability and damage reports registered up to 1:40 and 1:78 for cranes in potato fields, and ratios > 1 were also found for legumes, wheat and oats. Whooper swans on the other hand, showed a higher proportional damage on rapeseed fields, recording up to 1:65 in region I and 1:12 and 1:11 in regions V and VI, respectively (Table 1). Minority crops such as carrots recorded ratios of damage reports / availability of crops > 1 for greylag and bean goose in region VI (Table 1).

Combined damages by all the species showed that barley and potatoes were more frequently damaged than expected by availability in regions I, II, III and IV, due mainly to common cranes (Fig. 6). Similarly, rapeseed was more damaged than expected by availability in region I due to greylag geese and whooper swans; and in region VI, almost exclusively by whooper swans. Legumes were more damaged than expected by availability in region II due to common cranes, and in region VI due mainly to common cranes and greylag geese. Oat in region III was also more damaged than expected from its availability, in this case due to common cranes (Fig. 6). The impact of LGBs in region V resulted in wheat, barley and rapeseed fields being more frequently damaged than expected by availability, mostly due to greylag and barnacle geese, but also by common cranes for barley fields and whooper swans for rapeseed crops (Fig. 6).

4. Discussion

In this study, we investigated the spatio-temporal variation in crop damage caused by LGBs over a gradient stretching from the warm-summer humid continental to the arctic climate zone (Kottek et al., 2006). We identified six distinct trans-boundary regions sharing similar patterns of species causing damage, damaged crops and timing of damage (Fig. 1). We found consistency in the seasonal patterns of damage within and between the regions (Fig. 4), although the number of damage reports had increased during the study period (Montràs-Janer et al., 2019). Our findings imply that different parts and seasons of these migratory birds' flyways may require specific strategies for crop protection.

Damage caused by LGBs, like damage caused by other wildlife, depends on three basic factors: 1) presence and abundance of the species causing damage; 2) resource availability and 3) its timing in relation to presence of culprit species (Conover, 2002). It is therefore not surprising that Sweden, covering many climate zones, displays a large variation in damage patterns as presence and abundance of nuisance species, land use and resource availability vary throughout the country (Madsen et al., 1999; Kottek et al., 2006; Ottosson et al., 2012; Statistics Sweden, 2013). Additionally, nutritional requirements of the birds (Fox et al., 2017) may cause changes in preferences of habitats and crops within the year and between species (Baveco et al., 2011; Végvári and Barta, 2015; Nilsson et al., 2016). Therefore, we expected spatio-temporal variation of crop damage across Sweden. We also expected to find seasonal patterns of crop damage to be fairly consistent over the years, because of seasonality, phenology patterns and migratory routes

Table 1

Ratio *damage reports / crop availability* (mean ± S.E. for the period 2001–2014) for five different species of large grazing birds, in six different regions in Sweden, with similar monthly patterns of crop damage, and eight different crop types.

