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RESEARCH ARTICLE

More grazing, more damage? Assessed yield loss on agricultural grassland relates nonlinearly to goose grazing pressure

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Abstract

1. In recent decades, conflict between geese and agriculture has increased. Management practices to limit this conflict include concentrating geese in protected areas, derogation shooting or population reduction. To justify such management, we need to understand their effects on goose-related damages, which requires an understanding of how yield loss is influenced by goose abundance and species interactions.
2. We combined data from monthly goose counts and GPS-tracked geese to estimate grazing pressures by barnacle, white-fronted and greylag geese on agricultural grassland in Fryslân, the Netherlands. Using linear mixed models, we related this to damages assessed by professional inspectors.
3. Our results show a positive nonlinear relationship between yield loss and barnacle goose grazing pressure, where assessed damage increases with a decelerating rate as grazing pressure increases. For white-fronted geese, we find a negative relationship, while for greylag geese both positive and negative relationships occur. For each species, the relationship is influenced by the abundance of the other two.
4. For barnacle geese, the relationship can be explained by selection of fields offering the best balance between food intake and energy expenditure, and by grass regrowth, with highest grazing pressures occurring over a longer time period. The results for the other species are likely due to spatial and temporal differences in foraging preferences compared to barnacle geese, where larger species avoid areas with highest damages.
5. *Synthesis and applications*. Our results suggest that decreasing herbivore abundance may not translate directly to decreased yield loss, and management tools such as population reduction or derogation shooting should be used with care.

Management aimed at concentrating geese in refuges could help to alleviate farmer–goose conflict, although further studies are required to determine if it would lead to damage reduction. We also find that not all species contribute equally to agricultural damage; care should be taken to ensure wildlife management targets the right species.

KEYWORDS
derogation shooting, farmer herbivore conflict, geese abundance, goose accommodation, goose management, grassland yield loss, grazing pressure, large grazing birds

1 | INTRODUCTION

Wildlife often comes into conflict with agriculture, as shrinkage of native habitat and high food quality on cultivated land lure herbivores onto agricultural fields (Fox & Abraham, 2017; Fox & Madsen, 2017; Watve et al., 2016), where the damage can be substantial (Bleier et al., 2012; Conover & Kania, 1995; Hofman-Kaminska & Kowalczyk, 2012; Koffijberg et al., 2017; Montràs-Janer et al., 2019; Nilsson et al., 2016; Schley et al., 2008). Management of such conflicts is rarely straightforward, as both conservation and economics need to be considered. It is especially complicated when the damaging species has a protected status, such as threatened Asian elephant (Tisdell & Zhu, 1998), reintroduced bison (Hofman-Kaminska & Kowalczyk, 2012) or large grazing bird species that were nearly extinct mere decades ago, some of which are now protected under the EU Birds Directive (Fox & Madsen, 2017; Nilsson et al., 2016).

In the last century, following protective measures, increased feeding opportunities in farmland and, more recently, perhaps climate change, goose, swan and crane populations have shown extensive population growth, leading to increasing conflict with agriculture across the northern hemisphere (Fox & Abraham, 2017; Fox & Madsen, 2017; Jensen et al., 2014; Mason et al., 2018; Nilsson et al., 2016). The challenge is to find a management approach which decreases conflict, while maintaining large grazing bird species in a favourable conservation status. On a flyway level, active population management can be practiced, at least for species for which hunting is allowed. This combines close monitoring of changes in population size with active population reduction, ensuring a favourable conservation status is maintained, while aiming to decrease damages (Madsen et al., 2012, 2017). On a local scale, *refuge areas* can be created, comprised of *nature reserves* and/or *accommodation areas* (designated agricultural land where farmers are provided compensation to prevent intentional disturbance), which can be combined with active and lethal scaring or derogation shooting on agricultural land outside the refuges (Cope et al., 2003; Fox et al., 2017; Kwak et al., 2008; Percival et al., 1997; Tombre et al., 2005; Vickery & Gill, 1999). Possible goals of such management include protecting sensitive crops, reducing conflict with farmers and simplifying compensation schemes.

These management practices aim to influence the number of large grazing birds in an area, yet it remains unclear to what extent changes in abundance result in changes in yield loss, and therefore whether management is justified. While frequently studied for a variety of species, we still lack a basic understanding of the relationship between agricultural damage and herbivore abundance, which is complicated by external factors influencing both agricultural yields and wildlife distribution and behaviour (Bleier et al., 2012; Fox et al., 2017; Gill, 1992; Hofman-Kaminska & Kowalczyk, 2012; Lombardini et al., 2017; Merkens et al., 2012; Montràs-Janer et al., 2020; Naughton-Treves, 2008; Schley et al., 2008). A number of studies have found indications that this relationship may be nonlinear (Gill, 1992; Hörnberg, 2001; Montràs-Janer et al., 2019; Watve et al., 2016), which has important consequences for management of farmer–herbivore conflicts. For example, if the increase in agricultural damage slows down with increasing herbivore abundance, concentrating the same number of animals in part of the area will results in lower overall yield losses, while a reduction in population size would not lead to an equivalent decrease in yield loss.

