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Research article

More management, less damage? With increasing population size, economic costs of managing geese to minimize yield losses may outweigh benefits

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ABSTRACT

Conflicts between farmers and geese are intensifying; yet, it remains unclear how interactions between goose population size and management regimes affect yield loss and economic costs. We investigate the cost-effectiveness of accommodation and scaring areas in relation to barnacle goose (*Branta leucopsis*) population size. We use an existing individual-based model of barnacle geese foraging in nature, accommodation, and scaring areas in Friesland, the Netherlands, to study the most cost-effective management under varying population sizes (i.e., between 20 and 200% of the current size). Our study shows that population size non-linearly affects yield loss costs and total costs per goose. The most cost-effective management scenario for intermediate to large populations is to avoid scaring of geese. For small populations, intensive scaring resulted in minimized yield loss costs and total costs, but also substantially lower goose body mass. Our results strongly suggest that scaring becomes a less effective management measure as goose populations increase.

1. Introduction

Farmer-wildlife conflicts are becoming increasingly prevalent worldwide and represent an important challenge in the interaction between agriculture and nature conservation. As these conflicts arise due to competition for resources between farmers and wildlife, balancing agricultural needs and biodiversity conservation has become a complex matter (Redpath et al., 2013). Conflicts between farmers and wildlife are intensified even further by factors such as habitat fragmentation, climate change, and in some species, population recovery (Dickman, 2010). Understanding the underlying causes of farmer-wildlife conflicts is essential for devising effective and sustainable strategies that address the needs of both agricultural communities and wildlife conservation efforts.

After a severe decline, most populations of herbivorous waterfowl recuperated in Europe and North-America as a consequence of increased legislative protection measures, a shift from feeding on natural habitat to feeding on more profitable, intensively managed agricultural pastures, and for some species, a climate-change induced expansion of the breeding grounds (Fox and Abraham, 2017; Jensen et al., 2008; Mason et al., 2018; Jensen et al., 2014). For many goose species, this conservation success has resulted in the current conflict with agriculture, aviation, and nature management. Geese damage crops, collide with aircrafts, and can degrade habitats, particularly in their breeding area (Abraham et al., 2005; Bradbeer et al., 2017; Fox and Abraham, 2017). As a result, there is an increased call for management of goose populations to reduce these conflicts.

Various methods of reducing the impact of geese have been applied, such as land-use management (e.g. avoiding cultivation of attractive crops near airports), active population control, and decreasing

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attraction of agricultural land through scaring- and shooting practices (Cope et al., 2003; Fox et al., 2017; Percival et al., 1997; Tombre et al., 2005; Kwak, van der Jeugd, and Ebbinge, 2008; Vickery and Gill, 1999). These latter approaches are frequently combined with accommodation areas, defined as agricultural land, including grasslands, where geese are allowed to forage undisturbed and farmers are compensated for damage. The provision of additional refuge areas aims to encourage geese to avoid areas with active scaring, allowing protection of other areas (e.g. with sensitive crops), reducing farmer-goose conflicts, and simplifying compensation schemes.

A major problem with scaring as a management regime is that geese quickly habituate to stationary and predictable scaring devices (McKenzie and Shaw, 2017). While they do not appear to habituate to scaring by real humans in the field, this is labour-intensive and therefore expensive (McKenzie and Shaw, 2017). There are new techniques that are suggested and tested (Bomford and Obrien, 1990; Stevens et al., 2000; Steen et al., 2015; McKenzie and Shaw, 2017), but the cost of these novel techniques are similarly prohibitive (Stevens et al., 2000).

There is also debate about the benefits of scaring to manage goose damage. Scaring increases the energetic costs of geese significantly because it interrupts feeding and causes the geese to engage in energetically costly flying behaviour (Bechet et al., 2004; Jensen et al., 2016). Compensating the additionally spent energy requires additional foraging, which in turn may increase yield losses (i.e. the difference between yield without goose grazing and actual yield) and thus negatively affects farmers (Nolet et al., 2016). Indeed, research indicates that goose body mass, and likely reproduction, are affected by disturbance regimes (Mainguy et al., 2002; de Jager et al., 2023). Additionally, when disturbance rates are high, geese may leave the area altogether and move to neighbouring regions (Bauer et al., 2018). Thus, scaring can have negative consequences for farmers, their neighbours, and the geese themselves (Vickery and Summers, 1992; Jensen et al., 2008). Overall, the value of scaring geese as a management tool is uncertain and in need of evaluation, in particular whether the economic benefits actually outweigh the costs.

Given these uncertainties, it remains unknown how farmer-goose conflicts will develop in terms of yield loss, goose condition, and population survival (Fox and Madsen, 2017). Scaring by shooting might ultimately reduce population size, and in huntable species, population reduction might aim to decrease damage to agricultural fields and (tundra) ecosystems, while employing close monitoring to ensure a favourable conservation status is maintained (Madsen et al. 2012, 2017). However, how a reduction in population size would impact the economic costs, or the health of the population, is poorly understood. Additionally, it remains uncertain whether increasing or decreasing goose population size results in an equal change in agricultural damage; such a relation may in fact be non-linear (Hörnberg, 2001; Montras-Janer et al., 2019; Buitendijk et al., 2022). To direct management in alleviating the farmer-goose conflict, we need to understand the relationship between goose numbers and damage, and especially its interplay with best management regimes.