	Wheat	Barley	Oat	Leg[a]	Ley	Potato	Beet	Raps[a]		Wheat	Barley	Oat	Leg	Ley	Potato	Beet	Raps
Region I									**Region IV**								
CC	**7.3 ± 1.6**	**7.2 ± 0.7**	**1.3 ± 0.5**	–	–	**0.5 ± 0.1**	–	**1.9 ± 1.3**	CC	1.9 ± 0.6	5.2 ± 0.4	–	–	–	–	–	–
BG	–	–	–	–	–	–	–	–	**BG**	**0.2 ± 0.1**	**1.2 ± 0.2**	**1.0 ± 0.7**	**1.0 ± 0.7**	**1.0 ± 0.1**	–	**0.1 ± 0.1**	**1.0 ± 0.3**
GG	**1.0 ± 0.5**	**3.5 ± 1.1**	**0.1 ± 0.1**	–	**4.1 ± 1.1**	–	–	**1.3 ± 1.3**	GG	0.1 ± 0.1	0.7 ± 0.5	–	–	0.8 ± 0.2	–	–	–
WS	–	3.4 ± 1.4	1.0 ± 1.0	–	0.2 ± 0.2	–	–	65.4 ± 26.0	WS	–	–	–	–	–	–	–	–
BN	–	1.3 ± 0.1	–	–	1.3 ± 0.1	–	–	–	BN	–	–	–	–	–	–	–	–
Region II									**Region V**								
CC	**0.9 ± 0.7**	**3.9 ± 0.3**	**0.5 ± 0.3**	**0.8 ± 0.5**	–	**39.7 ± 8.6**	–	**6.0 ± 6.0**	CC	0.3 ± 0.2	3.4 ± 0.7	–	0.5 ± 0.5	–	5.3 ± 3.0	0.8 ± 0.5	–
BG	–	–	0.5 ± 0.5	–	0.2 ± 0.1	–	–	–	**BG**	**1.6 ± 0.5**	**0.9 ± 0.3**	–	**0.1 ± 0.1**	**0.9 ± 0.2**	–	–	**1.2 ± 0.4**
GG	2.3 ± 2.3	0.7 ± 0.5	–	–	0.2 ± 0.1	–	–	–	**GG**	**1.8 ± 0.3**	**1.6 ± 0.3**	**0.3 ± 0.2**	**1.5 ± 0.8**	**0.5 ± 0.2**	–	**0.7 ± 0.3**	**2.5 ± 0.9**
WS	–	–	–	–	–	–	–	–	WS	0.5 ± 0.3	0.1 ± 0.1	–	1.0 ± 1.0	–	–	0.7 ± 0.7	12 ± 3.2
BN	–	–	–	–	–	–	–	–	BN	1.5 ± 0.5	0.3 ± 0.3	–	2.0 ± 2.0	0.2 ± 0.1	–	0.7 ± 0.7	3.5 ± 2.9
Region III									**Region VI**								
CC	**69 ± 46**	**5.1 ± 0.5**	**1.7 ± 0.7**	**0.6 ± 0.3**	–	**3.8 ± 1.4**	–	–	**CC**	**1.0 ± 0.2**	**3.0 ± 0.4**	**0.3 ± 0.2**	**3.5 ± 0.9**	–	**77.5 ± 16**	–	**0.3 ± 0.2**
BG	–	–	–	3.1 ± 0.3	–	–	–	–	BG	0.2 ± 0.1	0.9 ± 0.7	–	4.4 ± 0.9	0.5 ± 0.1	–	–	–
GG	–	3.5 ± 1.0	–	–	–	–	–	–	**GG**	**1.0 ± 0.3**	**2.9 ± 0.7**	**0.2 ± 0.2**	**3.4 ± 0.9**	**0.3 ± 0.1**	–	–	**0.9 ± 0.5**
WS	–	0.9 ± 0.6	–	–	0.1 ± 0.1	–	–	–	**WS**	**0.1 ± 0.1**	**0.9 ± 0.4**	–	–	**0.2 ± 0.1**	–	–	**10.5 ± 2.9**
BN	–	0.9 ± 0.6	–	–	0.1 ± 0.1	–	–	–	**BN**	**1.4 ± 0.4**	**1.6 ± 0.6**	–	**0.5 ± 0.5**	**0.2 ± 0.1**	–	–	**1.8 ± 1.0**

[a] The availability of legumes also include other small scale crops (see main text). Leg = legumes. Raps = rapeseed. Ley refers to hay and pastures CC = common crane; BG = barnacle goose; GG = greylag goose; WS = whooper swan; BN = bean goose. In bold, species with > 10 % damage reports in the region. See Appendix D in Supporting information for details.