For geese on agricultural grassland, several studies have related dropping densities or goose counts to differences in yield inside and outside exclosures, consistently finding greater losses with higher grazing pressure (Bedard et al., 1986; Bjerke et al., 2021; Groot Bruinderink, 1989; Olsen et al., 2017; Percival & Houston, 1992; Summers & Stansfield, 1991). There are also indications of a threshold in grazing pressure, below which yield remains unaffected (Bjerke et al., 2021; Olsen et al., 2017). Montràs-Janer et al. (2019) found possibly nonlinear relationships between nationwide assessed yield losses and the Swedish population size of barnacle geese and greylag geese, but these were not significant when correcting for trends over time. It thus remains unclear how inflicted damage relates to goose abundance.

The relationship may be influenced by the interaction between different herbivorous bird species. Larger species, having a larger bill size, prefer to graze on taller grass, while smaller species, such as barnacle geese, prefer a shorter sward (Baveco et al., 2011; Durant et al., 2004; Tombre et al., 2019). By reducing tall grass to a more suitable height, larger species could facilitate grazing by smaller species (Tombre et al., 2019) while they may be outcompeted when smaller species maintain a short sward (Durant et al., 2003). In this way, barnacle geese may cause relocation of pink-footed geese in Norway (Tombre et al., 2019), and force larger species out of accommodation areas in the Netherlands (Kleijn et al., 2008). Similarly, Bewick's swans avoided refuges with a short sward height and high numbers of geese and wigeon in the United Kingdom (Rees, 1990).

With this study we aim to give further insight into the relationship between yield loss and abundance of different goose species, and show the importance of interactions between species. We bring together damage assessment reports, goose count data and GPS-tracking data to examine how the interplay between barnacle *Branta Leucopsis*, white-fronted *Anser albifrons* and greylag *Anser anser* goose abundance relates to assessed grassland damages in the province of Fryslân, the Netherlands.

2 | MATERIALS AND METHODS

2.1 | Damage data

Data on assessed yield losses attributed to geese were provided by BIJ12 (Figure 1, left panels; BIJ12, 2022). We focused exclusively on grassland damage at first harvest (late April–early May), in the winters of 2016/17 (hereafter, 2017) and 2017/18 (hereafter, 2018). We only selected damage reports from the accommodation areas, since *automatic taxations* took place in these areas during our study period. This means that goose-related yield loss was assessed irrespective of whether it was reported by the farmer. This prevents a reporting bias and ensured small yield losses are present in the data, providing a wide range of assessed damages and allowing a more complete picture of the relationship between yield loss and grazing pressure. We used the assessed damage, expressed as kg dry matter ha^{-1}, for our analysis.

Taxations of yield loss in Fryslân are performed by professional inspectors, in two or more visits (methods summarized here, for details see: BIJ12, 2019). During the first visit it is assessed where grazing occurs and by which species, and how many subsequent visits will be needed to monitor the development of the damages. Shortly before first harvest (or when geese have left the area and grass in damaged sections reaches a height of >10 cm), the amount of yield loss is measured using a rising plate metre, by determining the difference in sward height (cm) between damaged and undamaged sections. Previous studies have shown that 1 cm of difference across 1 ha, as measured with the rising plate metres used by damage inspectors, corresponds to 150 kg of dry matter ha^{-1} (BIJ12, 2019). The inspectors therefore multiply the difference measured in cm with 150, to go to kg dry matter ha^{-1}, and subsequently with the number of hectares across which the difference was measured, to get the total yield loss in kg. For the final report, the average yield loss ha^{-1} is calculated across all damaged sections connected to a single farm, by adding up all measured difference in kg dry matter, and dividing this by the total damaged area in ha. This is then assigned to individual goose species based on their occurrence during earlier visits. Assigning species was done mainly to provide a rough idea of which species forage where, and may not accurately represent actual contribution to yield loss. For each report we therefore summed all assessed damages assigned to geese, irrespective of the individual species.

This assessment of grassland yield losses by geese, being performed on a large scale and without the benefit of exclosures, may be limited in how exact it reflects true goose-inflicted damage. We