In the province of Friesland, the Netherlands, a management regime is used that combines provision of goose refuge in accommodation areas, with scaring on the remaining pastures. Every year, damage appraisals are performed to determine the compensation payments to farmers. In accommodation area, which takes up approximately 10% of the total agricultural grassland area, this is performed on all fields, regardless of whether the damage has been reported by the farmer (automatic taxation, or goose independent appraisal (GIA)). In the scaring area, only those fields reported as being damaged by geese are appraised. Barnacle goose (*Branta leucopsis*) is the main goose species causing agricultural damage, probably because it is able to graze the grass shorter than the other goose species (Durant et al., 2003; Buitendijk et al., 2022). Using an individual-based model of barnacle geese foraging on agricultural grasslands in Friesland, de Jager et al. (2023) showed that the most cost-effective scenario depends on the associated costs of compensation, appraisal and scaring. With the current barnacle goose population size of approximately 500,000 individuals, the most cost-effective method was, in most cases, to avoid all scaring, as the reduction in yield loss costs that would be gained from scaring activities would be outweighed by the scaring and appraisal costs.

Without any management, the barnacle goose population will likely increase, whereas heavy (derogation) shooting will probably lead to a smaller population size. In this paper, we therefore examine the effects of various population sizes of barnacle goose on yield reduction and total economic costs, while safeguarding goose survival, under different goose management scenarios in the province Friesland, the Netherlands. We used an existing individual-based model (de Jager et al., 2023), and modified it to simulate a range of barnacle goose population sizes. We assessed the effects of population size on yield reduction and expect a non-linear, positive relationship, where damage levels off with increasing population size (Montràs-Janer et al., 2019; Buitendijk et al., 2022). We therefore expect that the management scenario that minimizes total costs (assuming full compensation of yield loss) and yield loss costs is different for different barnacle goose population sizes.

2. Methods

We examined the effects of barnacle goose population size and goose management on yield loss costs and total costs, where total costs includes those due to compensation for yield reduction and those associated with appraisal of damages and scaring activities. We used an existing individual-based model (de Jager et al., 2023), which simulates flocks of 1000 barnacle geese foraging on grassland in nature, accommodation, and scaring areas in Friesland. Below follows a concise description of this spatially explicit individual-based model (IBM); a full account including equations is provided in supplements B and C of de Jager et al., (2023).

Goose movements were simulated per hour across 195 days (i.e., 4680 time steps), starting at sunrise of November 1st. Foraging and movement influences goose energy intake and expenditure. If daily energy intake exceeds expenditure, goose body mass increases; if intake is less than expenditure, body mass decreases. A flock dies when the average body mass of its geese falls below 1100 g (starting body mass = 1750 g). Foraging also reduces grass height at grazed patches. Each day the grass may grow, depending on temperature and solar radiation, following Monteith (1977).

During daylight hours (between sunrise and sunset), flocks forage, and move to a selected roost if maximum body mass is reached; if not, they continue foraging. During flight to a selected food patch, the flock may join one with other foraging geese, depending on the number of geese already present. After arriving at a food patch, flocks choose whether to forage there, or move again, depending on grass height (by its effect on intake rate). Additionally, flocks in scaring areas move if a disturbance occurs. Outside daylight hours, geese rest on a roost for at least 8 h; if a flock has a lower than expected mass and if sufficient moonlight is available, moonlight foraging occurs.

The original study (de Jager et al., 2023) was run with the current population size of barnacle geese in Friesland of approximately 500,000 individuals (Hornman et al., 2021). In the current study, we varied the population size, ranging from 100,000 to 1,000,000 barnacle geese, or 20–200% of the current population size. With each population size, we simulated 420 different management scenarios, differing in the percentage of agricultural grassland area assigned as accommodation area (A; Fig. S4 in De Jager et al., 2023) and scaring probability in scaring areas (P_S). Scaring probability is an hourly probability that a flock is scared off when foraging on a grassland patch in the scaring area. Each combination of management scenario and population size was run ten times. Per population size, we recorded yield loss costs and total costs: (i) under the *current management scenario* ($P_S = 0.1$; $A = 10\%$), (ii) in cases where there is *no management* ($P_S = 0$; $A = 0\%$), (iii) when using the scenario that minimized yield loss costs (hereafter "*minimum* *yield-loss scenario*"), and (iv) when using the scenario that minimized total costs (hereafter "*most cost-effective scenario*"). The minimum yield-loss and most cost-effective scenarios were selected from the 420 different scenario combinations simulated with our model.

Per hectare of agricultural grassland, yield loss was calculated from the difference in grass height between ungrazed grasslands and the focal patch. Following the workflow used in determining damage compensation by professional damage assessors, we multiplied the difference in grass height (in cm) with 150 (dry matter weight in kg of 1 cm grass across 1 ha) and €0.25 (monetary value of 1 kg dry grass; BIJ12, 2019) to obtain cost per ha. Total yield loss costs was obtained by summation of yield loss costs on all the agricultural grassland patches.

To calculate scaring costs, we recorded the number of scaring events that occurred per simulation (i.e. scaring effort). Scaring effort depends on the scaring probability and the frequency of occurrence of flocks foraging on regular agricultural grasslands. We calculated total damage for a range of scaring costs (€0 to €10 per scaring event). Given that appraisal costs were approximately €25 ha^{-1} in 2005/2006 and 2006/2007 (van der Zee et al., 2009), and average inflation until 2021 was c. 1.5% per year, appraisal costs were estimated to be €30 ha^{-1}. Two appraisal approaches were analysed: 'goose-independent' appraisal (GIA), where all patches in the accommodation area are appraised, regardless of whether these have been affected by geese, and 'goose-dependent' appraisal (GDA), where only those patches affected by geese are appraised. In both approaches, goose-dependent appraisal is used in the scaring area.