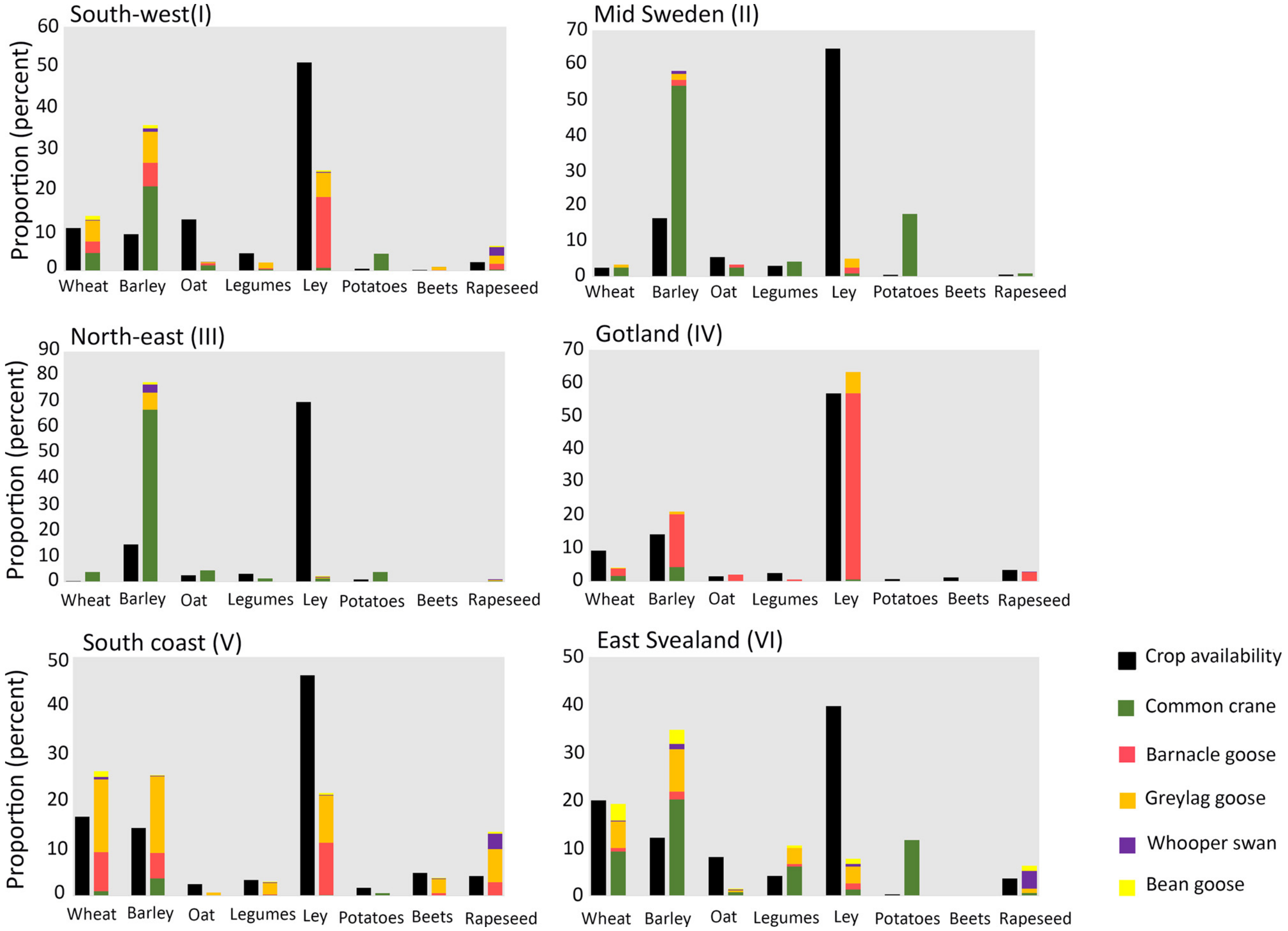

Fig. 6. Proportion of crop availability (in black) and proportion of damage reports (in colour identifying five different species of large grazing birds), for eight different crop categories in six different regions with similar monthly patterns of crop damage in Sweden, from 2001 - 2014. "Ley" refers to hay and pastures.