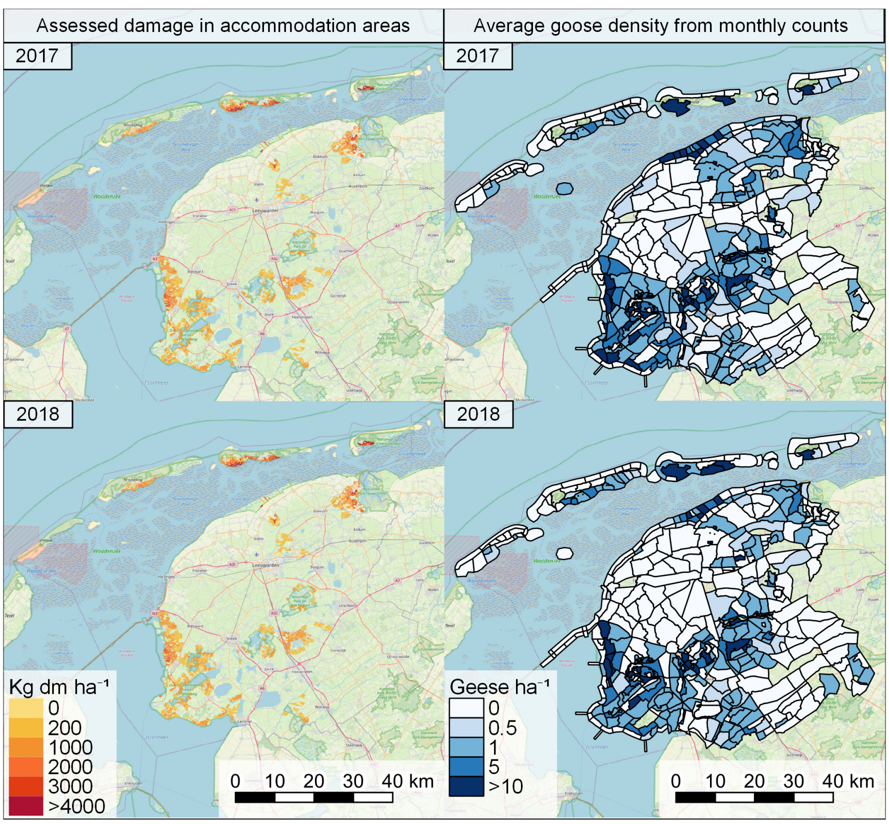

FIGURE 1 *Left*: Overview of assessed damage (in kg dry matter ha^{-1}) per damage report in accommodation areas in Fryslân from spring 2017 and 2018. *Right*: Goose density per count area, averaged across counts of barnacle, white-fronted and greylag geese from November to May, for 2016/17 and 2017/18.

therefore use the term 'assessed damage' in the remainder of the manuscript to refer to the reported yield losses in the damage reports.

2.2 | Count data

Data on goose counts were provided by the Dutch Centre for Field Ornithology (Sovon; Figure 1, right panels, Figure S1), which organizes monthly counts of water birds in the Netherlands from September to March (Hornman et al., 2020). In addition, there are counts in April and May focussed on relevant areas for brent and barnacle geese (Figure S2). Each province is divided into count areas (586 for Fryslân) counted by individual volunteers. We used data from the months November–May in the seasons 2017 and 2018 for the three most abundant species: barnacle, white-fronted and greylag goose (Figure 2). Volunteers submitted data either directly from the field (recording precise positions of goose flocks; 64% of the geese) or entered it afterwards (giving the sum per species, linked to the centre of the area; 23%). While most geese were actually counted, 13% was imputed based on previous counts, and the estimate linked to the centre of the count area (see Hornman et al., 2020). For a few count areas no data was available (45 in 2017 and 28 in 2018), but these are thought to contain few to no geese.

2.3 | GPS data

To bring together the spatially and temporally different damage reports and goose counts, we used data from individually tracked geese (described in next section). We used tracks from 57 barnacle, 73 white-fronted and 34 greylag geese (Table S1 for details; Buitendijk et al., 2022). For the months November–May, we selected hourly GPS points from 10 am to 3 pm (CET), thereby excluding data from roosts and roosting flights. For barnacle and white-fronted geese, we selected GPS points within the boundaries of Fryslân (52.82 < latitude < 53.52; 5.35 < longitude < 6.35). For greylag geese, we also used data from the neighbouring province Groningen (52.8 < latitude < 53.8; 5.3 < longitude < 7.3), as too few data points were available for Fryslân. These were resident geese, which have become more prevalent in the Netherlands than migrating greylag geese (Kleijn et al., 2012), and which likely behave similarly in the two provinces (see Section 4).

Ethical approval for placing GPS transmitters was provided by the CCD and DEC for the Netherlands (CCD protocol 20173788 and DEC protocol NIOO 13.14), by LAVES for Lower Saxony (AZ 33.19–42502–04-15/1956), and for Russia under the umbrella of a general permit to the Institute of Geography—RAS (to Peter Glazov).

2.4 | Estimated grazing pressure per damage report

We used the GPS data to estimate grazing pressure for the damage reports, by determining the probability P_r that in month *m*, a goose of species *s*, will visit a location of 1 hectare (ha), at a distance of *r* hectometres (hm) from where they were counted. For each individual, the distances between all hourly points within a month were calculated, rounded to hm. Taking all individuals of a species, we then determined the frequency of each distance *r* in each month. We divided these frequencies by $2\pi(r-0.5)$, to correct for the increase in surface area with increasing distance, and by the sum of all frequencies, to ensure the density of a goose across space remained 1. These corrected frequencies represent the chance P_{rsm} that, within a certain month, a goose will visit two different locations, based on the distance between them (Figure 3).

Subsequently, the number of geese ha^{-1} of species *s* that visited a field *i* from a damage report, in month *m* ($N_{i,s,m}$), could be estimated as:

$$N_{i,s,m} = \sum_{j=1}^{k} P_{r_{i,j},s,m} \times N_{j,s,m}, \quad (1)$$

where *k* is the number of count locations, *j* = 1, 2, 3, ... *k*. $P_{r_{i,j},s,m}$ is the probability of movement associated with distance $r_{i,j}$ between the

