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RESEARCH ARTICLE

Limiting scaring activities reduces economic costs associated with foraging barnacle geese: Results from an individual-based model

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Abstract

1. With increasing numbers of large grazing birds on agricultural grassland, conflict with farmers is rising. One management approach to alleviate conflict allows foraging on dedicated agricultural land (accommodation areas) and nature reserves, combined with scaring on remaining agricultural land. Here, we examine the cost-effectiveness of these measures by studying the influence on barnacle goose distribution and associated economic damage.
2. We present an individual/agent-based model of barnacle geese (*Branta leucopsis*) foraging on grasslands in Friesland, the Netherlands. The model is parameterized using field observations and GPS-tracks and allows simulation of management scenarios, differing in scaring probability and accommodation area size, with different potential management costs.
3. Our model shows that, while yield loss decreases with higher scaring probabilities, costs of damage appraisal increase because geese graze on more fields. With small accommodation areas, achieving high scaring probabilities takes more effort and could result in goose population decline. Total management costs are lowest without scaring activity.
4. *Synthesis and applications*. Considering costs of active scaring and the need to maintain the barnacle goose population in a favourable conservation status, our model suggests that the most cost-effective scenario is to prevent disturbance of geese. A high scaring probability could be beneficial if applied in small areas, for example around sensitive crops or airfields. Scaring in large areas could result in costs outweighing benefits and a declining barnacle goose population.

KEYWORDS
agricultural grassland, economic yield damage, farmer-herbivore conflict, goose foraging, goose management, individual-based/agent-based modelling, refuge areas, scaring

Monique de Jager and Nelleke H. Buitendijk shared first author.

1 | INTRODUCTION

After introduction of hunting regulations in the 1950–1970s, many populations of herbivorous migrant birds in the northern hemisphere grew exponentially (Ebbinge, 1991; Fox & Madsen, 2017). Geese, swans and cranes shifted from foraging on natural wetlands to feeding on intensively managed agricultural land (Fox et al., 2017; Nilsson, 2017). To alleviate intensifying farmer-wildlife conflicts, a variety of management regimes were implemented in wintering and stopover areas. With scaring practices such as approaching geese, shining a laser across a field, making loud noises or derogation shooting (i.e. licenced shooting with the purpose to limit damage), geese are chased out of *scaring areas* (agricultural land where grazing birds are unwelcome; Jensen et al., 2008; Koffijberg et al., 2017; Percival et al., 1997; Tombre et al., 2005; Vickery & Summers, 1992). This may be combined with the designation of *refuges*, including nature reserves and *accommodation areas* (agricultural land without purposeful disturbance), with or without compensation payments for goose damages (Baveco et al., 2011, 2017; Cope et al., 2003; Eythorsson et al., 2017; Jensen et al., 2008; Koffijberg et al., 2017).

While both intentional and unintentional disturbance can affect goose distribution (Bechet et al., 2004; Belanger & Bedard, 1989; Percival et al., 1997; Taylor & Kirby, 1990; Tombre et al., 2005; Vickery & Summers, 1992), management through scaring does not always seem to affect field use (Koffijberg et al., 2017; Percival et al., 1997). Frequent scaring during the day seems required to reduce grazing pressures (Simonsen et al., 2016), and scaring without adequate alternative foraging areas is unlikely to result in damage reduction (Jensen et al., 2008; Nilsson, 2017; Vickery & Summers, 1992). Previous studies show that frequent disturbance increases energy expenditures (Nolet et al., 2016) and decreases foraging time during the day (Owens, 1977), resulting in nocturnal feeding to compensate (Belanger & Bedard, 1989; Madsen & Fox, 1995; Riddington et al., 1996). The additional food consumption could result in higher overall damage (Nolet et al., 2016). Furthermore, costs associated with management, such as appraisal costs, costs associated with scaring, or additional compensation payments inside accommodation areas, can make a management scheme expensive (Percival et al., 1997). In the Netherlands, for example, subsidies were offered in addition to damage compensation inside accommodation areas to encourage farmer participation. This likely contributed to a sudden increase in financial costs associated with goose damages (van der Zee et al., 2009). Such costs are rarely taken into account in evaluations (Fox et al., 2017) and require further study (Clausen et al., 2022).

Here, we examine how changes in accommodation area and scaring probability affect foraging behaviour and distribution of barnacle geese (*Branta leucopsis*) foraging on natural and (intensively managed) agricultural grassland while considering various management costs, leading to increased insight into cost-efficient management practices. We focus on the province Friesland, the Netherlands, where around 500,000 barnacle geese overwinter in recent years (Hornman et al., 2021). A combination of accommodation areas and lethal scaring (under permit) are in place to reduce farmer-goose conflicts (Bij12, 2019). Inside accommodation areas, *automatic taxation* takes place: yield loss is assessed on all fields, regardless of whether farmers report it, with an additional subsidy when damages exceed a threshold of 600€ per damaged ha. Compensation payments are also made in the scaring area, but only when farmers report it. Furthermore, the percentage compensated is smaller, and farmers need to show they took measures to chase geese away, potentially in cooperation with local hunters. Costs of scaring are not reimbursed. However, for a fair cost–benefit analysis, these should still be taken into account.

We developed an individual-based model (IBM) in which flocks of barnacle geese (hereafter referred to as goose or geese) forage on grassland in nature, accommodation and scaring areas, and respond to scaring events, leading to estimated grazing pressures (summed goose $\mathrm{h\,ha^{-1}}$) per area type. Different management scenarios were tested, and associated costs of scaring and damage appraisal recorded. We expect that increasing scaring intensity and accommodation area will result in more geese in refuge areas. Spending more time in refuges decreases the likelihood of being scared away, potentially reducing overall grazing pressure. However, if scaring intensifies with little available accommodation area, we expect overall grazing pressure to rise, as geese need to compensate additional flying costs. Furthermore, decreasing grazing pressure may not necessarily lower overall costs if the required management is expensive.

2 | MATERIALS AND METHODS

2.1 | Study area

The model divides the mainland of Friesland, where barnacle geese overwinter between November and half of May, in patches of 100×100m (1ha), resulting in a 700×700 grid. We used 'Basisregistratie gewaspercelen', a map containing information on all fields in the Netherlands, to determine which patches are grassland (Table S1). Using further publicly available maps, these were divided into nature area (12,546 patches), accommodation area (15,533 patches) and scaring areas (139,324 patches; Figure 1; Table S1). Non-grassland patches were divided into roost-sites (7881 patches) and other. At night, barnacle geese aggregate in large numbers to roost on waterbodies. Using hourly GPS-points from tracked barnacle geese (Supporting Information A), we defined roost-sites as locations within a 1km area that were visited during at least four nights (between 00:00–04:00h, local time). The tracking study was approved by the Centrale Commissie Dierproeven under CCD protocol 20173788.

2.2 | The model

We developed a spatially explicit IBM in C++. The model concerns a single species, the barnacle goose, as this species' abundance is highly related to yield loss in Friesland. Below follows a concise description of the IBM; a full account is provided in the ODD in

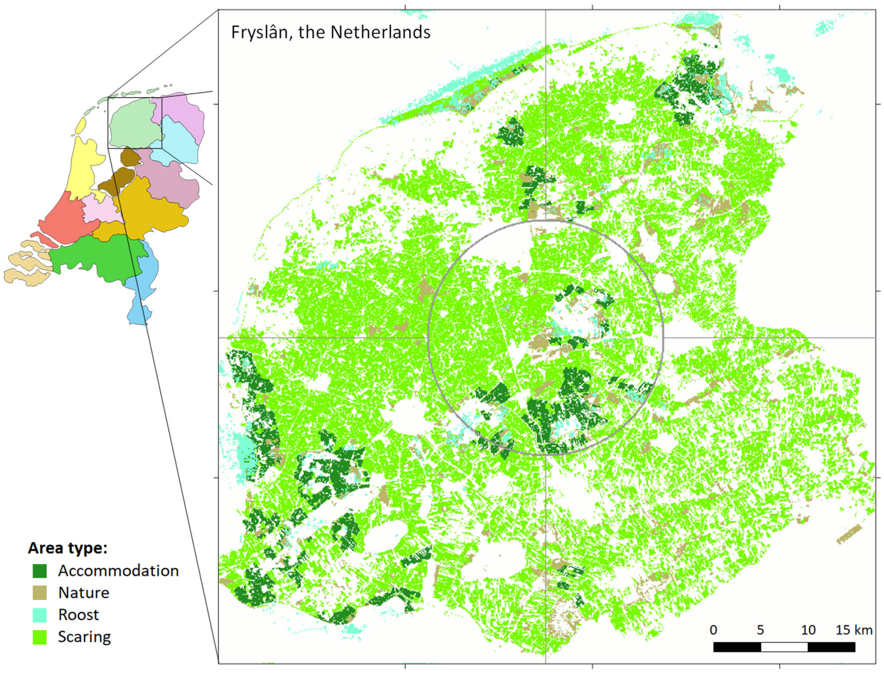

FIGURE 1 The simulated landscape, based on the province Friesland, the Netherlands. Grey lines indicate the different zones (North-East, South-East, South-West, North-West and Centre).