3. Results

Fewer geese survived in simulations with larger population sizes, especially in scenarios with high scaring probabilities and few accommodation patches (Fig. 1). Large populations with many deaths early on in the simulation would eventually result in little yield loss costs. As the death of flocks substantially affects grass height in our model simulations, we used only the management scenarios in which all flocks survived in determining the *minimum yield-loss* and *most cost-effective* scenarios (i.e. yellow areas in Fig. 1).

3.1. Current management scenario

For populations smaller than the current population size, the fraction of foraging time spent on agricultural grassland increased with population size (Fig. 2; Fig. S1A). As yield loss costs strongly correlated with the fraction of foraging time spent on agricultural grassland (Fig. S1B), population size thereby also affected yield loss costs. Average yield loss costs per ha in Friesland increased with barnacle goose population size (Fig. 3, top-left panel); this increase was not linear, as can be seen from the average yield loss costs per ha per goose, which was not constant but increased with a declining rate with population size (Fig. 3, bottom-left panel). In accommodation areas, average yield loss costs per ha increased with a declining rate with population size (Fig. 3, top-centre panel); here, the yield loss costs per goose first slightly increased with population size for small populations and then decreased more strongly with population size (Fig. 3, bottom-centre panel). In contrast, average yield loss costs per ha of scaring area increased exponentially with population size. Scaring effort increased with population size (Fig. 4, top row, yellow lines), as more flocks foraged on regular agricultural grassland. Due to scaring, geese required more foraging (Fig. 4, 2nd row, yellow lines), resulting in additional yield losses (Fig. 4, bottom row, yellow lines). The total costs per goose, including scaring and appraisal costs, were relatively high in small populations, due to the high costs involved in appraising all accommodation sites (Fig. 4, 3rd row, yellow lines). With increasing population size, total costs per goose decreased, until yield loss costs per goose combined with the costs of scaring outweighed the decreasing appraisal costs per goose. After this point, total costs per goose slightly increased with rising population size (Fig. 4, 3rd

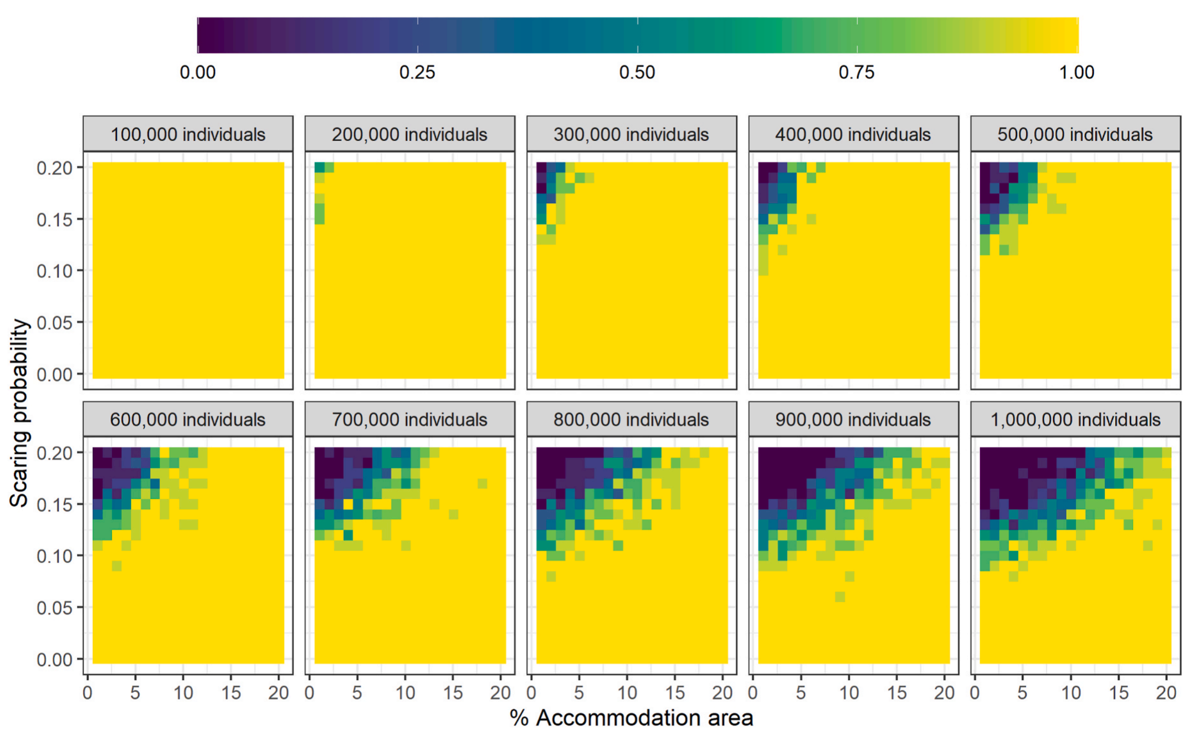

Fig. 1. The number of simulations per management scenario that resulted in the survival of all barnacle geese. Each scenario is a combination of the percentage of agricultural grassland area used as accommodation area (x-axes) and scaring probability in the remaining agricultural grassland area (y-axes). Each panel represents a different population size at the start of the simulation (given at the top of the panel); current population size is c. 500,000. Colours range from dark blue, indicating none out of ten simulations in which all geese survived, to yellow, indicating that all geese survived in all simulations for that specific management scenario and population size. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