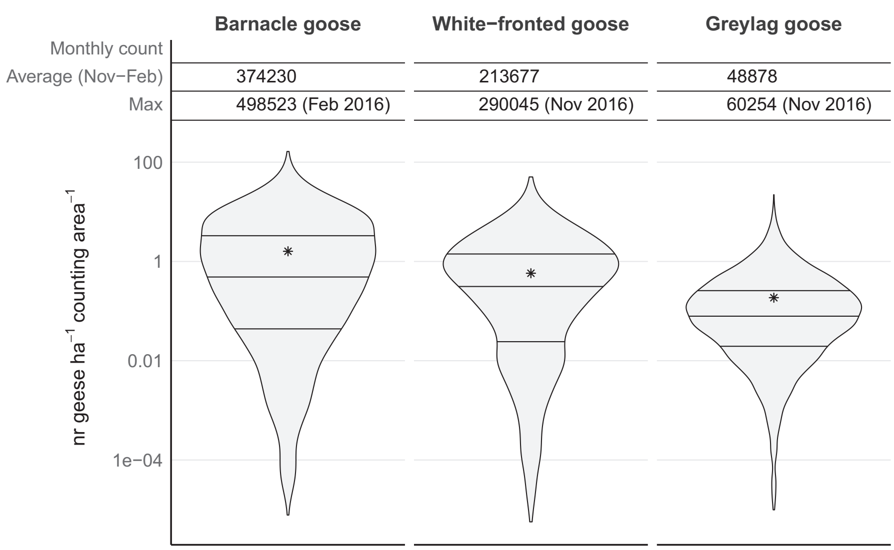

FIGURE 2 Violin plots showing goose densities, averaged per count-area across all months (November–May, 2016/17 and 2017/18). Star indicates the mean, lines the 25th, 50th and 75th percentile, and shape the spread of the data. Numbers at the top give average and highest monthly counts over the period with highest goose abundances (November–February). Note the logarithmic scale.

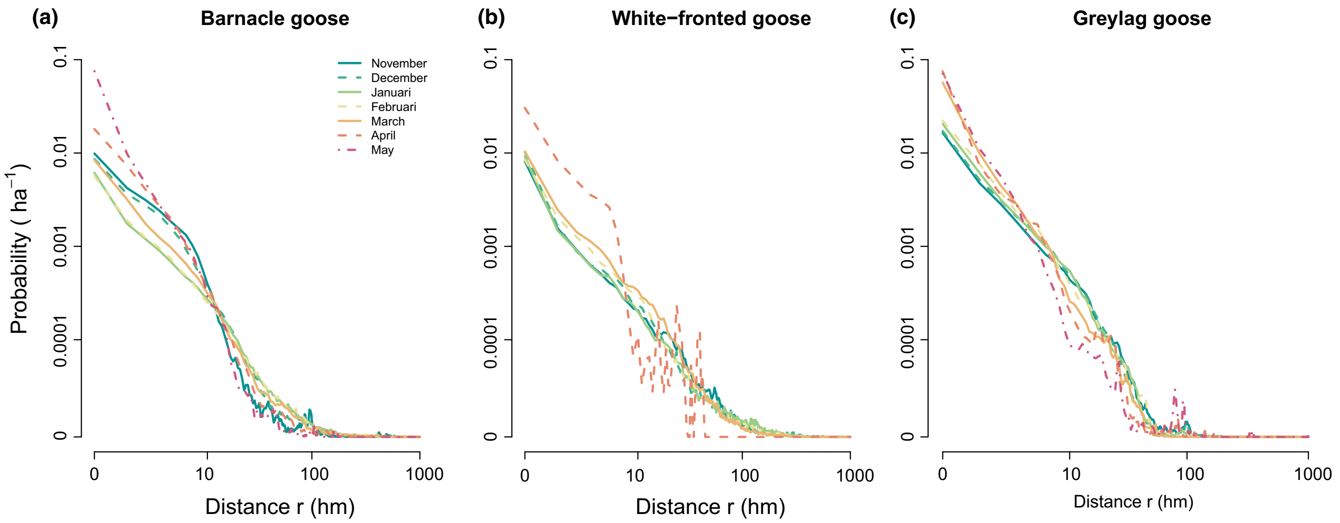

FIGURE 3 The probability that a goose will move between two locations of 1 ha each (P_r), set out against the distance between the locations (r), with combination of colour and pattern indicating the month. Note that there were only three (incomplete) tracks for white-fronted geese in April, and May is absent. Both scales are logarithmic

centre of a field (i) and a count location (j), for species s in month m. $N_{j,s,m}$ is the counted number of geese of species s at count location j during month m. To estimate the number of geese ha^{-1} for each report, we took the average of $N_{i,s,m}$ across all fields in a report, weighted by field size and averaged across all months. Finally, we multiplied these numbers with estimated daily grass intake (dry weight) per goose in winter, to account for the differences between species (barnacle: 97 g day^{-1}, white-fronted: 140 g day^{-1}, greylag: 170 g day^{-1}; Baveco et al., 2011), arriving at an average grazing pressure in g ha^{-1} day^{-1} for each species.

2.5 | Statistics

To determine the relationship between assessed damages and estimated grazing pressure, we fitted linear mixed effects models using the lmer function from R-package LME4 (Bates et al., 2015; R Core Team, 2020), with assessed damage (D) as response variable. We excluded damage reports with no damage (139 reports), and ln-transformed the data in order to obtain a normal distribution (Figure S3). This left us with a total of 1297 damage reports over 2 years. Goose grazing pressures (B, W and G for barnacle, white-fronted and greylag geese respectively) were also ln-transformed, to approximate a normal distribution of model residuals. We also added two-way interaction effects between the species. Although assessed damages did not differ significantly between 2017 and 2018 (Wilcoxon rank-sum test: $W = 217{,}897$, p-value $= 0.166$), we kept year as a random variable in the model (Y). This led to the following full model:

$$\ln(D) = \beta_1 \ln(B) + \beta_2 \ln(G) + \beta_3 \ln(W) + \beta_4 \ln(B)\ln(G) + \beta_5 \ln(B)\ln(W) + \beta_6 \ln(W)\ln(G) + bY + \epsilon. \quad (2)$$

In the development of the model we included a weighing factor, to weigh reports with well-connected fields and evenly spread damages more heavily. Each report represents a farm, where assessed damages is given as an average value, representing multiple fields. When these fields are near each other, it is likely that the reported average reflects that of the individual fields. However, when distances between fields are larger, the damage per field may deviate more from the reported average. This is also more likely to occur when damages are very local, and only a small percentage of the total area is affected. We corrected for this, by dividing the sum of the area of all fields, by the area of the convex hull surrounding them (Figure S4), giving a higher weight to reports with less space between fields. We multiplied this with the proportion of damaged area within a report, lowering the weight of reports with only local damage.

