Waterfowl grazing on winter wheat: Quantifying yield loss and compensatory growth

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ABSTRACT

Herbivorous waterfowl populations have increasingly adapted to forage on agricultural land and triggered a parallel rise in damage to agricultural crops. Winter wheat (\textit{Triticum aestivum}) is the most commonly reported crop damaged in northern Europe, and farmers increasingly demand management actions to mitigate economic impacts. Here, we apply two parallel approaches (exclosure experiments in undisturbed fields and yield assessments in fields subject to scaring) to quantify the impact of waterfowl grazing on winter wheat yield, crop height and nutrient content. We demonstrate that waterfowl grazing led to a substantial reduction in crop height during winter and early spring, but also that compensatory growth led to no significant effect on crop height at the time of harvest. In terms of grain yield, the effect of waterfowl grazing varied from non-significant to a 6% loss, and on fields subject to scaring, the negative effect of grazing was only significant when grazing continued into spring (the case for 7.6% of the area sampled). In addition, the exclosure experiments indicated that plots grazed both winter and spring had a protein content 9% lower than ungrazed plots. While these figures express an economic loss to the affected farmers, our findings also indicate that substantial economic impacts from grazing waterfowl on winter wheat was rare in our study area. This may also be the case elsewhere in the temperate region, when most waterfowl abandon crop foraging in due time to allow for compensatory growth in late spring, and as long as the early developmental stages survive the early impacts from grazing. A substantial scaring effort had only a limited effect on grain yield loss when fields were grazed during spring, but seemed to prevent damage on fields that were grazed only during winter. Future decision-making in relation to the waterfowl-agriculture conflict may benefit from studies looking in-depth at the costs and benefits associated with scaring efforts.

1. Introduction

Throughout the world, herbivorous waterfowl populations have increasingly adapted to forage on agricultural land (Gauthier et al., 2005; Jia et al., 2016; Fox et al., 2017; Austin et al., 2018; Clausen et al., 2018; Gorosabel et al., 2019). The change in habitat use from natural ecosystems to cultivated fields is driven by a combination of natural habitat loss and energetically favorable crops, and the transition has benefited many species and contributed to growing population numbers (Van Eerden et al., 1996; Abraham et al., 2005; Fox and Abraham, 2017). The convergence by waterfowl on farmland has prompted a parallel rise in reports of damage to agricultural crops (DeGrazio, 1978; Fox and Madsen, 2017; Petkov et al., 2017; Eriksson et al., 2020). The growing conflict has led to a wide array of mitigation measures, including simple scaring by farmers (Vickery and Summers, 1992; Simonsen et al., 2016), the application of lasers to displace geese (Clausen et al., 2019), the use of accommodation areas (Owen, 1977; Koffijberg et al., 2017) and population control (Madsen et al., 2017). In terms of damage, the economic impact of goose grazing differs substantially between different agricultural crops and between seasons (Fox et al., 2017). Grass crops may suffer from a lower available biomass for domestic animals (Clausen et al., 2019; Bjerke et al., 2021), while cereals and oil-seed rape may suffer from lower yields when grazed in early developmental stages (e.g. Summers, 1990; Mckay et al., 1993; Parrott and McKay, 2001).

In response to increasing waterfowl numbers foraging on farmland...
and a growing demand for action among affected farmers, schemes to economically compensate farmers for losses and the use of subsidies to allow geese to forage on farmland have increasingly gained a footing in waterfowl management (e.g. Vickery et al., 1994; Eythórsson et al., 2017). The socio-economic efficiency of such schemes relies on the ability to quantify actual economic impacts from waterfowl grazing – something that may be difficult in light of the many crop types involved, context-specific differences in the extent of damage and conflicting claims of different parties (Van Eerden, 1990; Van Bommel and van der Have, 2010; Koffijberg et al., 2017). As a result, up-to-date quantifications of yield loss of the affected crops is increasingly called for.

In Northern Europe winter-sown cereals, and especially winter wheat (*Triticum aestivum*), is among the most commonly reported crops damaged by grazing waterfowl (Clausen et al., 2020; Montras-Janer et al., 2020). The potential damage arises when waterfowl forage on green plant parts in the young developmental stages that are both high in nutrient content and easy to digest (Fox and Abraham, 2017). In addition, the winter wheat resource is available at a time of year when most other preferred foods are limited or unavailable. Winter wheat is the most commonly grown crop in Europe, and a highly valued and economically important crop in many countries (Eurostat, 2021). The often-mentioned conflict between waterfowl grazing and winter wheat yield therefore likely reflects the crop’s importance to farmers as well as its attraction of herbivorous waterfowl species.