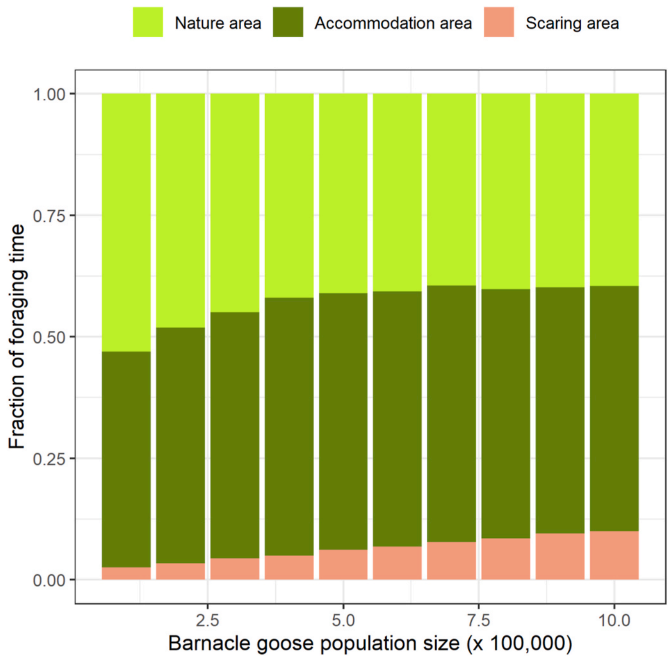

Fig. 2. The fraction of total foraging time spent in nature areas (light-green), accommodation areas (dark green), and scaring areas (salmon), per barnacle goose population size, under the current management regime. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

row, yellow lines).

3.2. No management

When no active management was applied ($P_S = 0$; $A = 0\%$), yield loss cost per goose was higher than that resulting from the current management scenario for population sizes smaller than 700,000 individuals (Fig. 4, bottom row). Beyond 700,000 geese, no management resulted in lower yield loss costs per goose than current management, since foraging time per goose per day was generally lowest with no management (Fig 4, 2nd row). Without scaring, total costs per goose were substantially lower than those under the current management, regardless of barnacle goose population size (Fig. 4, 3rd row), though it was only the most cost-effective approach with a medium to large population size. Like yield loss costs per goose, total costs per goose increased nonlinearly with population size, with a declining rate of change (Fig. 4, 3rd row).

3.3. Minimum yield-loss scenario

Scenarios that minimized yield loss costs consisted of little accommodation area with high scaring probabilities for small barnacle goose populations, or large accommodation areas and low scaring probabilities for large goose populations (Fig. 5a). This shift in optimal management scenario with population size corresponded to a decrease in foraging time per goose per day with increasing population size (Fig. 4, 2nd row), and the lowest fraction of foraging time spent on agricultural grassland per population size (Fig. S1A), in comparison with the three other management scenarios. Logically, yield loss costs per goose per population size (Fig. 4, bottom row) was lowest when applying the minimum-yield-loss scenario. Yet, minimizing yield loss costs by no

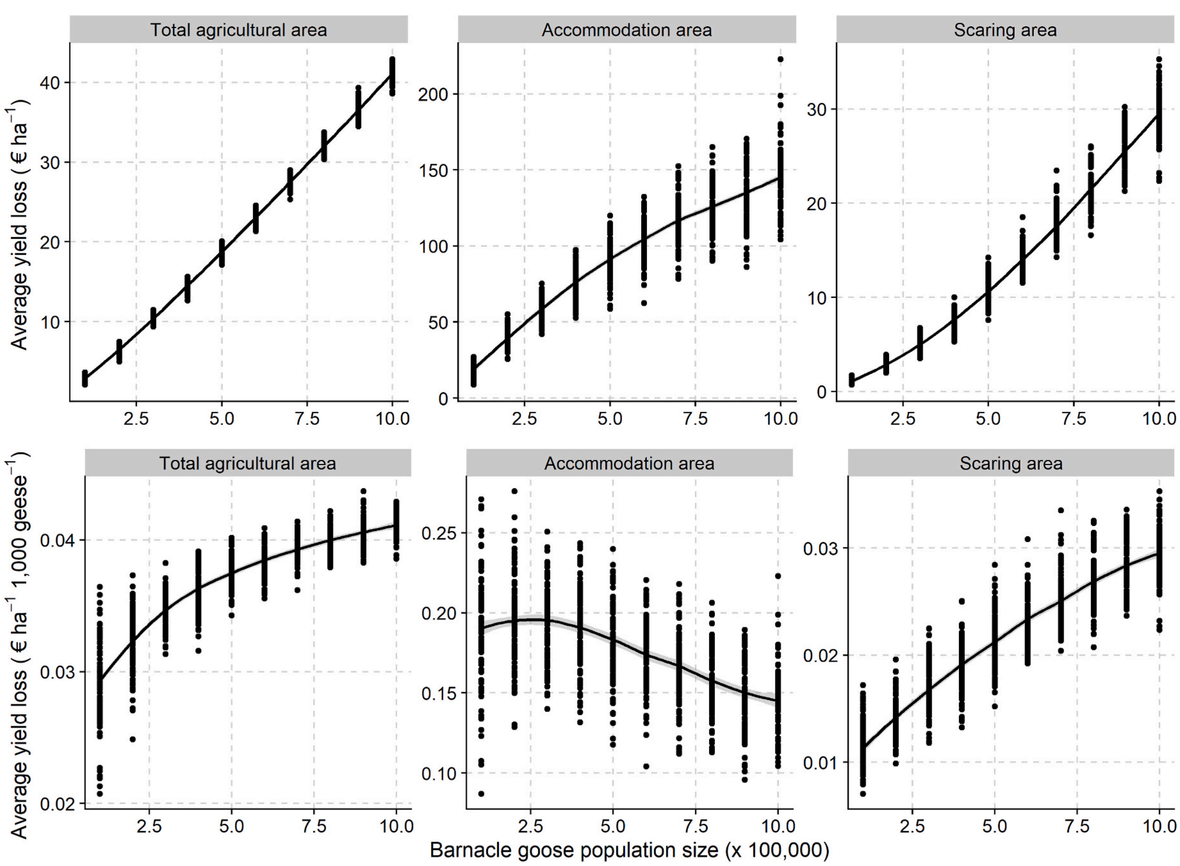

Fig. 3. Average yield loss (in €) per ha per area type (top panels) and average yield loss per ha per 1000 geese per area type (bottom panels), under the current management regime, in relation to barnacle goose population size. Total agricultural area represents the accommodation and scaring area combined.