To obtain the best descriptive, yet most parsimonious model, we examined all possible combinations of fixed variables and calculated the corresponding weighted AIC values ($e^{\frac{(AIC_{min} - AIC_i)}{2}}$). Using the intercept and coefficients from this model, we plotted the relationship between assessed damage and grazing pressure for a focal species under varying grazing pressures for the other two species.

3 | RESULTS

The GPS data revealed that there is some variation between species and months in the relationship between the probability of visiting two locations and the distance between those locations (Figure 3, note the logarithmic scale), mainly visible in the intercept. Greylag geese generally have a higher intercept (Figure 3c), indicating a large probability of moving short distances. Both barnacle and greylag geese decrease their space use from March to May, illustrated by the increasing intercept and steepness of the graph (Figure 3a,c). White-fronted geese leave Fryslân in late March, with only three tagged individuals remaining in April and none in May.

Barnacle geese have the highest estimated grazing pressure per damage report, with a median of 196 g ha^{-1} day^{-1} (Figure 4).

For white-fronted and greylag geese this is much lower at 87 and 12.6 $g\,ha^{-1}\,day^{-1}$ respectively.

In total, we analysed 64 different models describing assessed damage as a function of goose densities. The best fitting, most parsimonious model includes grazing pressure of barnacle and white-fronted geese, and interaction effects between greylag geese and the other two species (Table 1):

$$\ln(D) = \beta_0 + \beta_1 \ln(B) + \beta_3 \ln(W) + \beta_4 \ln(B)\ln(G) + \beta_6 \ln(W)\ln(G) + bY + \epsilon. \quad (3)$$

Setting out grazing pressures of greylag geese against the other species, we find that the highest estimates for barnacle geese coincide with low estimates for greylag geese, and vice versa (Figure 5a), while white-fronted and greylag geese often occur together in higher densities (Figure 5b). Furthermore, we find that damage reports with highest damages are associated most frequently with low grazing pressures of both these species (Figure 5b), although there are a few reports with high assessed damages when both are abundant.

Rewriting the preferred model (Equation 3) gives us more insight into the relationship between damages and grazing pressure per species (Figure S5). For barnacle and white-fronted geese we find:

$$D = 632.7 \times B^{0.44-0.07\ln(G)} \times W^{-0.47+0.09\ln(G)}. \quad (4)$$

These species influence the slope of the relationship for the other species, with the effect depending on the presence of greylag geese. Greylag geese also affect the exponent of these relationships, with a negative effect on barnacle-, and a positive effect on white-fronted geese. Overall, we find that assessed damages are positively related to grazing pressure of barnacle geese (Figure 5c, Figure S6a), but

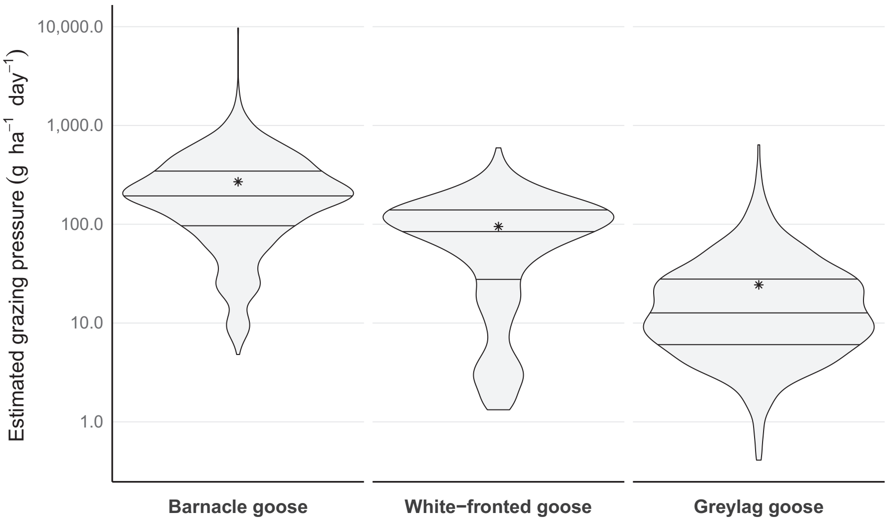

FIGURE 4 Violin plots showing estimated grazing pressures per damage report. Star indicates the mean, lines the 25th, 50th and 75th percentile, shape the spread of the data. Note the logarithmic scale on the *y*-axis.

TABLE 1 Overview of the AIC value, wAIC, ΔAIC, *k* (number of estimated parameters) and coefficient estimates (± SE) for the top five models.