Supporting Information B and the detailed model description in Supporting Information C.

We initialized the spatial distribution of our modelled geese based on roost count estimates collected in 2019 by the Dutch Centre for Field Ornithology (Sovon) under the Dutch National Roost Census (van Els & van Turnhout, 2021). While roost count estimates are incomplete, the counts give a rough indication of the distribution of barnacle geese across the roosts in Friesland. Sovon also provided monthly daytime goose counts covering the whole province (Hornman et al., 2021). These were used to determine the total number of geese present in each month (Figure S1), changing with migratory arrival and departure and peaking in January–February. We divided the geese into flocks of 1000 each and treated these as individuals to speed up simulations.

Flock movements were simulated per hour across 195 days (4680 time-steps), starting at sunrise of November 1st. Foraging and movement behaviour influences goose energy intake and expenditure. If daily energy intake exceeds expenditure, goose weight increases; if intake is less than expenditure, weight decreases. A flock dies when the weight of its geese falls below the lowest observed weight of 1100 g (starting weight = 1750 g; Figure S2). All geese within a single flock are identical and thus have the same weight. Foraging behaviour also reduces grass height at grazed patches (Supporting Information C, equation 18). Each day the grass grows, following Monteith (1977), depending on temperature and solar radiation.

Each time-step, a flock follows the decision tree illustrated in Figure 2. During daylight hours, flocks rest on the spot, if maximum weight (median goose weight estimated from field studies for that date plus 600 g; Figure S2) was reached. If not, they continue foraging. Foraging patches are selected based on memory or at random, depending on memory decay rate (λ), maximum probability to forage on memory (p_{maxM}), and memorized grass heights. To limit memory size, the oldest memory is replaced by the newest one, keeping a constant memory size of 100 locations and their grass heights. A memorized patch is selected based on memory age, the expected energy gain, and the energy required to move there, making it likely that the same patch is used in multiple consecutive time-steps. When foraging randomly, a patch is selected using a composite random walk, consisting of a Brownian (exponential distribution) and a truncated Lévy (bounded Pareto distribution) walk. We included this option to represent explorative behaviour, allowing the discovery of new patches.

During flight to the selected patch, the flock may encounter and join other foraging geese at a patch, depending on the number of geese already present (Supporting Information C, equation 14). After arriving at a patch, flocks choose whether to forage there, or move again, depending on grass height and maximum probability to forage at a patch (p_{maxF}). Additionally, flocks move following disturbances, which occur more frequently in scaring areas. To keep the model simple, memorized grass height for the patch is set to zero after disturbance, making a return in subsequent time-steps less likely.

As barnacle geese have been observed to forage at night (Lameris et al., 2021), we included this possibility when the flock has a lower than expected weight (Figure S2), provided they can rest for at least 8 h, and sufficient moonlight is available (Figure S3). Alternatively, geese roost from sunset to sunrise. Flocks return to the roost-site they used the previous night if this is located within 10 km; otherwise, a random roost-site is chosen, weighted by the distance to the current location.

2.3 | Model calibration

We used parameter values from a previous goose-modelling study (Baveco et al., 2011; Table S2), but added five parameters with

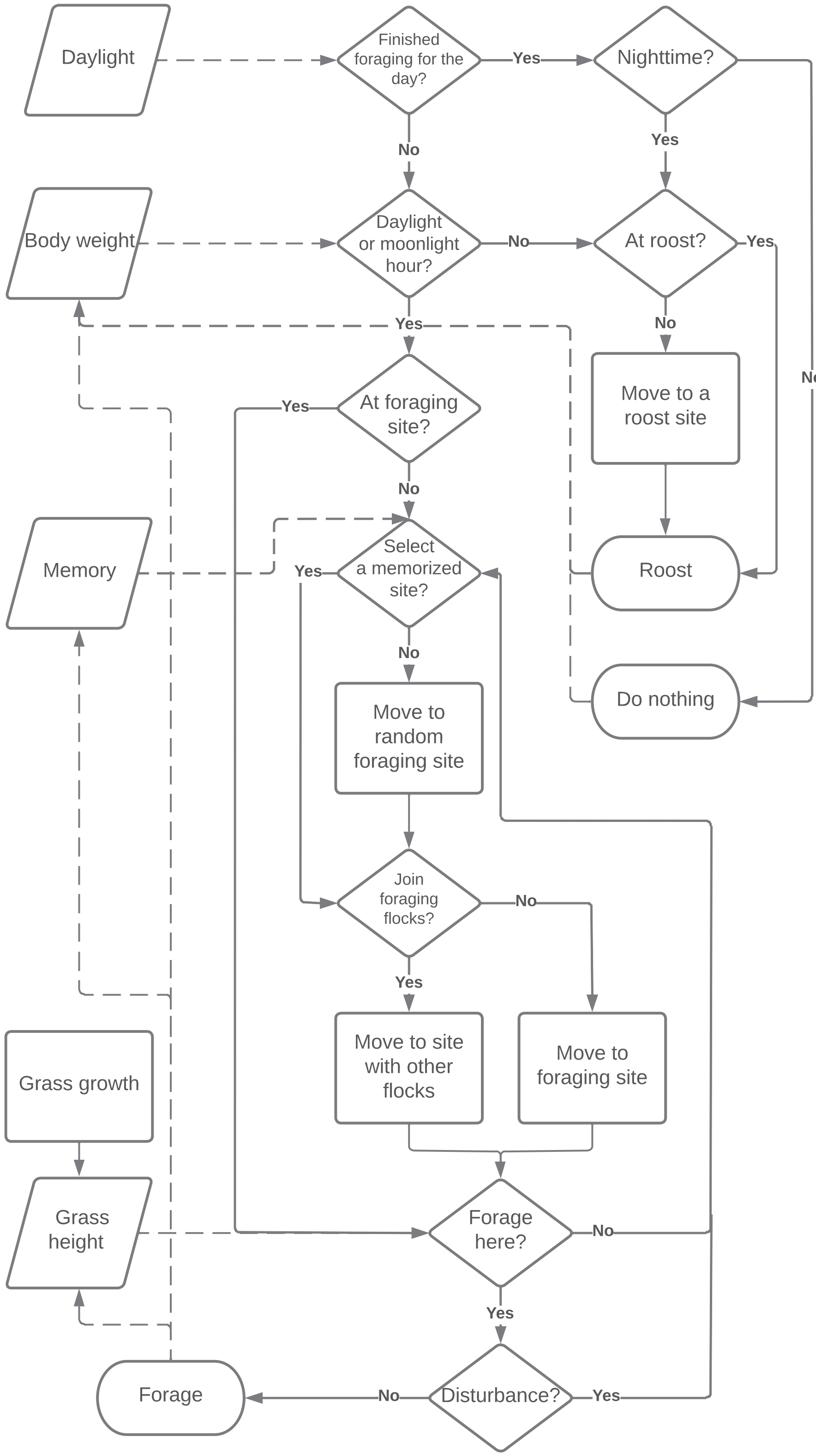

FIGURE 2 Schematic overview of the model. The diamond shapes, parallelograms, rectangles and oval shapes indicate decisions, data, processes and endpoints, respectively.

unknown values: (1) *The decay rate of memory* (λ) determines how the weight of a memorized patch decreases over time (Supporting Information C, equation 9). (2) *The maximum probability to forage on memory* (p_{maxM}) affects the comparative value of memorized patches (Supporting Information C, equation 8). Low values of p_{maxM} result in more random search behaviour, higher values in higher probabilities to forage by memory. (3) *The maximum probability to forage at a patch* (p_{maxF}) affects the probability that flocks will forage at the patch after arriving there (Supporting Information C, equation 6). (4) The *probability of unintentional disturbance* ($p_{disturb}$) gives the chance of a disturbance per time-step for any grassland patch, while (5) probability of intentional scaring

($p_{scaring}$) adds a chance of intentional disturbance in the scaring area.