In this paper, we apply two parallel approaches (exclosure experiments in undisturbed fields and yield assessments in fields subject to scaring) to quantify the impact of waterfowl grazing on winter wheat crop height, yield and nutrient content. We compare performance of the

![Fig. 1. Map of the study area showing the fields with exclosures and fields subject to scaring.](image-url)
crop in plots of grazed and ungrazed wheat, both in the absence of scaring activities as well as in a setting of regular and organized scaring of foraging birds. We hypothesized that 1) Waterfowl grazing would have a negative impact on crop height and grain yield of winter wheat, 2) Waterfowl grazing would have a negative impact on protein yield of the winter wheat and 3) Fields subject to scaring on a regular basis would be less affected by waterfowl grazing than fields with no scaring.

2. Methods

2.1. Study area

The study was carried out in Guldborgsund Municipality in Southeast Denmark, covering the two islands Falster and the eastern parts of Lolland (Lat, Long: 54.7, 11.9, Fig. 1). The area supports migrating and wintering populations of a number of waterfowl species, the most numerous being barnacle geese (Branta leucopsis), greylag geese (Anser anser) and whooper swans (Cygnus cygnus). In addition, greater white-fronted geese (Anser albifrons), tundra bean geese (Anser serrirostris), pink-footed geese (Anser brachyrhynchus) and mute swans (Cygnus olor) regularly occur in smaller numbers. The area consists mainly of intensively farmed agricultural land, and the most commonly cultivated crops include winter wheat, barley (Hordeum vulgare), sugar beet (Beta vulgaris), seed grasses (Lolium sp., Festuca sp. and Poa sp.) and oil-seed rape (Brassica napus). Grazing by waterfowl (and especially barnacle geese) is perceived as a big problem by local farmers, prompting local efforts to displace geese from winter wheat fields. It is the region in Denmark with the highest number of applications for licenses to shoot barnacle geese under derogation to protect crops, reflecting the agricultural conflict (Heldbjerg et al., 2022). After years of unorganized scaring by landowners in the area, a joint project on integrated management of barnacle geese was established in the southern parts of the study area in 2019, with the aim of reducing the conflict between waterfowl and agricultural interests (Madsen et al., 2020). As a result, goose numbers, scaring intensity and winter wheat yield have been monitored in close collaboration between farmers, researchers, hunters and NGO’s (https://projects.au.dk/can/integrated-management-barnacle-geese/).

Exclosure experiments took place in the northern part of the area near Vigsnæs (Lat, Long: 54.89, 11.67), while the yield assessments in fields subject to scaring were centered inside the area covered by the project on integrated management in the southern parts (Lat, Long: 54.66, 11.87, Fig. 1). During the study period (2020–2021), there were no extreme weather conditions affecting yield, and both growing seasons can be regarded as suitable for winter wheat. 2020 was slightly warmer than the average, but precipitation was at a normal level in both years.

2.2. Exclosure experiments

To enable an assessment of winter wheat yield loss from unregulated goose grazing in the absence of scaring, exclosure experiments were completed in 2020 and 2021 on four study fields (2 per year), where waterfowl had access to forage on the winter wheat crop without being disturbed. On each of the four fields we established 24 1 × 1 m sampling plots (eight blocks, each with three different treatments): 1) Full exclusion consisting of exclosures preventing access to the crop until May when the geese left the area, 2) Spring exclusion allowing access in autumn and winter, but preventing access to the crop in spring 3) No exclusion, allowing access to the crop all growing season. The distance between individual treatments and between individual blocks was in all cases 5 m, and the order of treatments was randomized within each block. Closed exclosures with a height of 100 cm and a 5 × 10 cm wire mesh were established in either September (full exclusion) or February (spring exclusion, Fig. A1 in Supplementary appendix). Summers (1990) found such exclosures not to affect microclimatic conditions. Treatments without exclosures were marked with a bolt and a small metal disc (3 cm in diameter) placed at ground level in the corner of plots. Development of the winter wheat crop was tracked by measuring the average crop height to the nearest cm using a ruler (based on 10 measurements), which was easily assessed as variation was very little. Assessments took place in late winter (2 – 6 February), late spring (6 – 7 May) and prior to harvest 30 July – 1 August), which reflected the usual time for harvesting in the area. In 2021, monitoring was expanded to include a dropping count to document the presence of geese in the study fields. These were completed by counting all droppings found in a circle with radius = 2 m just outside each block, and later converted to droppings per m². Dropping counts were conducted on a monthly basis from September to May, which should be frequent enough to ensure that no droppings would have dissolved and disappeared between visits (Clau- sen et al., 2019). At the time of harvest, the crop in all sampling plots was harvested by hand and analyzed with respect to grain yield (kg grain, normalized to 15% water), ears per m², protein content (%) and starch content (%). Water, protein and starch were measured with a Near Infrared Transmission (NIT) instrument (FOSS NOVA Infratec). In 2021, one study field was never exploited by geese and therefore excluded in the subsequent analysis described below. In addition, on another field, eight plots were found to be damaged by humans in the summer of 2020. Because of this, at the time of harvest sample size on this field was reduced to four blocks (12 samples) to balance the design. On a third field, one block including a plot with a flattened crop was likewise omitted, leading to a final sample size of seven blocks (21 samples).