(Madsen et al., 1999; Si et al., 2015), as well as land use consistency. Our results supported these expectations. Hence this opens up possibilities for predicting future patterns of crop damage within different regions, at least over a limited time-window. However, the introduction of new crop types (e.g. the use of maize is increasing in Sweden) or changes in distribution and composition of culprit species (Tombre et al., 2008; Nilsson, 2013; Fox and Madsen, 2017; Teitelbaum et al., 2016; Montràs-Janer et al., 2019) may change damage patterns in the future.

The degree of damage clearly varied between different crop types. Since our data is based on reports from farmers, our results are a mix of birds' preference and farmers' willingness to report and should be interpreted with some caution. For example, it is reasonable to assume that farmers may be more eager to report damage on costly cops (e.g. potato) than on cheaper crops (e.g. barley and ley) (Board of Agriculture, 2019). However, our results still provide some interesting species-wise crop selection patterns, which is also supported by earlier studies on crop preferences. For example, barley was damaged more than expected in relation to the crop availability by most of the species and in all regions. Nilsson et al. (2016) identified barley as a selected crop for common cranes to forage on. In contrast, other cereals like oat and wheat with similar market price than barley (Board of Agriculture, 2019), seemed to be in general less selected (Fig. 6) despite some exceptions (Table 1). Our study also supported earlier studies showing common crane and whooper swan selecting for potatoes and rapeseed respectively (Chisholm and Spray, 2002; Nilsson et al., 2016). Furthermore, the vast majority of damage caused by barnacle goose was on ley fields, but still leys appeared to be used in proportion to their availability. However, we were using quite a broad definition of ley (hay and pastures) and there could be a difference in selection if categorized by different types and agricultural practices (Vickery and Gill, 1999).

4.1. Conclusion and management implications

Our study introduced a methodology to describe spatio-temporal patterns of damage caused by LGBs. It also highlighted the importance of collecting species-specific damage data, to learn more about common and divergent species patterns across different spatio-temporal scales. This type of information and analysis can be used not only to guide management in terms of determining the appropriate scale of management units (e.g. areas with similar conditions), but also to adapt damage mitigation strategies to temporal and spatial-specific conditions. A common tool used to prevent crop damage, often in combination with scaring (i.e. birds are displaced from sensitive crops) is to introduce 'diversionary fields' (i.e. birds are attracted to sacrificial crops) (Fox et al., 2017). Our study suggests that, for example, legumes can be an appropriate sacrificial crop to alleviate damage caused by common cranes, barnacle and greylag geese in region VI; or that barley seems to be an appropriate sacrificial crop for most species and regions as this was a highly damaged crop. At the same time, our results indicated when and where certain measures (such as scaring, compensation of yield loss and potentially culling) may be needed to optimize the allocation of resources and protect specific crops, and identify which LGB species to target. However, other factors apart from crop type also affect field preference and crop damage risk, such as distance between the field and roost sites (Baveco et al., 2011; Chudzińska et al., 2015), crop stage (Nilsson et al., 2016), field size (Jensen et al., 2017), use of fertilizers (Fox et al., 2017) and disturbances (e.g. traffic and scaring) (Rosin et al., 2012; Simonsen et al., 2016; Månsson, 2017). For example, the probability of cranes being present on fields depend not only on crop type but also crop stage, time since harvest and distance to roosting sites (Nilsson et al., 2016). Damage by greylag geese have been suggested to be linked to the availability of crops and their suitability covering specific demands across the annual cycle (Fox et al., 2017). And damage by whooper swans may be associated with large fields close to water (Chisholm and Spray, 2002). Hence, the knowledge about crop damage gained in the present study may be integrated with knowledge about specific characteristics of fields (Forsyth et al., 2000; Conover, 2002), landscape structure and species-specific foraging strategies (Chudzińska et al., 2015). Such an approach could provide predictions to be used for mitigation and crop damage prevention.