We estimated these parameters through model calibration, using a full factorial assessment over a wide range of parameter value combinations (Table S3; Thiele et al., 2014). We attempted to find the combination that best fits observed data from GPS-tracked barnacle geese (Supporting Information A), using hourly GPS-points from November 1–May 15 2018/2019 (31 geese) and 2019/2020 (58 geese). During each simulation run, we recorded the hourly locations of 10 flocks. For each GPS-track and simulated flock we calculated: hourly displacement distances (i), total number of visits over the season per 1 ha patch (ii) and per 1 km^2 area (iii), and number of consecutive hours (i.e. visit duration) that a goose/flock has been located within the same 1 ha patch (iv) or 1 km^2 area (v). Both GPS data and model output include time spent at roost sites. We compared observed distributions (Table S4) with model outputs and calculated an average Goodness-of-Fit (GoF) ± SD (de Jager et al., 2019; Thiele et al., 2014; Supporting Information D).

We ran simulations with 14,520 different parameter-value combinations; each combination was run 10 times. Out of the 10 combinations that resulted in the highest overall GoF, we selected the one with the lowest SD (i.e. the one with the least variation between simulation results) as the default setting in all further simulations.

2.4 | Model validation

To verify that the chosen parameter settings result in consistent and reasonable goose foraging behaviour, we ran 100 simulations with the selected parameter value combinations and recorded the percentage of goose hours spent in each area type (nature, accommodation, scaring) and zone (north-east, south-east, south-west, north-west, and centre; Figure 1). We compared this to the percentage of geese counted in each area type or zone during detailed monthly goose counts in Friesland, collected in the winter of 2018/2019 (Hornman et al., 2021). We furthermore compared empirical data on body mass (Figure S2; 1976–2016, Müskens, unpublished; Boom, unpublished; Ebbinge et al. unpublished; Eichhorn et al., 2012; Ens et al., 2008; Lameris, unpublished) with the body mass of the modelled geese from 10 simulation runs.

2.5 | Model simulations

The calibrated model was used to determine how changing accommodation area size and/or scaring probability in scaring areas influences the effect of geese on agricultural grassland. Scaring probability ($p_{scaring}$) was varied between 0 and 0.2 and accommodation area between 1553 and 31,066 ha, representing 1%–20% of agricultural grassland area in Friesland (Figure S4). Which patches were removed or added as accommodation area was based on monthly goose counts from Sovon; the counts were projected on the 700 × 700 patches of the landscape, by calculating the kernel density estimate with a bandwidth of 20 patches (using the kde function of R-package ks, Chacon & Duong, 2018; Figure S5), and preference was given to areas with higher kernel densities. Areas currently assigned as accommodation area were chosen over current scaring areas; nature area was never assigned as accommodation area. Each possible scenario was run 20 times.

Each simulation, we calculated average goose pressure (summed goose h ha^{-1}) per grassland type (nature, accommodation, or scaring area), average grass height (cm), number of patches affected by geese (i.e. having been foraged upon by at least one flock), average goose weight (g), total scaring effort (number of scaring events) and economic damage (i.e. the sum of total yield loss in both accommodation and scaring area (kg dry matter ha^{-1}), scaring costs (million € (M€)), and appraisal costs (M€)). Yield loss was calculated from the difference in grass height (cm) between unaffected grasslands and the focal patch. Following the workflow used in the Netherlands by professional damage assessors to determine yield loss compensation, we multiplied the difference in grass height with 150 kg dry matter cm^{-1} ha^{-1} (to convert to kg dry matter ha^{-1}) and €0.25 (monetary value of 1 kg dry grass; Bij12, 2019). To calculate scaring costs, we recorded the number of scaring events that occurred per simulation. We calculated total damage for a range of scaring costs (€0–€10 per scaring event, based on personal communication), and with two possible approaches to damage appraisal. The first has been the recent practice in Friesland, where appraisal takes place on all patches inside accommodation area, regardless of whether these have been affected by geese, while in the scaring area only affected patches are assessed. In the second approach, damage appraisal only takes place on affected patches, both in accommodation and scaring areas. Given that appraisal costs were approximately €25 ha^{-1} in 2005/2006 and 2006/2007 (van der Zee et al., 2009) and average inflation is c. 1.5% $year^{-1}$, appraisal costs were estimated to be €30 ha^{-1}.

3 | RESULTS

3.1 | Parameterization and validation

Out of the 14,520 different parameter value combinations, for only 3,245 did >80% of the flocks maintain a goose weight of >1100 g in all 10 simulations, which we used as a threshold for population survival. We show the 10 best parameter value combinations (based on their average GoF) in Table S5. We chose the following parameter values for our model: $\lambda = 75$, $p_{maxF} = 1$, $p_{maxM} = 0.95$, $p_{disturb} = 0$ and $p_{scaring} = 0.1$.

We observed that the model is highly stochastic and results in a wide range of goose distributions (Figure 3a, light grey bars). Comparing simulated distributions with those found in the count data (Hornman et al., 2021), we find a similar distribution of geese across nature, accommodation, and scaring areas. The spatial distribution across the different zones also resembles that of the goose count data, except for the north-west and south-west corners of

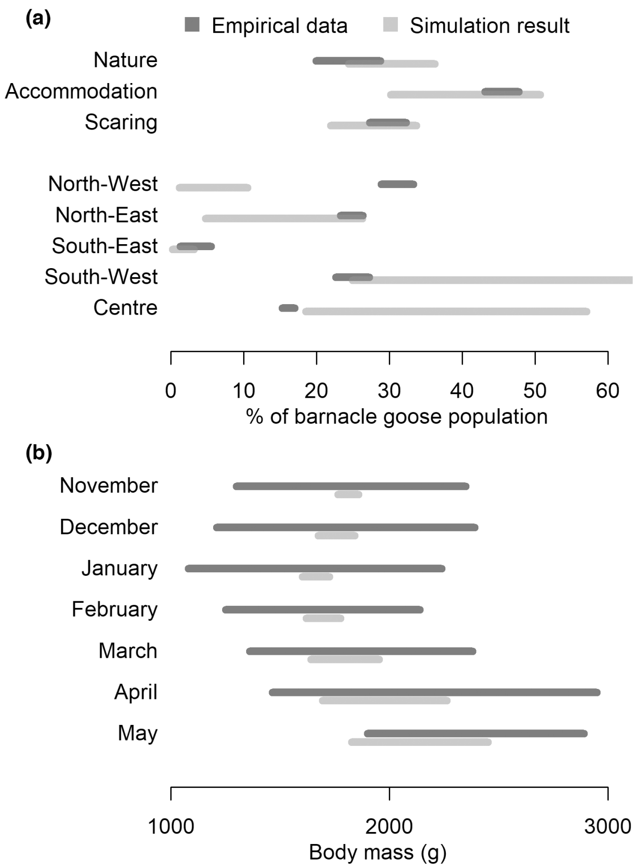

FIGURE 3 Comparison of simulation output and empirical data for (a) spatial barnacle goose distributions (count data: Hornman et al., 2021) and (b) body mass (measurements: 1976–2016, Müskens, unpublished; Boom, unpublished; Ebbinge et al. unpublished; Eichhorn et al., 2012; Ens et al., 2008; Lameris, unpublished). In (a), both count data and simulation output were transformed to percentages of geese present in that area (nature, accommodation, or scaring in top panel, and north-west, north-east, south-east, south-west or centre in bottom panel). Bars represent the entire range of values occurring in the data.

Friesland, where we respectively underestimate and overestimate goose numbers with our model. Variation in body mass is larger in empirical data than in the simulations (Figure 3b); which is due to the initially identical weights in the model. Nevertheless, simulated and empirical body mass follow the same seasonal pattern.

3.2 | Effects of management scenarios

Changing the number of accommodation patches significantly affects simulation results (Figure 4a,c,e). Average goose pressure at agricultural grassland patches (both accommodation and scaring area) increases with total accommodation area (Figure 4a-black), while the fraction of patches affected by geese decreases (Figure 4a-blue). This coincides with fewer occurrences of scaring events (Figure 4c-blue). Average grass height also declines when accommodation area is expanded (Figure S6), resulting in higher yield losses (Figure 4c-black). In scenarios with few accommodation patches, average goose weight is lower than in scenarios with larger numbers of accommodation patches (Figure 4e).