2.3. Fields subject to scaring

The assessment of potential effects of waterfowl grazing on winter wheat fields subject to scaring covered 30 fields. All study fields were visited 2 times a day, six days a week (Monday – Saturday) in the period late October – late May, to count and scare the waterfowl present. The scaring of waterfowl followed a clearly defined protocol described by Madsen (2021), where the type of scaring gradually intensified in five levels: 1) No scaring, 2) Passive scaring using flags, bags or dog silhouettes, 3) active scaring by foot, in a vehicle or by means of a handheld laser, 4) acoustic scaring using a shotgun or scare gun and 5) lethal scaring, by shooting birds using either a rifle or a shotgun in connection with decoys and hides (derogation shooting). On Sundays, landowners were responsible for carrying out the scaring according to the protocol. The type of scaring on individual fields was intensified (one step up) whenever a field was exploited by waterfowl on two consecutive days despite the current level of scaring. Eight of the winter wheat study fields were located relatively close to accommodation areas for waterfowl (harvested sugar beet). In order not to displace geese from accommodation areas, scaring on neighboring winter wheat fields was limited to levels 1–3 until the food resource was depleted and the geese had abandoned the adjacent accommodation field. At the end of the experiment the number of fields that had reached a given level of scaring was distributed as follows: 6 fields with no scaring, 2 fields with passive scaring, 7 fields with active scaring, 10 fields with acoustic scaring and 5 fields with lethal scaring. The scaring protocol was part of a project assessing the efficiency of different scaring techniques for displacing birds (Madsen, 2021), and as such not directly related to the current study. However, the standardized scaring with two visits a day on all fields enabled us to quantify the use by waterfowl given a known scaring effort. As such, the conditions were perfect for investigating the effect of regular scaring on winter wheat yield.

For collection of data, each of the study fields was divided into 1 ha polygons using the “Polygon Divider” tool in QGIS (v. 3.4 Madeira). In the middle of each polygon, a circular sampling plot was defined by a GPS position and a diameter of 20 m around the GPS coordinates. Hence, sampling plots were not visible on the field and did not affect foraging birds. Because of the size of polygons, plots near field margins were located on average 50 m from hedgerows, ditches, roads and other elements bordering the fields, which should prevent edge effects when
measuring crop height and yield. A total of 464 sampling plots were defined, and each of these was visited three times in late winter (24 February – 2 March), late spring (27 April – 2 May) and prior to harvest (19 – 23 July), respectively, to assess crop height and occurrence of waterfowl grazing. Of all the randomly defined plots, one was omitted from the analysis due to flooding and a very low and damaged crop. Data collection was carried out using Aarhus University’s online platform www.fugledata.dk operated on iPads in the field, ensuring that measurements were taken exactly at the location of previously defined plots with an accuracy of few meters. The average crop height was measured to the nearest cm near the center of each plot using a ruler, based on three random measurements. Signs of grazing was assessed by means of a simple yes/no evaluation based on the presence/absence of bitten wheat plants inside each plot, and in most cases the assessment of whether a crop was grazed or not was straightforward (see Fig. A2 in Supplementary appendix). Based on the presence of bitten crops we defined three types of grazing histories: None (no signs of grazing in any of the visits), only winter (plots that had only been grazed at the first visit in late winter) and winter + spring (plots that had been grazed at both visits in late winter and late spring). No grazing was observed after the second visit, and all plots that had been grazed in spring during the second assessment had also been grazed during winter as assessed at the first visit. Hence, the situation that grazing only took place in spring did not occur in any plots in our data set. Given that we had one plot per ha across all fields, the proportion of fields grazed between individual assessments was calculated as: Number of plots with signs of grazing / total number of plots.