Management decisions to reduce crop damage are conducted at different spatial levels from field (farm) to regional, national and flyway level (Madsen and Williams, 2012; Månsson et al., 2015; Fox and Madsen, 2017) and require spatially and temporally explicit data on bird numbers and damage. Our study provides an example on how to analyze such data to inform future management at different scales and how certain preventive actions should be evaluated as spatio-temporal patterns of crop damage, that do not naturally follow administrative spatial units (e.g. counties or municipalities; Meisingset et al., 2018). The use of spatial units based directly on the observed patterns of damage without considering the administrative boundaries, would therefore likely increase not only the efficiency to mitigate crop damages, but also successfully design tailored management strategies for LGBs in general.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

FORMAS financial support grant no. 942-2015-1360 (JM), grant no. 215-2014-1425 (TP), grant no. 2018-00463 (LN) and FORMAS grant no. 2017-1064 (JK); Swedish EPA grant no. 13/361 (TP) and 16/71; NV-00695-17 (JM) and a grant of the 2017-2018 Belmont Forum and BiodivERsA joint call for research proposals, under the BiodivScen ERA-Net COFUND programme (FORMAS 2018-02440; TP). Mikael Åkesson, Henrik Andrén and two anonymous reviewers whose comments highly improved this manuscript. David Flumm for English proof review. Ana Villa, Faruk Djodjic and Elin Widén Nilsson for allowing the use of the gridded crop data 2001 – 2014 (www.smed.se).

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agee.2020.107001.

References

Ahti, T., Hämet-Ahti, L., Jalas, J., 1968. Vegetation zones and their sections in northwestern Europe. An. Botacini Fennici. 5 (3), 169–211.

Baveco, J.M., Kuipers, H., Nolet, B.A., 2011. A large-scale multi-species spatial depletion model for overwintering waterfowl. Ecol. Model. 222, 3773–3784. https://doi.org/10.1016/j.ecolmodel.2011.09.012.

Béchet, A., Giroux, J.F., Gauthier, G., Nichols, J.D., Hines, J.E., 2003. Spring hunting changes the regional movements of migrating greater snow geese. J. Appl. Ecol. 40, 553–564. https://doi.org/10.1046/j.1365-2664.2003.00812.x.

Board of Agriculture, 2019. Jordbruksverket. Swedish Board of Agriculture. www.jordbruksverket.se.

Chisholm, H., Spray, C., 2002. Habitat usage and field choice by Mute and Whooper Swans in the Tweed Valley, Scotland. Waterbirds 25, 177–182.

Chudzińska, M.E., van Beest, F.M., Madsen, J., Nabe-Nielsen, J., 2015. Using habitat selection theories to predict the spatiotemporal distribution of migratory birds during stopover - a case study of pink-footed geese *Anser brachyrhynchus*. Oikos 124, 851–860. https://doi.org/10.1111/oik.01881.

Conover, M.R., 2002. Resolving Human-Wildlife Conflicts. The Science of Wildlife Damage Management. CRC Press, Lewis Publishers.

Drent, R.H., Ebbinge, B.S., Weijand, B., 1978. Balancing the energy budgets of arctic breeding geese throughout the annual cycle: a progress report. Verh Orn Ges Bayern 23, 239–264.

Dunn, P.K., Smyth, G.K., 1996. Randomized quantile residuals. J. Comput. Graph. Stat. 5 (3), 236–244. https://doi.org/10.2307/1390802.

Ebbinge, B.S., 1991. The impact of hunting on mortality rates and spatial distribution of geese wintering in the Western Palearctic. Ardea 79, 197–209.

Forsyth, D.M., Parkes, J.P., Hickling, G.J., 2000. A case for multi-species management of sympatric herbivore pest impacts in the central Southern Alps, New Zealand. N. Z. J. Ecol. 24 (1), 97–103.