Changing the scaring probability has opposite effects to changing accommodation area (Figure 4b,d,f). Increasing scaring probability leads to a higher fraction of patches affected by geese (Figure 4b-blue) but lowers average grazing pressure (Figure 4b-black), resulting in an overall decrease in yield loss. Scaring effort increases substantially with higher scaring probabilities (Figure 4d-blue), while average goose weight declines (Figure 4f).

Average goose grazing pressure, total yield loss, and average goose weight are all highest with low scaring probabilities and large accommodation areas (Figure 5a,c,d), and lowest when accommodation areas are small and scaring probability is high. The opposite is found for the fraction of patches affected by geese (Figure 5b) and the required scaring effort (Figure 5d).

The two approaches to damage appraisal result in different distributions of the total economic damage (Figures 6 and 7) but both show that, to minimize economic costs, scaring effort should be lower with higher costs per scaring event. The scaring probability of the most cost-effective scenario decreases as costs per scaring event go up, towards no scaring when costs per event exceed €4.91 or €5.18 in case of appraisal approach 1 or 2, respectively. As appraisal of accommodation area increases with its size in the first appraisal approach, all cost-effective scenarios have the smallest simulated accommodation area (1%) here. The number of required scaring events therefore declines with decreasing scaring probability (and subsequently increasing scaring costs). When only patches visited by geese are appraised (approach 2), both in accommodation and scaring areas, we observe a different pattern in the cost-effectiveness of the different management scenarios (Figure 7). Disregarding scaring costs, the most cost-effective management scenarios are found in the upper-right corner of the parameter space, that is when accommodation areas are large and the scaring probability in the leftover scaring areas is high (Figure 7a).

4 | DISCUSSION

Considering a wide range of management scenarios and taking into account yield loss, appraisal costs, and scaring costs, we find that a scenario with intermediate accommodation area and scaring probability, such as currently used in Friesland, may not be most cost-effective. In contrast, with little to no scaring, scaring costs are low while the number of patches affected by geese decreases, thus lowering appraisal costs. Therefore, the best approach may be to prevent scaring altogether, even though yield losses may be higher. In this scenario, accommodation areas lose their function as refuge. However, regions with high goose densities might still function as diversionary feeding ground, and receive certain benefits, such as automatic taxation or additional subsidies, to reduce farmer-herbivore conflict and simplify compensation schemes.

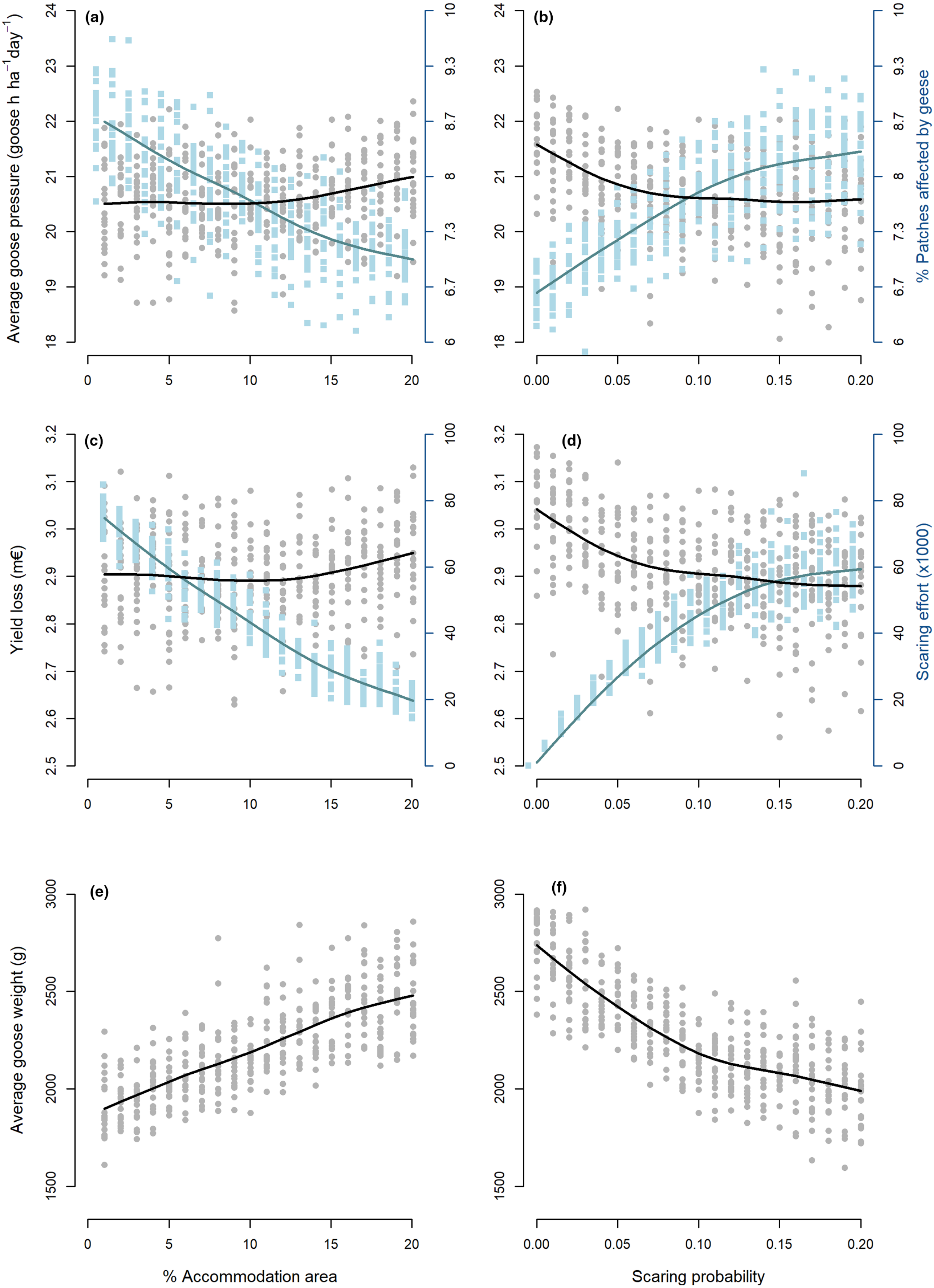

FIGURE 4 The effects of accommodation area size (a, c, e) and scaring probability (b, d, f) on average barnacle goose pressure (black in a, b), fraction of patches affected by barnacle geese (blue in a, b), total yield loss (black in c, d), scaring effort (blue in c, d), and average barnacle goose weight (e, f).