In the analysis of yield, the 463 sampling plots were too many to harvest by hand, and instead we made use of data from the grain yield monitors of combine harvesters operating the study fields. Yield monitors incorporate data from a yield sensor with a global positioning system (GPS) to monitor yield as a function of location on small spatial scales, and is generally a very reliable way to estimate grain yield (for details, see Arslan and Colvin, 2002). Data on winter wheat yield (in metric tonnes/ha) were obtained from a total of 368 plots covering 23 fields, either by extracting yield values from digital yield map files in a GIS, using the individual sampling plots as a mask (243 plots, Fig. A3 in Supplementary appendix), or by manually assessing the yield when passing individual sampling plots during harvest (125 plots). In the latter case, the operator of the harvester was equipped with a digital map on an iPad, showing him/her when the plots were harvested, which enabled him/her to note down yield measurements when the harvester passed. In some occasions, parts of a sampling plot were situated near tractor tracks and well covers, or harvested with less than full header width, and when such deviating measurements occurred (often resulting in less than half the value of the surrounding measurements) they were omitted after visual inspection of the data. All the removed values were obvious local artefacts of less than optimal harvest (e.g. tracks of tractor and well covers) harvested with less than full header width.

Statistical analysis

The effect of waterfowl grazing on winter wheat crop height and yield was evaluated using general linear modeling. For the exclosure experiment, response variables included three measures of crop height (in late winter, late spring and prior to harvest), grain yield, no. of ears, protein content (%) and starch content (%). As explanatory variables we included treatment (full exclosure, spring exclosure and no exclosure), field (representing the three study fields to account for differences between fields) and block (indicating the eight blocks of treatments on individual fields). As blocks were nested within fields this was treated as a nested variable. For the 2021 data with dropping counts available, an additional model was fitted to investigate the potential relationship between yield loss (full exclosure - no exclosure) and the number of droppings counted in connection with each block.

On the fields subject to scaring, the response variables included three measures of crop height (in late winter, late spring and prior to harvest) and grain yield. As explanatory variables, we included grazing history (none, only winter and winter + spring) and field. Because crop height and yield can vary considerably among fields due to other factors than goose grazing, “field” was included as a factor to account for this variation. This allowed us to investigate the effect of different grazing histories once the among-field variation was accounted for. Comparing grain yield and crop height between the fields limited to scaring levels 1–3 (those located close to accommodation areas) and the fields with all types of scaring available showed no significant differences (t-tests with p > 0.517). Hence, the fields close to accommodation areas were maintained in the analyzes.

To investigate the potential effect of differences in grazing pressure across the individual fields subject to scaring (the geographical level with data on waterfowl numbers), we defined a variable indicating waterfowl exploitation, by calculating the number of birds counted (and scared) per ha of field. Birds would usually be foraging on the fields when scaring took place, so these counts should reflect the exploitation of waterfowl on individual fields. In doing so, a “bird” was defined as a barnacle goose (the smallest and most numerous species), and the contribution of other waterfowl species scaled according to their basal metabolic rate (greylag goose = 1.45 barnacle goose, whooper swan = 2.88 barnacle goose, Ballesteros et al., 2018). We then fitted general linear models relating average vegetation height and average yield of individual fields to the number of waterfowl per ha of field. Please note that in this analysis, contrary to the analyzes described above, among-field variation not related to goose grazing could not be accounted for as waterfowl counts were only available on the level of individual fields. In the models of vegetation heights in late winter and late spring, only birds counted prior to these measurements were included in the explanatory variable. For all models, the residuals did not deviate from the assumptions of normal distribution and homoscedasticity, which was evaluated by means of Shapiro-Wilk tests (Shapiro and Wilk, 1965) and plots of residuals vs. predicted values. Statistical analysis and graphical representations were conducted in JMP 14.0.0 (SAS Institute Inc., 2018) and R 4.1.0 (R Core Team, 2021), and based on our hypothesis stating a negative impacts of waterfowl grazing on crop height, grain yield and protein content, one-tailed t-tests were used when conducting pairwise comparisons between the different grazing histories. Given the small number of hypothesis tests on single data sets (between 1 and 3) no adjustments for multiple testing was considered.