Fox, A.D., Abraham, K.F., 2017. Why geese benefit from the transition from natural vegetation to agriculture. Ambio 46, 188–197. https://doi.org/10.1007/s13280-016-0879-1.

Fox, A.D., Madsen, J., 2017. Threatened species to super-abundance: the unexpected international implications of successful goose conservation. Ambio 46, 179–187. https://doi.org/10.1007/s13280-016-0878-2.

Fox, A.D., Madsen, J., Boyd, H., Kuijken, E., Norriss, D.W., Tombre, I.M., Stroud, D.A., 2005. Effects of agricultural change and abundance, fitness components and distribution of two arctic-nesting goose populations. Glob. Change Biol. 11, 881–893. https://doi.org/10.1111/j.1365-2486.2005.00941.x.

Fox, A.D., Elmberg, J., Tombre, I.M., Hessel, R., 2017. Agriculture and herbivorous waterfowl: a review of the scientific basis for improved management. Biol. Rev. 92, 854–877. https://doi.org/10.1111/brv.12258.

Hake, M., Månsson, J., Wiberg, A., 2010. A working model for preventing crop damage caused by increasing goose populations in Sweden. Ornis Svec. 20, 225–233.

Jensen, G.H., Madsen, J., Johnson, F.A., Tamstorf, M.P., 2014. Snow conditions as an estimator of the breeding output in high-Arctic pink-footed geese *Anser brachyrhynchus*. Pol. Biol. 37, 1–14. https://doi.org/10.1007/s00300-013-1404-7.

Jensen, G.H., Pellissier, L., Tombre, I.M., Madsen, J., 2017. Landscape selection by migratory geese: Implications for hunting organisation. Wild. Biol. 17. https://doi.org/10.2981/wlb.00192.

Knape, J., Arlt, D., Barraquand, F., Berg, Å., Chevalier, M., Pärt, T., Ruete, A., Zmihorski, M., 2018. Sensitivity of binomial N-mixture models to overdispersion: the importance of assessing model fit. Methods Ecol. Evol. 9, 2102–2114. https://doi.org/10.1111/2041-210X.13062.

Kottek, M., Grieser, J., Beck, C., Rudolf, B., Rubel, F., 2006. World map of the Köppen-Geiger climate classification updated. Meteorologische Zeitschrift 15 (3), 259–263.

Kruckenberg, H., Borbach-Jaene, J., 2004. Do greylag geese (Anser anser) use traditional roosts? Site fidelity of colour-marked Nordic greylag geese during spring migration. J. Ornithol. 145 (2), 117–122. https://doi.org/10.1007/s10336-004-0021-1.

Madsen, J., Williams, J.H., 2012. International Species Management Plan for the Svalbard population of the pink-footed goose Anser brachyrhynchus. AEWA Technical Report, 48. African-Eurasian Waterbird Agreement, Bonn, Germany.

Madsen, J., Cracknell, G., Fox, A.D. (Eds.), 1999. Goose Populations of the Western Palearctic. A Review of Status and Distribution. Wetlands International Publ. No. 48, Wetlands International, Wageningen, The Netherlands, National Environmental Research Institute, Rønde, Denmark.

Madsen, J., Williams, J.H., Johnson, F.A., Tombre, I.M., Dereliev, S., Kuijken, E., 2017. Implementation of the first adaptive management plan for a European migratory waterbird population: the case of the Svalbard pink-footed goose *Anser brachyrhynchus*. Ambio. 46, S275–S289. https://doi.org/10.1007/s13280-016-0888-0.

Månsson, J., 2017. Lethal scaring - behavioral and short-term numerical response of greylag goose Anser anser. J. Crop Prot. 96, 258–264. https://doi.org/10.1016/j.cropro.2017.03.001.

Månsson, J., Levin, M., Larsson, I., Hake, M., Ängsteg, I., Wiberg, A., 2011. Besiktnng av viltskador på gröda – med inriktning på fredade fåglar. Viltskadecenter, Grimsö Forskningsstation.