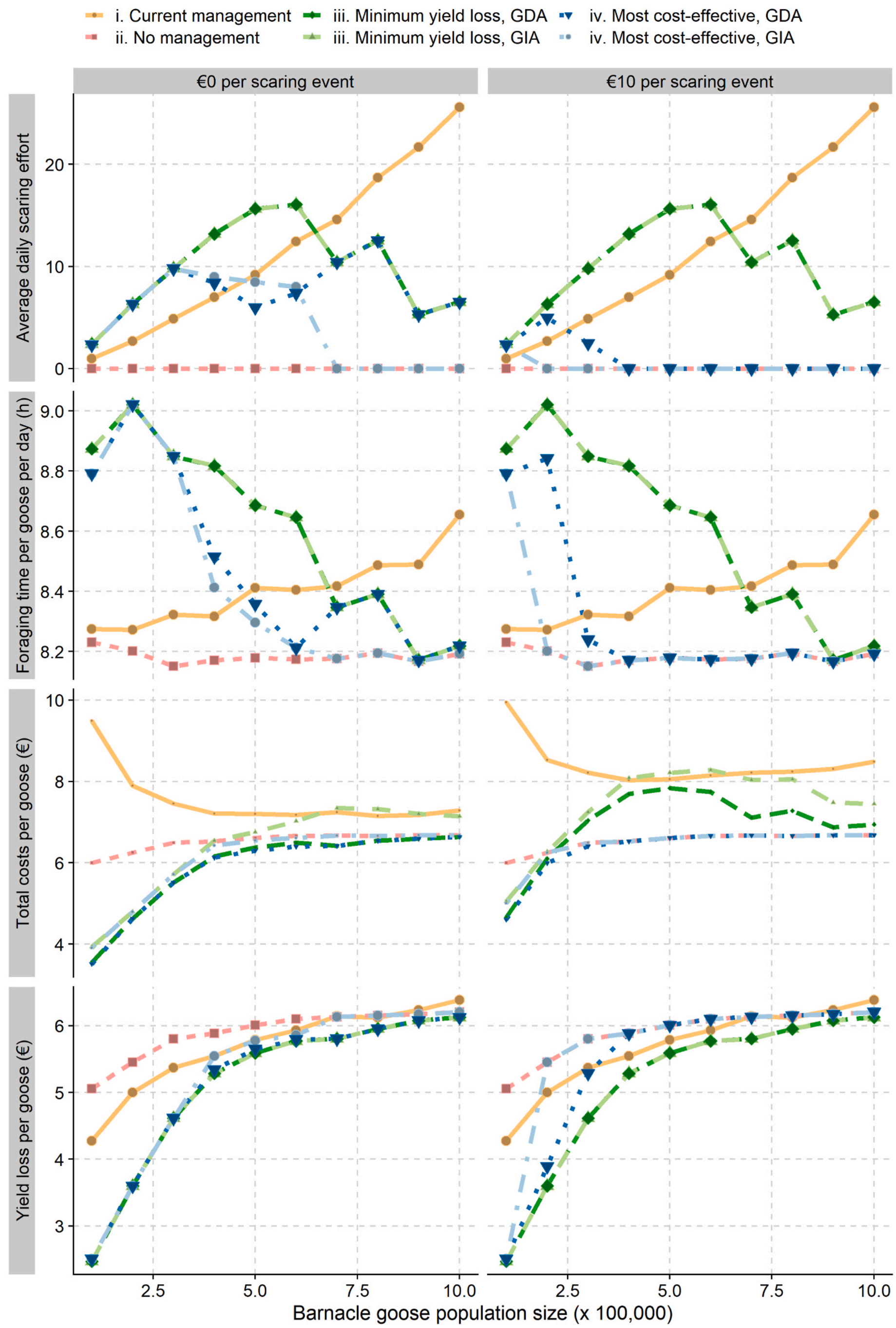

Fig. 4. Simulation results per management scenario (i-iv) and per barnacle goose population size (x-axes), without scaring costs (left panels) and with €10 per scaring event (right panels). From top to bottom, y-axes illustrate average daily scaring effort (i.e. mean number of scaring events per day), average foraging time per goose per day, total costs per goose (including yield loss, appraisal and scaring costs), and yield loss costs per goose. Colours indicate the different management scenarios and include (i - yellow) the current management scenario ($P_S = 0.1$; $A = 10\%$, goose-independent appraisal (GIA) in accommodation areas), (ii - red) no management ($P_S = 0$; $A = 0\%$), (iii - dark green) minimum yield-loss scenario under goose-dependent appraisal (GDA), (iii – light green) minimum yield-loss scenario under GIA, (iv – dark blue) most cost-effective scenario under GDA, and (iv – light blue) most cost-effective scenario under GIA. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

means minimizes total costs (Fig. 4, 3rd row); these scenarios were never the most cost-effective. However, at small population sizes, they were more cost-effective than current or no management (Fig. 4, 3rd row). Unsurprisingly, the 'goose-dependent' appraisal approach (with damage appraisals only occurring following goose attendance) resulted in lower total costs than the 'goose-independent' approach.