3. Results

3.1. Exclosure experiments

In 2021, when waterfowl exploitation of an experimental field was monitored by counting droppings, these revealed that birds were mainly present in the period October – March (Fig. 2). The monthly dropping counts in the 12.57 m² circles varied between 0 and 57, and grazing was observed in all eight blocks. In both years, only barnacle geese were observed on the fields with exclosures during visits, and although no droppings were counted in the plots after mid-March (maybe partly due to difficulties detecting droppings in an increasingly higher crop), smaller numbers of barnacle geese were observed on the field until early May. While we have no data on droppings to assess the use of fields with exclosures in 2020, the proportional differences in vegetation height between no exclosure and full exclusion in late spring (when grazing had ceased) was similar across the three fields (0.69, 0.62 and 0.69, respectively). This indicated that the level of exploitation by waterfowl on the three fields with exclosure experiments was at least comparable.

In late winter, wheat crop height was significantly lower in grazed plots (no exclusion and spring exclusion) compared to the control
In late spring, similar and significant differences were still apparent, and the spring exclusion treatment showed an intermediate crop height ($N = 72, F_{2,46} = 124.28, p < 0.001, \text{Fig. 3}$). Prior to harvest, all differences in crop height between treatments had disappeared ($N = 72, F_{2,46} = 0.38, p = 0.687, \text{Fig. 3}$). Grain yield varied between treatments ($N = 57, F_{2,36} = 3.71, p = 0.034$), and was highest in the ungrazed plots (Table 1). As evident from the partitioned sum of squares (Table 1), the proportion of the total variation in the model explained by the differences across fields ($\approx 71\%$) was much higher than that explained by the different grazing treatments ($\approx 3\%$). Pairwise t-tests between the three levels of treatment indicated that compared to the control (full exclusion), spring exclusion had a significantly lower yield while no exclusion was not significantly lower. Least square means indicated a reduction in grain yield up to 6% (Table 1), and there was no significant difference between the "no exclusion" and "spring exclusion" treatments ($N = 57, t = 1.13, p = 0.266$). We found no differences in the number of ears per m$^2$ ($N = 57, F_{2,36} = 0.521, p = 0.598$), but both protein content ($N = 57, F_{2,36} = 24.35, p < 0.001$) and starch content ($N = 57, F_{2,36} = 14.15, p < 0.001$) varied across treatments. Protein content was significantly lower (and starch content significantly higher) in plots with no exclusion of geese compared to the other treatments (Table 1). The reduction in protein content of plots with no exclusion was approximately 9% (Table 1). Across the blocks from 2021 with data on goose droppings, there was no significant relationship between the number of droppings counted and the grain yield loss ($N = 8, t = 1.19, p = 0.281$), probably reflecting that all plots were heavily grazed.

Fig. 2. The cumulative number of goose droppings counted monthly (numbers per m$^2$) in eight blocks in an experimental field with exclosure experiments during the period September 2020 to May 2021. Different symbols indicate different blocks and the solid line the average across blocks.

Fig. 3. Average crop height of winter wheat in the three different treatments of the exclosure experiments (full exclusion, spring exclusion and no exclusion) at the three assessments in late winter, late spring and prior to harvest, respectively. Error bars indicate the 95% confidence limits.

Table 1

| Factor                     | Sum of squares | F-ratio | P-value  |
|----------------------------|----------------|---------|----------|
| Grazing history            | 0.045          | 3.713   | 0.034    |
| Field                      | 1.013          | 83.699  | < 0.001  |
| Block                      | 0.177          | 1.825   | 0.067    |
| Level                      | Estimate       | SE      | Pairwise test |
| Grain yield (kg/m$^2$)     |                |         |          |
| Full exclusion             | 1.194          | 0.018   |          |
| Spring exclusion           | 1.126          | 0.018   | 0.005    |
| No exclusion               | 1.154          | 0.018   | 0.061    |
| Protein content (% of dry matter) |            |         |          |
| Full exclusion             | 10.331         | 0.106   |          |
| Spring exclusion           | 10.167         | 0.106   | 0.138    |
| No exclusion               | 9.367          | 0.106   | < 0.001  |
| Starch content (% of dry matter) |            |         |          |
| Full exclusion             | 71.750         | 0.087   |          |
| Spring exclusion           | 71.776         | 0.087   | 0.586    |
| No exclusion               | 72.318         | 0.087   | < 0.001  |
### 3.2. Fields subject to scaring