Månsson, J., Risberg, P., Ängsteg, I., Hagbarth, U., 2015. Riktlinjer för förvaltning av stora fåglar i odlingslandskapet – åtgärder, ersättningar och bidrag. Rapport från Naturvårdsverket och Viltskadecenter, SLU 2015-3.

Meisingset, E.L., Loe, L.E., Brekkum, Ø., Bischof, R., Rivrud, I.M., Lande, U.S., Zimmermann, B., Veiberg, V., Mysterud, A., 2018. Spatial mismatch between management units and movement ecology of a partially migratory ungulate. J. Appl. Ecol. 55, 745–753. https://doi.org/10.1111/1365-2664.13003.

Montràs-Janer, T., Knape, J., Nilsson, L., Tombre, I., Pärt, T., Månsson, J., 2019. Relating national levels of crop damage to the abundance of large grazing birds: implications for management. J. Appl. Ecol. 00, 1–12. https://doi.org/10.1111/1365-2664.13457.

Nilsson, L., 2013. Censuses of autumn staging and wintering goose populations in Sweden 1977/1978–2011/2012. Ornis Svec. 23, 1–40.

Nilsson, L., Bunnefeld, N., Persson, J., Månsson, J., 2016. Large grazing birds and agriculture—predicting field use of common cranes and implications for crop damage prevention. Agric. Ecosyst. Environ. 219, 163–170. https://doi.org/10.1016/j.agee.2015.12.021.

Nilsson, L., Aronsson, M., Persson, J., Månsson, J., 2018. Drifting space use of common cranes—is there a mismatch between daytime behaviour and management? Ecol. Indic. 85, 556–562. https://doi.org/10.1016/j.ecolind.2017.11.007.

Nilsson, L., Bunnefeld, N., Persson, J., Žydelis, R., Månsson, J., 2019. Conservation success or increased crop damage risk? The Natura 2000 network for a thriving migratory and protected bird. Biol. Conserv. 236, 1–7. https://doi.org/10.1016/j.biocon.2019.05.006.

Ottosson, U., Ottvall, R., Elmberg, J., Green, M., Gustafsson, R., Haas, F., et al., 2012. Fåglarna i Sverige – antal och förekomst. Swedish Ornithological Society, Halmstad.

Owen, M., 1980. Wild Geese of the World. Batsford, London.

R Core Team, 2017. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Rosin, Z.M., Skórka, P., Wylegała, P., Krakowski, B., Tobolka, M., Myczko, Ł., Sparks, T.H., Tryjanowski, P., 2012. Landscape structure, human disturbance and crop management affect foraging ground selection by migrating geese. J. Ornithol. 153, 747–759. https://doi.org/10.1007/s10336-011-0791-1.

Shah, M., Coulson, S., 2018. Artportalen (Swedish Species Observation System). Version 92.131. ArtDatabanken. Occurrence dataset https://doi.org/10.15468/kllkyl accessed via GBIF.org on 2018-11-26. .

Si, Y., Xin, Q., de Boer, W.F., Gong, P., Ydenberg, R.C., Prins, H.H.T., 2015. Do Arctic breeding geese track or overtake a green wave during spring migration? Sci. Rep. 5, 8749. https://doi.org/10.1038/srep08749.

Simonsen, C.E., Madsen, J., Tombre, I.M., Nabe-Nielsen, J., 2016. Is it worthwhile scaring geese to alleviate damage to crops? - An experimental study. J. Appl. Ecol. 53, 916–924. https://doi.org/10.1111/1365-2664.12604.

Statistics Sweden, 2013. Jordbruksstatistisk årsbok 2013. Sveriges Officiella Statistik. Jordbruksveeket. Statistiska centralbyrån. www.scb.se.

Statistics Sweden, 2019. Statistika centralbyrån. Statistics Sweden. www.scb.se.