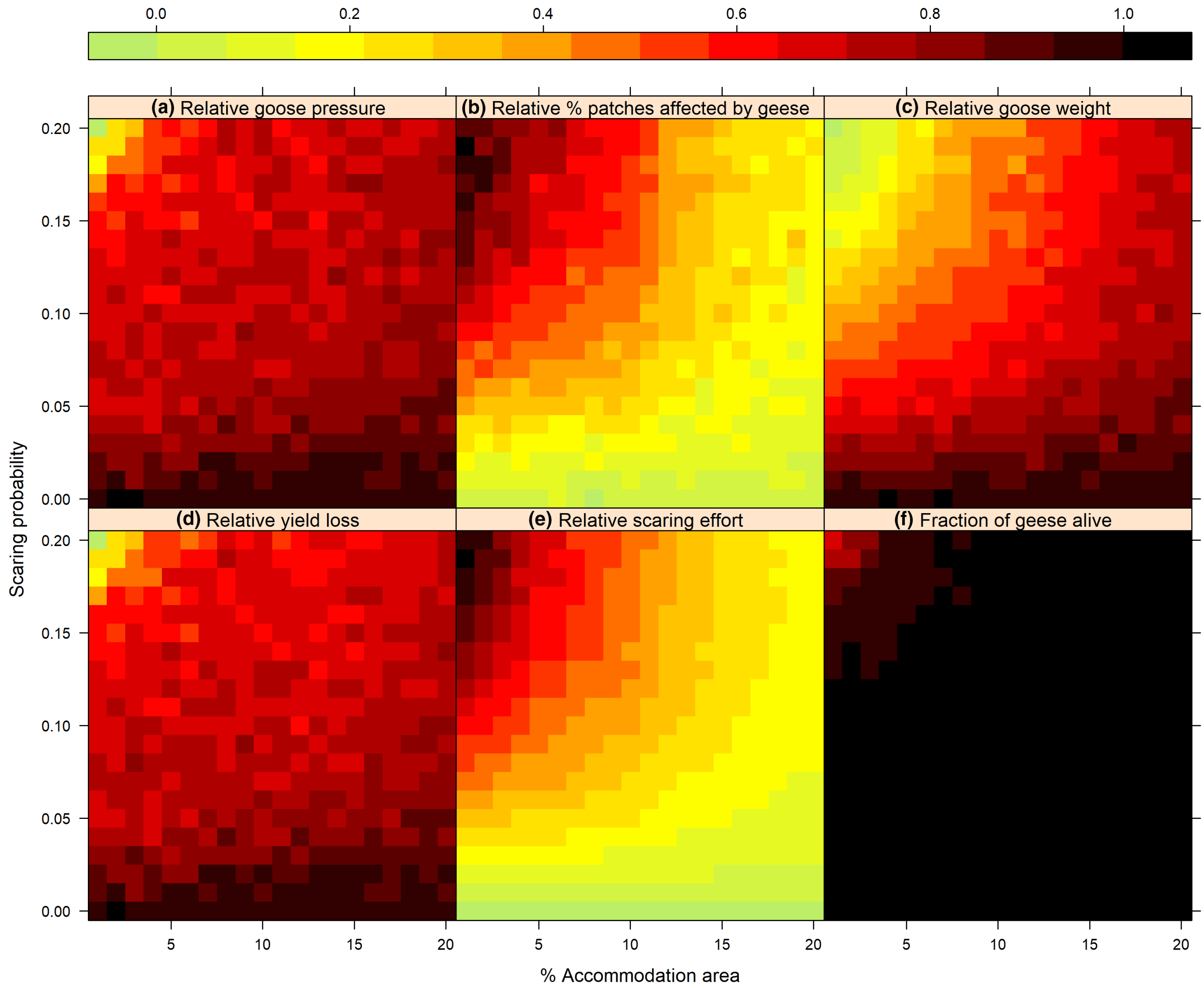

FIGURE 5 Interaction effects of accommodation area size and scaring probability on (a) average barnacle goose pressure (goose $\text{h ha}^{-1}\text{day}^{-1}$), (b) % patches affected by barnacle geese, (c) relative barnacle goose weight (g), (d) relative yield loss (m€), (e) relative scaring effort, and (f) fraction of barnacle geese alive. These are relative averages across 20 simulations, calculated as $(x-\min(x)/(\max(x)-\min(x))$. White squares indicate scenarios with <80% population survival.

Our results indicate that using a high scaring probability as a management tool should always be combined with a large accommodation area. If this is not the case, the model predicts a strong negative impact on goose survival through starvation. Contrary to our expectation, we furthermore found a decrease in grazing pressure under such scenarios. This indicates that modelled geese spend most available daylight and moonlit hours foraging, regardless of scaring probability, leaving no time to compensate the energy and time lost to disturbance. Thus, frequent disturbance prevents geese from foraging enough to maintain their body weight (keeping in mind that geese in our model cannot forage outside Friesland when scared off). Previous studies indeed show that nocturnal feeding may be required regardless of organized scaring (Owens, 1977), to compensate limited daylight in midwinter, or to increase fuelling rates in spring (Boom et al., 2023; Lameris et al., 2021). Furthermore, in other field studies, intensive disturbance was related to lower body mass and reproductive success of geese (Madsen, 1995; Mainguy et al., 2002).

Besides nocturnal foraging, the model did not allow any behavioural changes which might have prevented decreasing body weight, such as decreases in flying time and responsiveness to disturbance (Beale & Monaghan, 2004a; Frid & Dill, 2002). However, the current version of the model also does not include additional costs of disturbance that could have further negative effects on fitness and survival, such as decreased foraging efficiency (Bechet et al., 2004; Belanger & Bedard, 1990) or physiological responses (Beale & Monaghan, 2004b). Since both compensatory mechanisms and additional costs were excluded, we expect that the overall effect on goose survival has not been overestimated. The model also simplifies the memory of disturbance: in reality geese would memorize disturbances, estimate associated predation risk, and weigh this against patch quality and energy requirements.

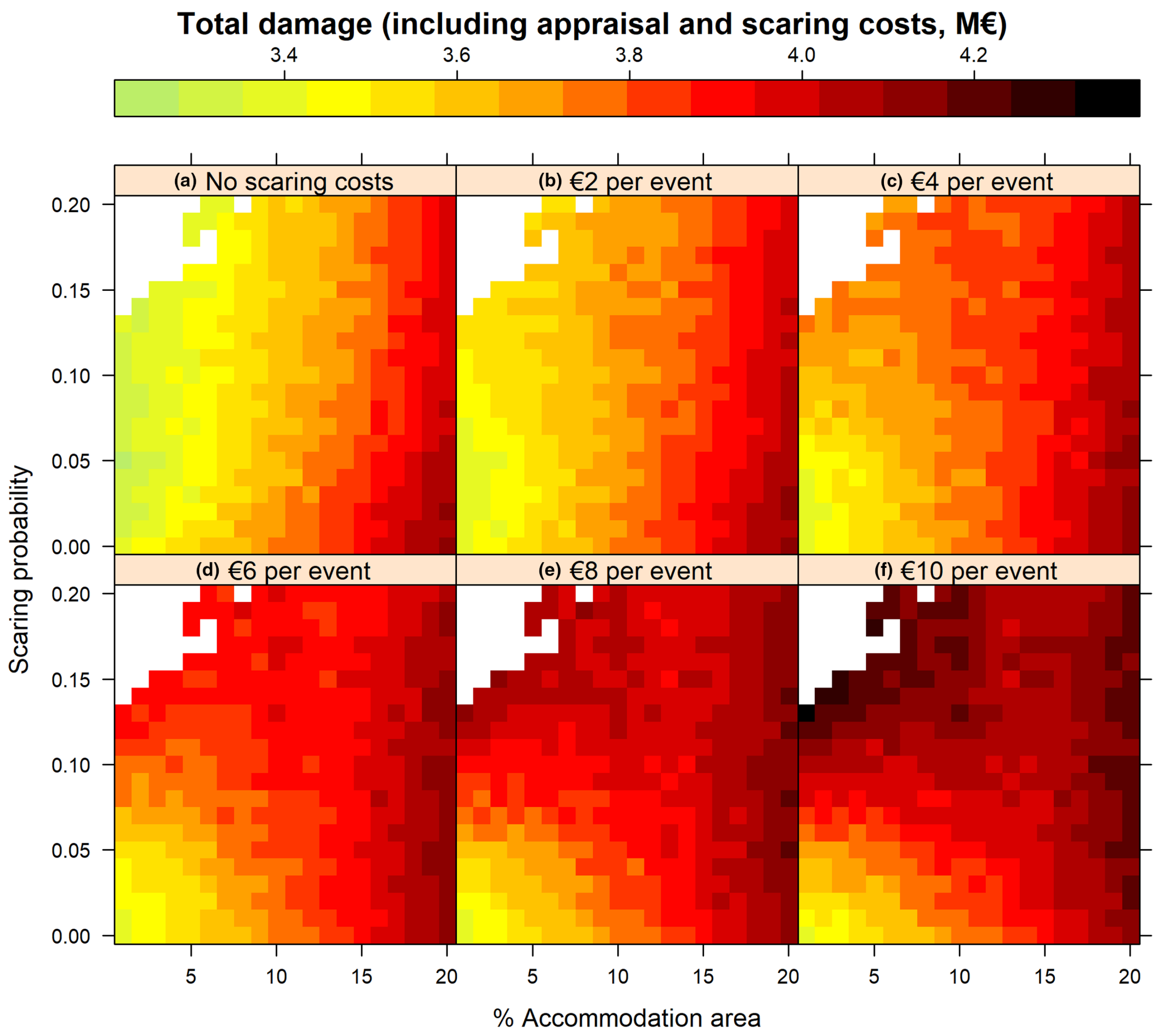

FIGURE 6 Total damage (including appraisal and scaring costs, in M€) with appraisal approach 1 (all patches in accommodation area appraised), for all scenarios with different combinations of accommodation area size and scaring probability in scaring areas, with scaring costs ranging from €0 in (a) to €10 in (f), per event. White squares indicate scenarios with <80% population survival.

When refuge areas are inadequate to support the population, a large part of the population is forced to forage in scaring areas, with negative consequences at population level, as also suggested in other studies (Jensen et al., 2008; Nilsson, 2017). Conversely, geese may leave the region altogether, shifting the problem to neighbouring regions (Bauer et al., 2018). The low relative goose weight found with high scaring probabilities with the current accommodation area size in Friesland (10%) indicates that refuges may be inadequate to support the wintering barnacle goose population. Since several other waterfowl species also winter in Friesland, this could be problematic if scaring intensity is increased. We should note that starvation due to decreased foraging time is the only cause of mortality in the model; direct mortality due to (lethal) scaring has not been included. Overall, our results suggest exercising extreme caution when applying high scaring efforts, ensuring availability of adequate alternative foraging ground.