	Top five models:				
	1	2	3	4	5
Model fit					
AIC	3045.43	3050.11	3054.37	3057.47	3059.04
wAIC	1	0.1	0.01	0.00	0.00
ΔAIC	0	4.68	8.94	12.04	13.61
k	4	5	5	4	6
Coefficient estimates (± SE)					
Intercept	6.45 ± 0.12	6.59 ± 0.23	6.53 ± 0.23	7.23 ± 0.16	6.61 ± 0.26
β_1 ln(*B*)	0.44 ± 0.03	0.42 ± 0.04	0.43 ± 0.05	0.26 ± 0.02	0.42 ± 0.05
β_2 ln(*G*)		−0.06 ± 0.08		−0.3 ± 0.05	−0.05 ± 0.08
β_3 ln(*W*)	−0.47 ± 0.04	−0.47 ± 0.04	−0.49 ± 0.07	−0.42 ± 0.03	−0.48 ± 0.07
β_4 ln(*B*):ln(*G*)	−0.07 ± 0.01	−0.06 ± 0.02	−0.07 ± 0.01		−0.06 ± 0.02
β_5 ln(*B*):ln(*W*)			0.004 ± 0.01		0.002 ± 0.01
$\beta 6$ ln(*W*):ln(*G*)	0.09 ± 0.01	0.09 ± 0.01	0.09 ± 0.01	0.07 ± 0.01	0.09 ± 0.01

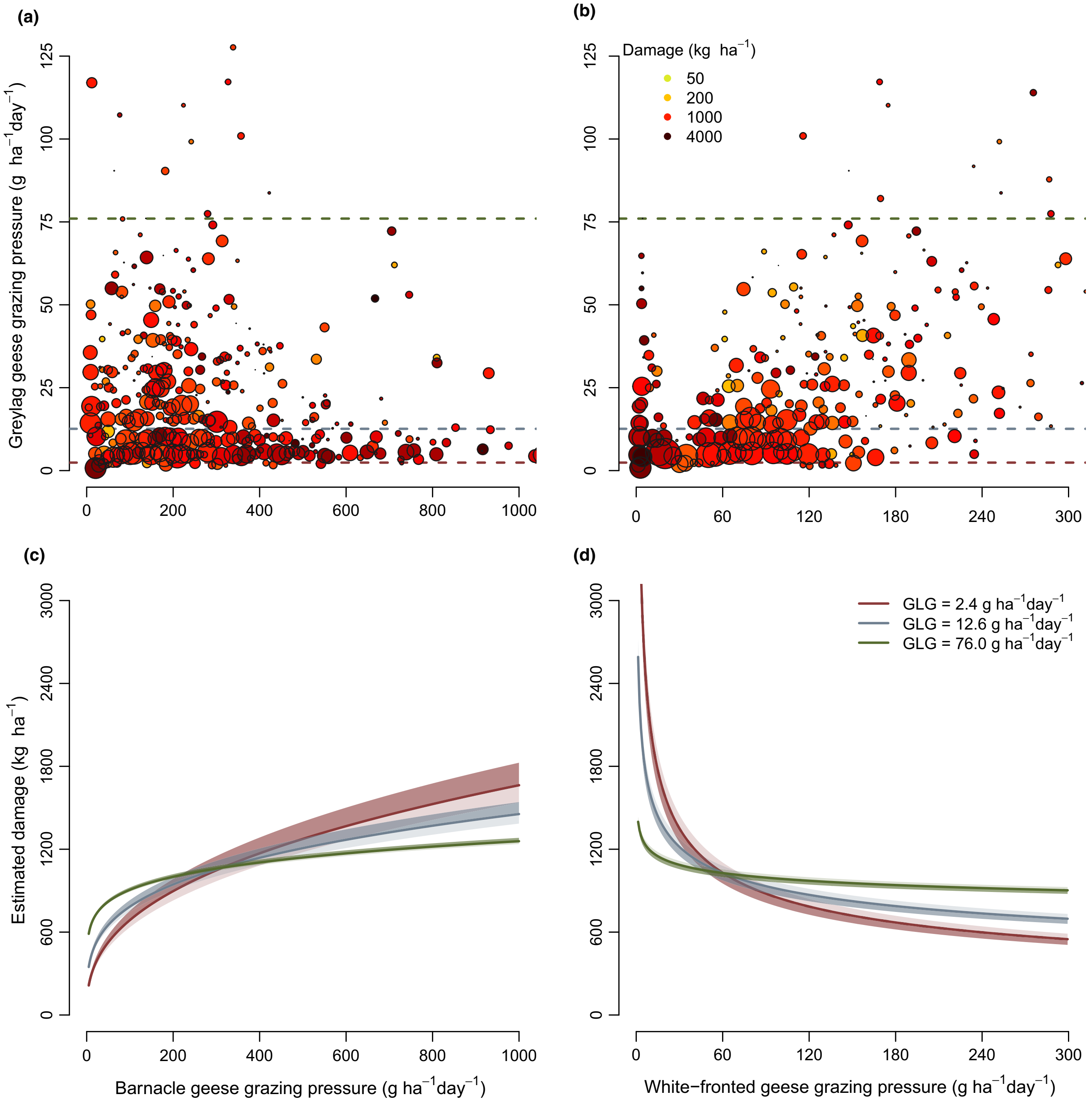

FIGURE 5 *Top*: Estimated grazing pressure for greylag geese in relation to barnacle geese (a) and white-fronted geese (b). Points represent clustered damage reports, colour indicates assessed damage, size represents the sum of the weights of the clustered reports. Horizontal lines indicate three potential grazing pressures for greylag geese, which are used in (c) and (d). *Bottom*: Three potential relationships between estimated damage and grazing pressure for barnacle (c) and white-fronted geese (d) at three grazing pressures of greylag geese (GLG). Shading indicates variation in slope when varying grazing pressure of the third species (white-fronted in c, barnacle in d) between the 0.4th (darker colour) and 0.6th (lighter colour) percentile of all estimates. To improve visualization, the graphs exclude the highest 2.5% of grazing pressures for barnacle and white-fronted geese, and the highest grazing pressures which together added up to 2% of the total weight for greylag geese. For damage estimates for all combinations of grazing pressures and the higher grazing pressures of greylag geese, see Figure S6.

negatively for white-fronted geese (Figure 5d, Figure S6b), while both show a decelerating rate.