Suzuki, R., Shimodaira, H., 2004. An application of multiscale bootstrap resampling to hierarchical clustering of microarray data: how accurate are these clusters? The Fifteenth International Conference on Genome Informatics P034. https://www.jsbi.org/pdfs/journal1/GIW04/GIW04P034.pdf.

Suzuki, R., Shimodaira, H., 2006. Pvclust: an R package for assessing the uncertainty in hierarchical clustering. Bioinform 22 (12), 1540–1542. https://doi.org/10.1093/bioinformatics/btl117.

Teitelbaum, C.S., Converse, S.J., Fagan, W.F., Böhning-Gaese, K., O'Hara, R.B., Lacy, A.E., Mueller, T., 2016. Experience drives innovation of new migration patterns of whooping cranes in response to global change. Nat. Commun. 7, 12793. https://doi.org/10.1038/ncomms12793.

Tombre, I.M., Høgda, K.A., Madsen, J., Griffin, L.R., Kuijken, E., Shimmings, P., Rees, E., Verscheure, C., 2008. The onset of spring and timing of migration in two arctic nesting goose populations: the pink-footed goose Anser bachyrhynchus and the barnacle goose Branta leucopsis. J. Avian Biol. 39, 691–703. https://doi.org/10.1111/j.1600-048X.2008.04440.x.

Tombre, I.M., Eythórsson, E., Madsen, J., 2013. Towards a solution to the goose-agriculture conflict in North Norway, 1988–2012: the interplay between policy, stakeholder influence and goose population dynamics (HA El-Shemy, Ed.). PLoS One 8, e71912. https://doi.org/10.1371/journal.pone.0071912.

Van Eerden, M.R., Zijlstra, M., Van Roomen, M., Timmerman, A., 1996. The response of Anatidae to changes in agricultural practice: long-term shifts in the carrying capacity of wintering waterfowl. Gibier Faune Sauvage 13, 681–706.

Végvári, Z., Barta, Z., 2015. Roost site selection of the Common Crane in its largest European stop-over site. Ardea 103, 175–181. https://doi.org/10.5253/arde.v103i2.a6.

Vickery, J., Gill, J., 1999. Managing grassland for wild geese in Britain: a review. Biol. Conserv. 89 (1), 93–106. https://doi.org/10.1016/S0006-3207(98)00134-7.

Warren, S.M., Walsh, A.J., Merne, O.J., Wilson, H.J., Fox, A.D., 1992. Wintering Site Interchange Amongst Greenland White-Fronted Geese (Anser albifrons Flavirostris) Captured at Wexford Slobs, Ireland. Bird Study Vol. 39. pp. 186–194.

Wei, J., Xin, Q., Ji, L., Gong, P., Si, Y., 2019. A new satellite-based indicator to identify spatiotemporal foraging areas for herbivorous waterfowl. Ecol. Indic. 99. https://doi.org/10.1016/j.ecolind.2018.12.016.

Widén-Nilsson, E., Djodjic, F., Englund, D., Hellgren, S., Liljeberg, M., Olshammar, M., Olsson, H., Orback, C., Tengdelius-Brunell, J., 2016. Kartdata till PLC6 – Underlagsrapport till Pollution Load Compilation 6 rörande markanvändning, vattenförekomstområden, regionsindelning, jordbruksmarkens jordart, lutning och fosforhalt samt medelvärdesberäkningar. SMED Rapport Nr186 2016. https://admin.smed.se/app/uploads/2016/05/SMED-Rapport-186-2016_GIS_PLC6.pdf.

Wood, S.N., 2004. Stable and efficient multiple smoothing parameter estimation for generalized additive models. J. Am. Stat. Assoc. 99, 673–686. https://doi.org/10.1198/016214504000000980.

Wood, S.N., 2006. Generalised Additive Models: an Introduction With R. J. Stat. Softw. July 2006, Book Review 3 Vol. 16 Chapman$Hall/CRC, Florida, USA.