Combining high scaring probabilities with large accommodation areas can be cost-effective, but the costs of maintaining accommodation areas should be carefully considered. When these costs grow with accommodation area size, they can become quite substantial. In our example, the automatic taxations pose an additional cost of 0.10–0.14 M€ (Figures S7 and S8), which could be even larger considering farmers often report only substantial yield losses (Montras-Janer et al., 2019), leading to fewer appraisals in the absence of automatic taxations. Other possible costs include subsidies to stimulate farmer involvement or organizing and maintenance costs, especially for fields managed as diversionary feeding ground. However, with ample accommodation and limited scaring area,

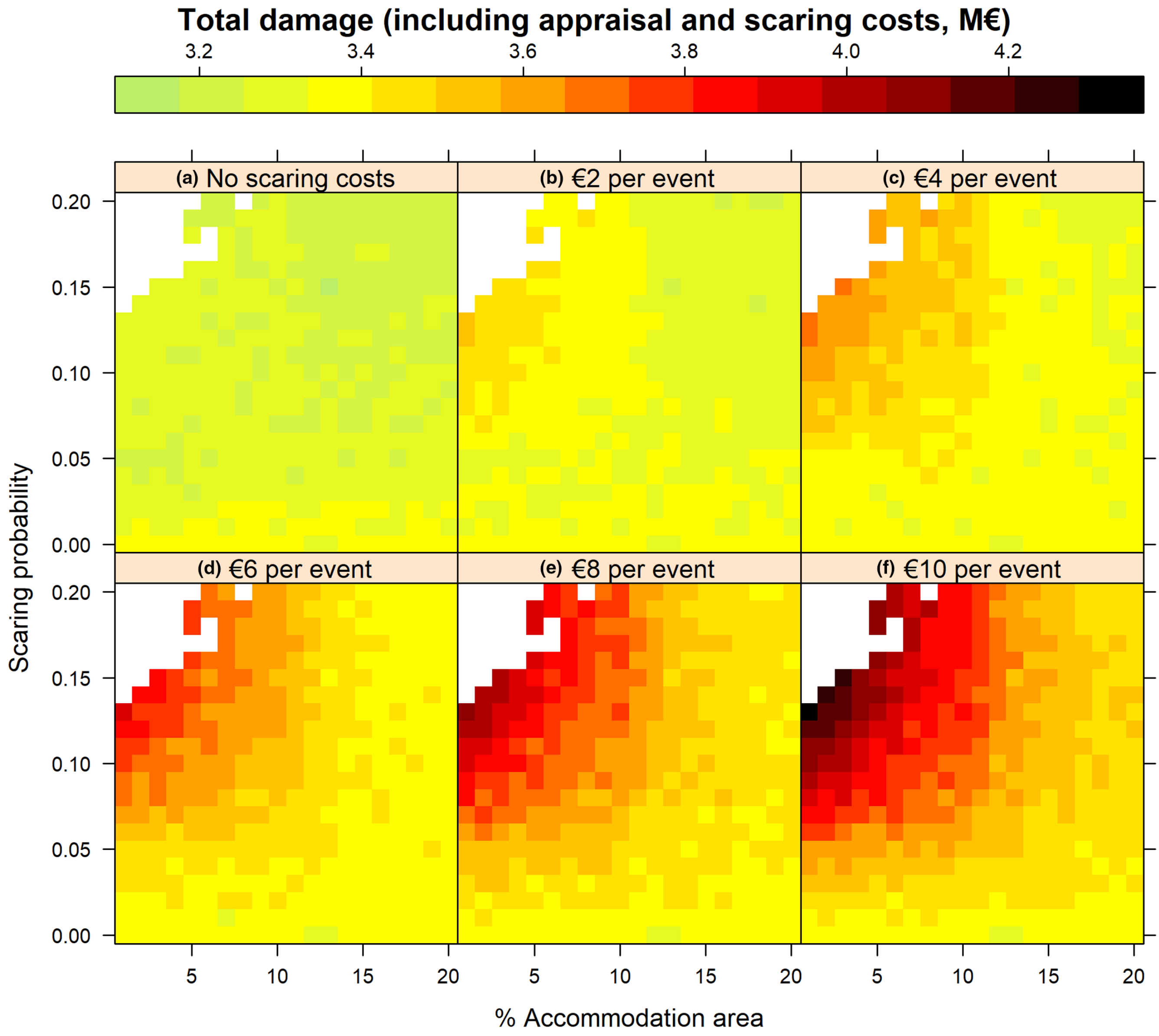

FIGURE 7 Total damage (including appraisal and scaring costs, in M€) with appraisal approach 2 (only affected patches appraised), for all scenarios with different combinations of accommodation area size and scaring probability in scaring areas, with scaring costs ranging from €0 in (a) to €10 in (f), per event. White squares indicate scenarios with <80% population survival.

required scaring efforts remain relatively minor. Thus, a higher price per scaring event is possible with a smaller scaring area without losing cost-effectiveness. This can make it worthwhile to protect areas of particular interest, with valuable or sensitive crops, or higher aircraft collision risks. When economic benefits of protecting an area increase, the cost–benefit ratio also improves. Furthermore, there could be non-economic benefits, like reducing conflict or accidents. However, if scaring probability is inadequate to make geese leave, one risks spreading them across a larger area and increasing overall damage. Thus, careful consideration should be given to feasibility and costs of required scaring probabilities.

Scaring costs differ per technique. Unfortunately, studies on scaring techniques rarely provide details on associated costs or functional lifetime (which decreases with habituation and equipment deterioration), and evidence of scaring efficiency is frequently inconclusive (Buij et al., 2016), making cost–benefit analyses difficult. Animals habituate quickly to predictable disturbances (Steen et al., 2015). For example, they adjust their foraging time accordingly (Bechet et al., 2004; Madsen & Fox, 1995; Owens, 1977), such as greylag geese delaying morning flights to avoid hunters (Bregnballe & Madsen, 2004). A study in Norway found that grazing pressure only decreased with over five daily scaring events (Simonsen et al., 2016). Adaptive scaring devices reduce habituation and simultaneously provide a high scaring probability, by responding to arriving geese (Steen et al., 2015; Stevens et al., 2000). However, cost-effectiveness may be low when the scaring area is large, due to high initial prices and subsequent maintenance costs (Stevens et al., 2000), and long-term studies are needed to ensure geese do not habituate over time.

Scaring can pose high costs, as it is frequently performed by humans, sometimes combined with derogation shooting. In Friesland, (lethal) scaring is usually performed by farmers or volunteering hunters, whose availability may be limited to predictable moments. This practice poses costs in terms of material and time to farmers or hunters. Hiring human scarers can also be costly, estimated at approximately £33.00 to £44.50 ha^{-1} in North Norfolk, UK (Vickery & Summers, 1992), while on Islay, Scotland, such costs exceeded those saved in grassland yield (Percival et al., 1997).

To properly assess benefits of redistributing geese through management, we need a better understanding of how yield loss changes with goose numbers. Several studies suggest grazing may not result in harvest reduction when below a threshold grazing pressure (Bjerke et al., 2021; Olsen et al., 2017). Winter grazing may also have a smaller impact than spring grazing (Fox et al., 2017), with more time available for compensatory growth (Clausen et al., 2022). Furthermore, while yield loss may increase with growing goose numbers, its increase occurs with a decelerating rate for barnacle geese in both Sweden (Montras-Janer et al., 2019) and Friesland (Buitendijk, de Jager, Hornman, et al., 2022). Thus, spreading the same number of geese across a larger area, as found with high scaring probabilities and inadequate accommodation area, could result in larger yield losses.

Natural areas are, both in real life and in our model, important refuge areas for geese. Our model may underestimate the attractions of natural areas in spring. Food quality is assumed to remain constant; however, this actually increases in spring, possibly more strongly in natural habitats (Prins & Ydenberg, 1985). Furthermore, saltmarshes could provide alternative high quality food sources (Dokter et al., 2018). Flight costs are also lower in natural areas, which may be partially due to lower disturbance rates (Pot et al., 2019). With increasing agricultural activity in spring, natural habitats may offer low-gain/low-cost foraging opportunities, leading to habitat switches in some geese (Pot et al., 2019; Prins & Ydenberg, 1985). Together, these factors likely explain the underestimate of geese in the North-West zone by our model (Figure 3). One particular region (Noord-Friesland Bûtendyks), consisting largely of saltmarshes and natural grasslands, is used very intensively according to count data (Figure S5) but primarily in November and March–May.