For greylag geese we find the following relationship:

$$D = 632.7 \times B^{0.44} \times W^{-0.47} \times G^{-0.07 ln(B)+0.09 ln(W)}. \quad (5)$$

Their relationship to assessed damage depends on the other two species and can be positive (barnacle scarce, white-fronted abundant), negative (barnacle abundant, white-fronted scarce) or neutral (equal pressure from both species) (Figure 5c,d, Figure S6c).

4 | DISCUSSION

4.1 | Barnacle geese—A nonlinear relationship

The decelerating rate in the relationship between assessed agricultural damage and barnacle goose abundance corresponds with previous findings of (Montràs-Janer et al., 2019). Several explanations are possible for this type of relationship. Geese may prefer fields offering the best balance between food intake and energy expenditure, leading to lower energy requirements. For example, fields offering high-quality grass of a preferred sward height, allow fast intake rates and efficient digestion (Durant et al., 2004), while fields closer to roost sites limit energy-expensive foraging flights (Baveco et al., 2011; Si et al., 2011). Another explanation follows from the ability of grass to regrow after grazing. Previous studies suggest that geese maintain grass at a preferred height through cyclic grazing (Drent & van der Wal, 1997; Prins et al., 1980; Rowcliffe et al., 1995), stimulating continual regrowth (Bakker & Loonen, 1998; Hik & Jefferies, 1990; McNaughton, 1979). As grass recovers after each grazing event, grazing pressure accumulates, but damage does not, causing fields grazed over a longer period of time to experience less damage in relation to grazing pressures than those grazed less frequently. Additionally, there is a seasonal increase in the potential for grass (re)growth, which may coincide with an increase in grazing pressure. For example, Brent geese were found to concentrate in higher numbers as the growing season progresses, to be able to maintain a preferred grass height under increasing grass growth rates (Bos et al., 2004). We find a similar pattern for barnacle geese: in April and May, movements are limited (Figure 3), densities are higher (Figure S1) and a smaller area is used (Figures S2 and S8).

4.2 | Species differences lead to negative relationships

The negative interactions and relationships found in this study likely result from differences between the three goose species. Barnacle geese are able to maintain a short sward height, which is less profitable to larger-billed species (Baveco et al., 2011; Durant et al., 2003), while the larger species more readily exploit food sources such as harvest remains, beets and tubers (Nilsson & Persson, 2000), or grasses with a higher fibre content (Bakker et al., 2018), which are found mainly outside accommodation areas. (Koffijberg et al., 2017) found that across the Netherlands almost 75% of the barnacle goose population foraged inside refuge areas, compared to 55% and 50% for white-fronted and greylag geese respectively. This did not differ between the 10 years before management implementation and the 7 years following, indicating an inherent difference in space use rather than a response to management. The GPS data also show distinct areas used by only barnacle or only white-fronted geese (Figures S7 and S8). Furthermore, barnacle geese are rarely estimated in high abundances together with the other two species (Figure 5a). Thus, it seems likely that there are spatial differences in the preferred feeding sites of these species, at least partially attributable to competition among species. The accommodation areas appear to match best with barnacle geese, which is unsurprising, as these were selected based partially on barnacle goose presence.

There are also temporal differences between the species. White-fronted geese leave Fryslân in late March or early April (Figure S1, Figure S8), while most greylag geese retreat into marshes to breed (Bakker et al., 2018; Kleijn et al., 2012). In the same period, barnacle geese appear to concentrate in higher densities in specific areas. It appears that the overall higher grazing pressures found for barnacle geese compared to white-fronted geese follows mainly from additional foraging by barnacle geese in April and May (Figure S1). As spring grazing is thought to contribute more strongly to damage than winter grazing (Fox et al., 2017), it is likely that the larger species indeed contribute less to overall damages.

These differences explain why high assessed damages occur when the two larger species are both scarce; they reflect areas where barnacle geese maintain a short sward height, which are avoided by the larger species. The few situations where both barnacle and greylag geese are abundant and assessed damages are high, likely occur in May, when breeding greylag geese utilize fields grazed by barnacle geese to provide their goslings with short, nutritious grass. Excluding the damages attributed primarily to barnacle geese may lead to a positive relationship between assessed damage and abundance of white-fronted and greylag geese (Figure 5b), but this likely remains insubstantial compared to the effect of barnacle geese.