3.4. Most cost-effective scenario

The most cost-effective management scenario depended on population size, costs per scaring event, and appraisal approach (Fig. 6). Using the goose-independent appraisal approach, all most cost-effective scenarios had a small accommodation area size (Fig. 6, top panels), which kept the appraisal costs low. High scaring probabilities minimized management costs in small populations, while no scaring was the most cost-effective solution in intermediate to large populations, especially

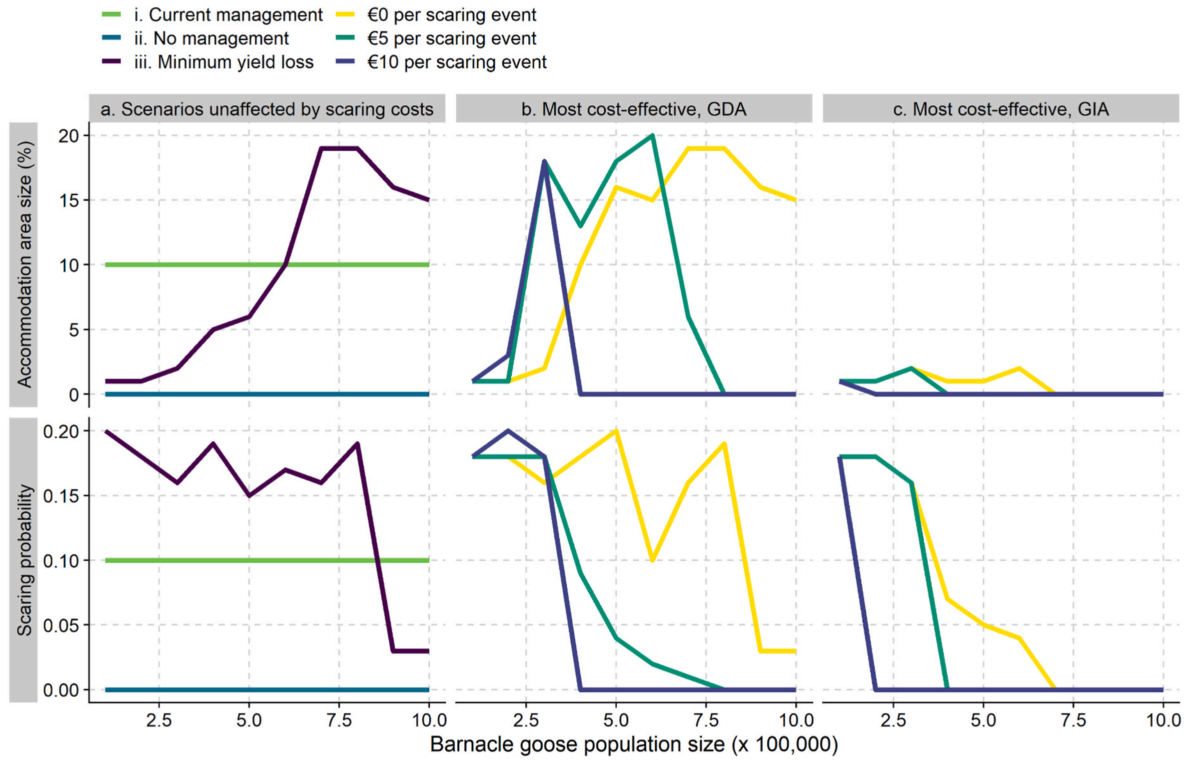

Fig. 5. Accommodation area size and scaring probability that were used in the management scenarios. (a) Shows the scenarios that were unaffected by scaring costs (i. current management scenario ($A = 10\%$, $P_S = 0.1$, green line), ii. no management scenario ($A = 0\%$, $P_S = 0$, dark blue line), and iii. minimum yield loss scenarios (goose-dependent and goose independent appraisal provide equal results, purple line)). (b) and (c) show the most cost-effective scenarios with goose-dependent (GDA) and goose-independent appraisal (GIA), respectively, with scaring costs of €0 (yellow line), €5 (turquoise line), and €10 per scaring event (dark blue line). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