Our model's current results already provide relevant insights into the conditions under which scaring and accommodation may be a viable management practice. It illustrates that no management may often be most cost-effective, especially considering that the model likely underestimates use of natural areas. However, we did not consider how management changes with population size, and whether continued population growth may influence the most cost-effective option. We have also not addressed the option of active population reduction. While not permissible for the listed barnacle goose, active population management has been applied in non-protected species (Madsen et al., 2017). A future project could run the model with different population sizes or include the effects of direct mortality following scaring events.

The model we created lends itself to many more interesting simulation studies, including the effect on foraging behaviour/efficiency with changing parameters, such as vigilance, population size, or presence of other species. Later versions of the model, which are outside the scope of this paper, will include multiple goose species and their interactions. The model could also be expanded to reflect seasonal changes in food quality, disturbance rates, and movement behaviour, allowing exploration of seasonal changes in distribution This is especially valuable if combined with behavioural changes due to disturbance and weight loss, informing where and when scaring practices might be most efficient and how refuge areas might better attract geese. It might also elucidate the mechanisms behind the relationship between damages and grazing pressure. Further exploration of GPS-data could provide more insight into site fidelity or the effect of buildings, trees, and roads on field use, while accelerometer data might show how behaviour varies with increasing predation risk. Furthermore, by combining tracking data with field studies, as done by Bechet et al. (2004) and Heim et al. (2022), a better understanding may be acquired of return rates and behavioural changes after disturbance.

AUTHOR CONTRIBUTIONS

Monique de Jager, Nelleke H. Buitendijk, Johannes M. Baveco, and Bart A. Nolet conceived research ideas. Monique de Jager developed the model and ran simulations. Nelleke H. Buitendijk and Johannes M. Baveco generated the model landscape. Nelleke H. Buitendijk and Paul van Els collected data. Nelleke H. Buitendijk contributed to model improvement. Bart A. Nolet acquired funding. Monique de Jager and Nelleke H. Buitendijk led writing of the manuscript. All authors discussed model results and contributed critically to the manuscript.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Count data are archived by Sovon, and available upon request. Sovon has an agreement with many volunteers to not make their data publicly available at this level of detail, since it includes detailed locations of wintering geese. Contact details are as follows: menno.hornman@sovon.nl, Dutch Centre For Field Ornithology (Sovon), Toernooiveld 1, 6525 ED Nijmegen, Netherlands. The GPS-tracks are available through Movebank (https://www.movebank.org) in the study "Goose grazing pressure and agricultural damages", published in the Movebank Data Repository found at https://doi.org/10.5441/001/1.fk899541 (Buitendijk, de Jager, Kruckenberg, et al., 2022). These data are embargoed for one year and will become available after November 2023. The source code of the model (C++) and generated datasets are available at Dryad (https://doi.org/10.5061/dryad.sn02v6x8j; de Jager et al., 2023). Datasets used to generate the landscape are publicly available (Table S1).

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REFERENCES

Bauer, S., Lisovski, S., Eikelenboom-Kil, R. J. F. M., Shariati, M., & Nolet, B. A. (2018). Shooting may aggravate rather than alleviate conflicts between migratory geese and agriculture. *Journal of Applied Ecology*, *55*, 2653–2662. https://doi.org/10.1111/1365-2664.13152

Baveco, J. M., Bergjord, A.-K., Bjerke, J. W., Chudzinska, M. E., Pellissier, L., Simonsen, C. E., Madsen, J., Tombre, I. M., & Nolet, B. A. (2017). Combining modelling tools to evaluate a goose management scheme. *Ambio*, *46*, 210–223. https://doi.org/10.1007/s13280-017-0899-5

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

Beale, C. M., & Monaghan, P. (2004a). Behavioural responses to human disturbance: A matter of choice? *Animal Behaviour*, *68*, 1065–1069. https://doi.org/10.1016/j.anbehav.2004.07.002

Beale, C. M., & Monaghan, P. (2004b). Human disturbance: People as predation-free predators? *Journal of Applied Ecology*, *41*, 335–343. https://doi.org/10.1111/j.0021-8901.2004.00900.x

Bechet, A., Giroux, J. F., & Gauthier, G. (2004). The effects of disturbance on behaviour, habitat use and energy of spring staging snow geese. *Journal of Applied Ecology*, *41*, 689–700. https://doi.org/10.1111/j.0021-8901.2004.00928.x

Belanger, L., & Bedard, J. (1989). Responses of staging greater snow geese to human disturbance. *Journal of Wildlife Management*, *53*, 713–719. https://doi.org/10.2307/3809202

Belanger, L., & Bedard, J. (1990). Energetic cost of man-induced disturbance to staging snow geese. *Journal of Wildlife Management*, *54*, 36–41. https://doi.org/10.2307/3808897

Bij12. (2019). *Protocollen en richtlijnen taxaties faunaschade: B. Taxatierichtlijn Graslandschade Voorjaar (Eerste Snede)*.

Bjerke, J. W., Tombre, I. M., Hanssen, M., & Olsen, A. K. B. (2021). Springtime grazing by Arctic-breeding geese reduces first- and second-harvest yields on sub-Arctic agricultural grasslands. *Science of the Total Environment*, *793*, 148619. https://doi.org/10.1016/j.scitotenv.2021.148619

Boom, M. P., Lameris, T. K., Schreven, K. H. T., Buitendijk, N. H., Moonen, S., de Vries, P. P., Zaynagutdinova, E., Nolet, B. A., van der Jeugd, H. P., & Eichhorn, G. (2023). Year-round activity levels reveal diurnal foraging constraints in the annual cycle of migratory and non-migratory barnacle geese. *Oecologia*. https://doi.org/10.1007/s00442-023-05386-x

Bregnballe, T., & Madsen, J. (2004). Tools in waterfowl reserve management: Effects of intermittent hunting adjacent to a shooting-free core area. *Wildlife Biology*, *10*, 261–268.

Buij, R., Lammertsma, D. R., & Melman, T. C. P. (2016). *Effectiviteit Wildschadepreventie: Beoordelingsmethodiek en Literatuurreview*. https://doi.org/10.18174/388768

Buitendijk, N. H., de Jager, M., Hornman, M., Kruckenberg, H., Kölzsch, A., Moonen, S., & Nolet, B. A. (2022). More grazing, more damage? Assessed yield loss on agricultural grassland relates nonlinearly to goose grazing pressure. *Journal of Applied Ecology*, *59*, 2878–2889. https://doi.org/10.1111/1365-2664.14306

Buitendijk, N. H., de Jager, M., Kruckenberg, H., Kölzsch, A., Moonen, S., Müskens, G. J. D. M., & Nolet, B. A. (2022). GPS data from: More grazing, more damage? Assessed yield loss on agricultural grassland relates non-linearly to goose grazing pressure. *Movebank Data Repository*. https://doi.org/10.5441/001/1.fk899541

Chacon, J. E., & Duong, T. (2018). *Multivariate kernel smoothing and its applications*. Chapman & Hall/CRC.

Clausen, K. K., Thorsted, M. D., Pedersen, J., & Madsen, J. (2022). Waterfowl grazing on winter wheat: Quantifying yield loss and compensatory growth. *Agriculture, Ecosystems and Environment*, *332*, 107936. https://doi.org/10.1016/j.agee.2022.107936

Cope, D. R., Pettifor, R. A., Griffin, L. R., & Rowcliffe, J. M. (2003). Integrating farming and wildlife conservation: The barnacle goose management scheme. *Biological Conservation*, *110*, 113–122. https://doi.org/10.1016/S0006-3207(02)00182-9

de Jager, M., Buitendijk, N., Baveco, H., van Els, P., & Nolet, B. (2023). Limiting scaring activities reduces economic costs associated with foraging barnacle geese: Results from an individual-based model. *Dryad, Dataset*. https://doi.org/10.5061/dryad.sn02v6x8j

de Jager, M., Hengeveld, G. M., Mooij, W. M., & Slooten, E. (2019). Modelling the spatial dynamics of Maui dolphins using individual-based models. *Ecological Modelling*, *402*, 59–65. https://doi.org/10.1016/j.ecolmodel.2019.04.009

Dokter, A. M., Fokkema, W., Ebbinge, B. S., Olff, H., van der Jeugd, H. P., & Nolet, B. A. (2018). Agricultural pastures challenge the attractiveness of natural saltmarsh for a migratory goose. *Journal of Applied Ecology*, *55*, 2707–2718. https://doi.org/10.1111/1365-2664.13168

Ebbinge, B. (1991). The impact of hunting on mortality-rates and spatial-distribution of geese wintering in the Western palearctic. *Ardea*, *79*, 197–209.