4.3 | Model limitations

Geese were divided across the landscape based solely on the distance to a count location, while in reality many factors can influence choice of foraging location (reviewed in Fox et al., 2017). It is possible to create a model of the distribution of geese in response to roads, buildings, woodlands and water bodies, as was done by Jensen et al. (2008). However, our study area consisted primarily of permanent hay-land, with similar farming practices and landscape characteristics, removing several factors for which selectivity can occur. Many of the remaining factors are regional, such as soil type and water table, which may affect grass quality and growth, site fidelity or distance to roosts, and these are to a large extent accounted for through the count data. Geese are more likely encountered in a region with positive attributes than in a less suitable location, thus we would expect more counts of geese on and near favoured fields. As we used a large number of counts, across both space and time, we expect higher estimates of grazing pressures for areas used preferentially. This allows factors influencing goose presence to play a role in our model, provided they affect a large area. This leaves a number of finer scaled factors that we did not account for, since these can vary between adjacent fields and even between years, making them very hard to quantify. These include grazing history within a year, availability of water on a field or incidental reseeding. We also assumed equal daily food intake across all months, while this may be higher when geese are fuelling for migration (Lameris et al., 2021; Olsen et al., 2017). As a consequence, we expect under- and over-estimates of the highest and lowest grazing pressures respectively. This probably does not change the basic shape of the relationships found here, allowing the results and conclusions to remain credible.

A similar over and underestimate may be present in the damage estimates. There are indications that damage assessments may occur too early (Latour et al., 2019), with some regrowth occurring on ungrazed plots, while yield loss can still increase on plots where grazing continues after assessment. In addition, it can be difficult to find ungrazed reference plots, which could also lead to under-estimates in assessed damages. Finally, there is a question about the extent to which assessed damage is inflicted by goose grazing. Factors like weather and grazing by other species (voles, wigeons) can also contribute to yield losses. While these limitations show that assessed damage may not correspond directly to grazing pressure, we expect that the general patterns still hold.

4.4 | Management implications

Assessed damage to managed grassland appears to increase with increasing grazing pressure from barnacle geese, but at a decreasing rate. Currently, management does not aim for large-scale reductions in population sizes, however, derogation shooting of barnacle geese to decrease yield losses is sometimes employed. This study shows that a reduction of the number of geese will not necessarily result in an equal reduction in yield loss. Utilizing accommodation areas to simplify compensation schemes may be a viable approach to goose management, but as the underlying mechanisms for the barnacle goose relationship remain unclear, we cannot be certain whether concentrating these geese in a smaller area will indeed lead to a decrease in overall assessed damage. Understanding why and when geese forage on a field, how crops compensate grazing and how this change over the course of a season and with changing climatological conditions, will likely contribute to further improvement of goose management. This requires detailed field studies, comparing yield in grazed and ungrazed plots with actual grazing pressure at frequent intervals throughout the season. Such data could be combined with distribution or depletion models, such as Baveco et al. (2017), to predict when and where yield loss is likely to occur.

We also find that in the accommodation areas in Fryslân, white-fronted and greylag geese contribute significantly less to assessed grassland damages compared to barnacle geese. Instead, these geese seem to avoid areas grazed most intensely by barnacle geese and are no longer present in spring, when the fields are most sensitive to damage. At the same time, it appears that a larger portion of their population occurs outside of the accommodation areas (Koffijberg et al., 2017), a consequence of the method with which the accommodation areas have been selected. This could lead to a disproportionate effect of scaring and derogation shooting on the larger species, while these appear to contribute comparatively less to assessed agricultural damages. The ability of smaller goose species to monopolize grassland fields could acerbate this in situations with an intense scaring regime. To avoid this, accommodation areas should be expanded to cover preferred habitats of all goose species, and scaring efforts should be delayed until the start of spring, when a number of geese have already started migrating or breeding. The natural tendency of remaining barnacle geese to aggregate at this time of year can be utilized to assist scaring efforts, thus saving on associated costs.

To conclude, we believe that, while the details of our results may be specific to our study area, they do show the importance of a multiple-species approach in any system where multiple wild herbivore species interact with agriculture. Furthermore, the possibility of a nonlinear relationship between agricultural damages and herbivore grazing pressure should be taken into account in the development of international species management plans, especially when considering population reduction, derogation shooting or concentration of herbivores as an approach to managing farmer–herbivore conflicts.

AUTHOR CONTRIBUTIONS

Nelleke Buitendijk, Monique de Jager and Bart Nolet conceived ideas and designed methodology; Bart Nolet, Andrea Kölzsch and Helmut Kruckenberg obtained funding; Nelleke Buitendijk, Menno Hornman, Helmut Kruckenberg, Andrea Kölzsch and Sander Moonen collected the data; Nelleke Buitendijk and Monique de Jager processed the data. Monique de Jager analysed the data; Nelleke Buitendijk led writing of the manuscript. All authors contributed to drafts and gave final approval for publication.

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Statement on inclusion: Local scientists conducted the study, in cooperation with scientist from neighbouring countries. Data was provided by national institutions. Members of these institutions were also actively involved in study design and execution. Where relevant, literature published by scientists from the region was cited, including relevant work in the local language.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Damage reports from BIJ12 are archived on DataverseNL. As it contains data on individual farms, only the metadata is directly available, access to the data itself can be requested through DataverseNL, https://doi.org/10.34894/MUAMQP (BIJ12, 2022).

Count data are archived by Sovon, and available upon request. The volunteers who contributed to the monthly goose counts collectively own these data, and since it contains detailed locations of wintering geese, it will not be made publicly available. Contact details: menno.hornman@sovon.nl, Dutch Centre For Field Ornithology (Sovon), Toernooiveld 1, 6525 ED Nijmegen, Netherlands.

The GPS tracks are available through Movebank (www.movebank.org) in the study 'GPS data from: More grazing, more damage? Assessed yield loss on agricultural grassland relates non-linearly to goose grazing pressure', published in the Movebank Data Repository https://doi.org/10.5441/001/1.fk899541 (Buitendijk et al., 2022).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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