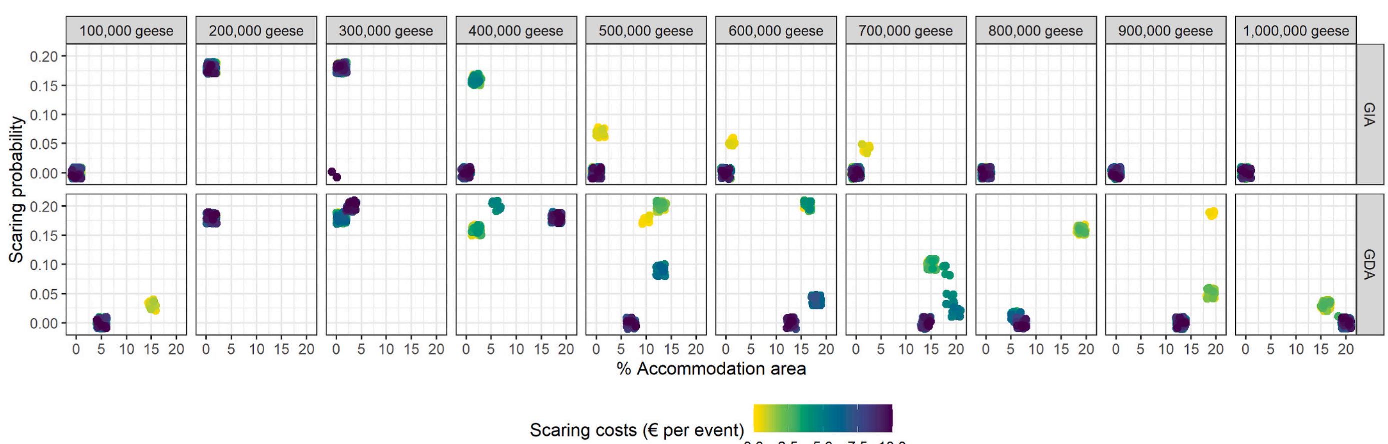

Fig. 6. Most cost-effective management scenarios as a function of barnacle goose population size (columns) and scaring cost (colours). Top panels show the most cost-effective scenarios using goose-independent appraisal, while bottom panels correspond to the most cost-effective scenarios under goose-dependent appraisal. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

when combined with intermediate to high costs per scaring event (Fig. 5, bottom panels). Using the ‘goose-dependent’ appraisal approach, accommodation area size of the most cost-effective scenarios was small for small populations, but large for intermediate to large populations (Fig. S1A). As with the ‘goose-independent’ approach, scaring probabilities were high for small populations, and decreased with population size, though at a much lower rate, and depending more strongly on the cost per scaring event (Fig. 6, bottom panels).

The most cost-effective scenario using the ‘goose-independent’ appraisal approach (Fig. 5c) resulted in low yield loss costs per goose for small populations, equal to that of the minimum yield-loss scenario, but increased faster with rising population size, until it joined the no management yield loss costs-line in Fig. 4. This corresponds with no management being the most cost-effective scenario for larger barnacle goose populations. Under the ‘goose-dependent’ approach, the most cost-effective scenario (Fig. 5b) also resulted in minimized yield loss costs when simulating small populations, but yield loss costs increased less steeply with population size than under the ‘goose-independent’ appraisal approach. As intended, the most cost-effective scenario resulted in the lowest total costs per goose per population size, with the costs being minimized when the ‘goose-dependent’ appraisal approach was used.

4. Discussion

Individual-based models (IBMs) simulate the behaviours and interactions of individual organisms within a population, and thereby allow for a relatively comprehensive and realistic understanding of emergent ecological processes. By considering the unique behaviours and spatial movements of individuals, IBMs enable us to explore emergent spatial patterns and their impacts on human-wildlife conflicts. In our case, simulations of goose movements under different management scenarios and goose population sizes result in different barnacle goose spatial distributions, which subsequently affect yield loss, appraisal costs, and scaring activity.

Our model suggests that yield loss costs per barnacle goose increase non-linearly with population size because resources are limited in nature areas and, consequently, a larger fraction of the goose population needs to forage on agricultural grasslands rather than in nature areas when population size increases (Fig. 2; Fig. S1A). The fraction of foraging time spent on agricultural grassland increases with population size in all scenarios (Fig. S1A). A possible explanation is that geese initially use the natural habitats and move to agricultural land when these habitats become insufficient. This preference for natural habitats is unlikely to be due to a higher scaring risk on agricultural land, since we find the same pattern in the no-management scenario, where no scaring occurs. A more likely explanation is that the roost-sites are surrounded by natural habitat. Since these areas are closer to the roost-sites, they are exploited first, before geese increasingly spill over to the agricultural land as population size increases.

The observed relation between population size and fraction of time spent on agricultural land instead of in nature areas agrees with the trend observed in monthly count data (Sovon, 2016–2019, Hornman et al., 2021; Fig. S2), that - although arising from a seasonal pattern rather than a change in peak goose abundance - provides confidence that these trends are realistic.

In order to minimize total costs, it does not suffice to minimize yield loss costs; appraisal and scaring costs need to be considered as well to achieve the most cost-effective management scenario. Appraisal and scaring costs strongly depend on the distribution of geese across the different area types, which in turn is affected by population size through intraspecific competition, the location and intensity of scaring activities, and potentially the location of roost-sites. Our results corroborate our hypotheses: no management was the most cost-effective option for large barnacle goose population sizes. Scaring and appraisal costs rise with increasing population size, as more geese need to be scared off the agricultural grasslands, and there are more fields requiring damage appraisal. Moreover, a larger accommodation area would be needed to sustain a larger population. In contrast, for smaller population sizes, scaring, in combination with sufficient accommodation area, was the most cost-effective management scenario. Under the current management scenario, economic costs per goose in small populations are high due to the extensive appraisal costs, following the goose-independent appraisal.

Depending on population size and scaring costs, we observe a sudden shift from high scaring effort to no scaring in the most cost-effective management scenarios. With increasing population size, average goose body mass decreases through competition. Scaring – especially in combination with little accommodation area – further amplifies this decrease in body mass, and results in decreased flock-survival due to starvation. Hence, this would not be an ethical management option in large populations. Furthermore, a high scaring probability in large populations coincides with a high number of scaring events; scaring costs would become too great for such a scenario to be cost-effective. In small populations, the fraction of foraging time spent on agricultural grassland can effectively be reduced through scaring, which can redistribute flocks from scaring areas to nature and accommodation areas (Fig. S1B). However, such a high scaring intensity results in low goose body mass (Fig. S3); in real life, these geese would probably have adjusted their behaviour by becoming less responsive to disturbances combined with migration outside of the simulated area (Frid and Dill, 2002; Beale and Monaghan, 2004). Furthermore, high scaring intensity at low population sizes may not be viable in reality, as we did not account for the effort of finding geese on agricultural grasslands in the scaring area, the costs of which increase with area size.