Eichhorn, G., Meijer, H. A. J., Oosterbeek, K., & Klaassen, M. (2012). Does agricultural food provide a good alternative to a natural diet for body store deposition in geese? *Ecosphere*, *3*, art35. https://doi.org/10.1890/ES11-00316.1

Ens, B. J., Bairlein, F., Camphuysen, C. J., De Boer, P., Exo, K.-M., Gallego, N., Hoye, B. J., Klaassen, R., & Oosterbeek, K. (2008). *SOVON-onderzoeksrapport 2008/10: Tracking of individual birds. Report on WP 3230 (bird tracking sensor characterization) and WP 4130 (sensor adaptation and calibration for bird tracking system) of the FlySafe basic activities project*. SOVON Vogelonderzoek Nederland, Beek-Ubbergen.

Eythorsson, E., Tombre, I. M., & Madsen, J. (2017). Goose management schemes to resolve conflicts with agriculture: Theory, practice and effects. *Ambio*, *46*, 231–240. https://doi.org/10.1007/s13280-016-0884-4

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

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

Frid, A., & Dill, L. (2002). Human-caused disturbance stimuli as a form of predation risk. *Conservation Ecology*, *6*, 11.

Heim, W., Piironen, A., Heim, R. J., Piha, M., Seimoda, T., Forsman, J. T., & Laaksonen, T. (2022). Effects of multiple targeted repelling measures on the behaviour of individually tracked birds in an area of increasing human–wildlife conflict. *Journal of Applied Ecology*, *59*, 3027–3037. https://doi.org/10.1111/1365-2664.14297

Hornman, M., Kavelaars, M., Koffijberg, K., Hustings, F., van Winden, E., van Els, P., & Kleefstra, R. (2021). *Sovon Ganzen-en Zwanenwerkgroup & Soldaat L. Watervogels in Nederland in 2018/2019*. Sovon Rapport 2021/01. RWS–rapport BM 21.08. Sovon Vogelonderzoek Nederland.

Jensen, R. A., Wisz, M. S., & Madsen, J. (2008). Prioritizing refuge sites for migratory geese to alleviate conflicts with agriculture. *Biological Conservation*, *141*, 1806–1818. https://doi.org/10.1016/j.biocon.2008.04.027

Koffijberg, K., Schekkerman, H., van der Jeugd, H., Hornman, M., & van Winden, E. (2017). Responses of wintering geese to the designation of goose foraging areas in The Netherlands. *Ambio*, *46*, 241–250. https://doi.org/10.1007/s13280-016-0885-3

Lameris, T. K., Dokter, A. M., van der Jeugd, H. P., Bouten, W., Koster, J., Sand, S. H. H., Westerduin, C., & Nolet, B. A. (2021). Nocturnal foraging lifts time constraints in winter for migratory geese but hardly speeds up fueling. *Behavioral Ecology*, *32*, 539–552. https://doi.org/10.1093/beheco/araa152

Madsen, J. (1995). Impacts of disturbance on migratory waterfowl. *Ibis*, *137*, S67–S74. https://doi.org/10.1111/j.1474-919X.1995.tb08459.x

Madsen, J., & Fox, A. D. (1995). Impacts of hunting disturbance on waterbirds—A review. *Wildlife Biology*, *1*, 193–207. https://doi.org/10.2981/wlb.1995.0025

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*, 275–289. https://doi.org/10.1007/s13280-016-0888-0

Mainguy, J., Bety, J., Gauthier, G., & Giroux, J. F. (2002). Are body condition and reproductive effort of laying greater snow geese affected by the spring hunt? *The Condor*, *104*, 156–161.

Monteith, J. (1977). Climate and efficiency of crop production in Britain. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *281*, 277–294. https://doi.org/10.1098/rstb.1977.0140

Montras-Janer, T., Knape, J., Nilsson, L., Tombre, I., Part, T., & Mansson, J. (2019). Relating national levels of crop damage to the abundance of large grazing birds: Implications for management. *Journal of Applied Ecology*, *56*, 2286–2297. https://doi.org/10.1111/1365-2664.13457

Nilsson, L. (2017). *Factors affecting field use of large grazing birds*. Department of Ecology, Swedish University of Agricultural Sciences.

Nolet, B. A., Kölzsch, A., Elderenbosch, M., & van Noordwijk, A. J. (2016). Scaring waterfowl as a management tool: How much more do geese forage after disturbance? *Journal of Applied Ecology*, *53*, 1413–1421. https://doi.org/10.1111/1365-2664.12698

Olsen, A. K. B., Bjerke, J. W., & Tombre, I. M. (2017). Yield reductions in agricultural grasslands in Norway after springtime grazing by pink-footed geese. *Journal of Applied Ecology*, *54*, 1836–1846. https://doi.org/10.1111/1365-2664.12914

Owens, N. W. (1977). Responses of wintering Brent geese to human disturbance. *Wild*, *28*, 10.

Percival, S. M., Halpin, Y., & Houston, D. C. (1997). Managing the distribution of barnacle geese on Islay, Scotland, through deliberate human disturbance. *Biological Conservation*, *82*, 273–277. https://doi.org/10.1016/S0006-3207(97)00041-4

Pot, M. T., de Koning, S., Westerduin, C., de Boer, W. F., Shariati, M., & Lameris, T. K. (2019). Wintering geese trade-off energetic gains and costs when switching from agricultural to natural habitats. *Ardea*, *107*, 183–196. https://doi.org/10.5253/arde.v107i2.a6

Prins, H., & Ydenberg, R. (1985). Vegetation growth and a seasonal habitat shift of the barnacle goose (branta-Leucopsis). *Oecologia*, *66*, 122–125. https://doi.org/10.1007/BF00378563

Riddington, R., Hassall, M., Lane, S. J., Turner, P. A., & Walters, R. (1996). The impact of disturbance on the behaviour and energy budgets of Brent geese Branta-b-bernicla. *Bird Study*, *43*, 269–279. https://doi.org/10.1080/00063659609461019

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. *Journal of Applied Ecology*, *53*, 916–924. https://doi.org/10.1111/1365-2664.12604

Steen, K. A., Therkildsen, O. R., Karstoft, H., & Green, O. (2015). An adaptive scaring device. *International Journal of Sustainable Agricultural Management and Informatics*, *1*, 130–141. https://doi.org/10.1504/IJSAMI.2015.070746

Stevens, G. R., Rogue, J., Weber, R., & Clark, L. (2000). Evaluation of a radar-activated, demand-performance bird hazing system. *International Biodeterioration and Biodegradation*, *45*, 129–137. https://doi.org/10.1016/S0964-8305(00)00065-2

Taylor, J., & Kirby, R. (1990). Experimental dispersal of wintering snow and Ross geese. *Wildlife Society Bulletin*, *18*, 312–319.

Thiele, J. C., Kurth, W., & Grimm, V. (2014). Facilitating parameter estimation and sensitivity analysis of agent-based models: A cookbook using NetLogo and R. *Journal of Artificial Societies and Social Simulation*, *17*, 11.

Tombre, I. M., Madsen, J., Tommervik, H., Haugen, K. P., & Eythorsson, E. (2005). Influence of organised scaring on distribution and habitat choice of geese on pastures in Northern Norway. *Agriculture, Ecosystems and Environment*, *111*, 311–320. https://doi.org/10.1016/j.agee.2005.06.007

van der Zee, F. F., Verhoeven, R. H. M., & Melman, D. (2009). *Evaluatie opvangbeleid overwinterende ganzen en smienten (No. 2009/dk120)*. Directie Kennis, Ministerie van Landbouw, Natuur en Voedselkwaliteit, Ede.

van Els, P., & van Turnhout, C. (2021). Communal roost counts in the Netherlands: A summary of 10 years of monitoring. *Bird Census News*, *34*(1), 3–8.

Vickery, J. A., & Summers, R. W. (1992). Cost-effectiveness of scaring Brent geese Branta b. bernicla from fields of arable crops by a human bird scarer. *Crop Protection*, *11*, 480–484. https://doi.org/10.1016/0261-2194(92)90034-3

SUPPORTING INFORMATION

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

Appendix S1. Supplementary methods, tables and figures.

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