When we examine the effect of barnacle goose population size on yield loss costs within accommodation areas, we find the same non-linear relation as Buitendijk et al. (2022; Fig. 3). Buitendijk et al. (2022) found that total yield loss at a field increased non-linearly with barnacle goose density, whereas yield loss per goose decreased with goose density. In contrast to this study and the effects we found in accommodation areas, yield loss costs in scaring areas show an opposing relation with population size: with increasing population size, yield loss costs in scaring areas increase, with a growing rate of change (Fig. 3). These results are the consequence of the relation between population size and goose pressure per area type (which determines yield loss; Fig. 2): with increasing population size, the population distribution expands from nature area to accommodation and scaring area.

Our model is per definition a simplification of reality, and may therefore lack essential features, such as perhaps changes in goose behaviour and grass quality over time. While barnacle geese are known to aggregate in large groups in nature areas before spring migration (Engelmoer et al., 2001), the model does not take this into account. This aggregation effect could be linked to limited intake rates at high grass heights or avoidance of tall grasses due to the perceived increased predation risk. While tall grass typically remains ungrazed by barnacle geese in real life, the instantaneous intake rate we used in our model, which is derived from Baveco et al. (2011) and based on empirical data from (Lang and Black, 2001; Durant et al., 2003; van der Graaf et al., 2006), does not show a substantial decline with grass height, likely because measurements on grass heights above 15 cm are generally missing (but see Heuermann et al., 2011). Hence, modelled geese are not forced to aggregate on fewer grasslands that have short grass height.

In addition, the model may overestimate the attractiveness of the natural areas, especially during winter. We did not model any seasonal differences in grass quality. The energetic contents of grass differ between natural and agricultural grasslands in the model, but not over time, while grass is known to be of higher quality during spring than in winter, especially in the nature areas (Prins and Ydenberg, 1985). Also, there may be differences in search rates between natural and agricultural areas that we did not consider, which could lead to lower instantaneous intake rates in nature areas due to a higher variation in plant species and thus in increased search time (Prop and Deerenberg, 1991). Geese on agricultural pastures take more (presumably digestive) pauses, as their intake rate is apparently not limited by the handling rate, but by digestion rate (Dokter et al., 2018). We also did not include any side effects of geese foraging on grasslands, such as trampling, puddle formation, and faeces, since studies have been unable to show such effects (Fox et al., 2017). Another limitation of the model used in this study is that it disregards potentially important ecological factors, like interactions with other species or landscape features associated with predation risk. Furthermore, while it is known that grass height impacts grass growth (Buitendijk and Nolet, 2023), we did not model differences in grass growth between patches as a consequence of differences in grass height. Future additions to the model may elucidate how these model simplifications have affected our results.

Conforming to our results, we can provide several management recommendations. Allocation of accommodation area, scaring intensity in the other agricultural areas, and barnacle goose population size have interactive effects on yield loss costs and total economic costs. At small population sizes, high scaring intensity combined with a small accommodation area results in minimized total costs, though this may negatively impact goose well-being and survival or shift the problem to a neighbouring region. At intermediate to large population sizes, no scaring should occur, as none of the active management scenarios will result in lower total costs compared to the no management scenario. Of course, whether cost reduction is the best basis for management is debatable, as it is of importance to know who is paying for the damage (farmers vs. government); one might argue that higher costs are acceptable if individual farmers suffer less. For example, 'goose-dependent' appraisal does incur fewer costs than 'goose-independent' appraisal but requires more administrative work that needs to be performed by the farmers. Future research should therefore consider not only the economic costs and benefits, but include also the social factors of farmer-goose conflict in a human-wildlife coexistence framework in order to adequately account for all relevant stakeholders (Dickman, 2010; Mansson et al., 2023).

5. Conclusions

Our model results suggest that yield loss costs per goose relate non-linearly to barnacle goose population size, with geese in small populations doing the least damage, both per individual and as a whole. Yet, under the current management regime, total costs per goose are highest in these small populations, due to the high costs of appraisal in accommodation area. While intensive scaring, in combination with little accommodation area, decreases yield loss costs and total costs when dealing with small barnacle goose populations (but also decreases goose mass and survival), scaring of geese should be ceased with increasing population sizes. Geese in large populations are no longer able to fulfil their energetic needs in nature and accommodation areas alone, as these become saturated with increasing population size. Hence, many flocks will forage in the scaring area. Scaring large numbers of flocks requires great effort and associated costs. Furthermore, flocks are more likely to return to the scaring area when other grasslands are being depleted. Scaring in large populations thus will not relocate geese to nature and accommodation areas as intended, but rather increases their foraging time on agricultural lands due to higher energetic costs, or reduce survival if energy requirements cannot be met. Accordingly, the costs associated with scaring increase and its effectiveness decreases substantially. Alternatively, the geese may move to neighbouring regions, which only shifts the problem. Scaring can have many direct and indirect consequences, some counter-intuitively, which should be taken into account if management is to reach the desired goal.

CRediT authorship contribution statement

Monique de Jager: Conceptualization, Formal analysis, Methodology, Writing - original draft, Writing - review & editing. **Nelleke H. Buitendijk:** Data curation, Investigation, Validation, Writing - original draft, Writing - review & editing. **J.N.(Yannick) Wiegers:** Investigation, Writing - original draft, Writing - review & editing. **J. (Hans) M. Baveco:** Supervision, Writing - review & editing. **Bart A. Nolet:** Conceptualization, Funding acquisition, Supervision, Writing - original draft, Writing - review & editing.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.119949.

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