In the fields subject to scaring, waterfowl were present from October until mid-March, after which the number of counted and scared birds decreased (Fig. 4). Of all the waterfowl observed on the fields, barnacle geese accounted for 88%, other geese (mainly greylag geese, but also pink-footed goose, greater white-fronted goose and bean goose) for 11% and whooper swans for 1%. Across all fields, 39.3% of plots were never grazed, 53.1% were grazed only in winter and 7.6% were grazed both winter and spring. The exploitation of individual fields (measured as the total sum of scared waterfowl per ha) from October to May) varied between 0 and 990 birds (barnacle goose equivalents) per ha, with an average ± SD of 362 ± 316.

At the first assessment of crop height in late winter, grazed plots had a significantly lower crop height than ungrazed plots (N = 463, F_{1,432} = 342.86, p < 0.001, Fig. 5). At the second assessment in late spring, crop height was highest in ungrazed plots, intermediate in plots grazed only winter and lowest in plots grazed both winter and spring (N = 463, F_{2,431} = 56.91, p < 0.001, Fig. 5). At the assessment prior to harvest, there were no differences in crop height between the three types of grazing histories (N = 463, F_{2,431} = 0.89, p = 0.411, Fig. 5). In the overall general model, grain yield did not differ significantly between plots with no grazing, plots with grazing only in winter and plots with grazing in both winter and spring (N = 368, F_{2,343} = 1.39, p = 0.251, Table 2). Again, differences among fields explained almost the entire variation in the model (≈ 73%), while differences between the three types of grazing histories explained very little (≈ 0.2%, Table 2).

Nonetheless, one-tailed pairwise comparisons between the three grazing histories indicated that plots grazed both winter and spring had lower yields than plots that were never grazed (Table 2). The reduction in grain yield was approximately 5% (Table 2).

Across individual fields, the number of scared birds per ha was significantly related to average vegetation height in late winter (N = 30, t = −4.22, p < 0.001), but this relationship had disappeared by late spring (N = 30, t = −1.42, p = 0.166). In addition, the average grain yield of individual fields was not related to the amount of scared waterfowl when compared across the level of individual fields (N = 23, t = 1.67, p = 0.110).

### 4. Discussion

In this study we included two different approaches to measure grazing impacts (exclosure experiments and large-scale yield data) analyzed with the same approach (assessing the differences between grazing histories when the variation among fields was accounted for). Both of these approaches showed that waterfowl grazing led to reductions in crop height of affected winter wheat fields during winter and spring, and this effect was evident even for the fields with scaring of grazing waterfowl two times a day. Despite the clear differences early in the season, no significant effect of grazing on crop height was found at the time of harvest in any of the experiments. These findings suggest that with respect to plant height, the winter wheat crop is capable of full compensatory growth after waterfowl grazing, at least when meteorological conditions are right and grazing ceases early in spring. In our study area most waterfowl had left the area by April, allowing for four months of undisturbed growth prior to harvest. When looking at grain yield, the effect of undisturbed grazing (the exclosure experiment) ranged between non-significant and a 6% reduction in yield. This approach was somewhat hampered by small sample sizes owing to the difficulties (and economic costs) associated with establishing undisturbed conditions on productive farmland. While this may question the generality of the exclosure approach, we have no reason to believe that these fields should not be representative of the study area. Nonetheless, the fact that grazing impact was highest in plots with spring exclusion, and insignificant (but with a similar trend) in plots with no exclusion of geese, may reflect limitations associated with the small sample size. The effect of waterfowl grazing on the fields subject to scaring ranged between non-significant (on fields grazed only in winter) and losses of 5% (fields grazed both winter and spring). In both types of experiments, the effect of grazing on grain yield was borderline significant, signifying the lack of a clear negative effect of waterfowl grazing. Nonetheless, trends were identical in all of our analyzes, indicating a small negative effect. Collectively, our studies highlight that waterfowl grazing may not always significantly affect grain yield, and that even prolonged exploitation may only lead to one-digit proportional losses. With no apparent effect of grazing on the number of ears present in the crop, this yield loss may be explained by fewer kernels per ear or a reduction in kernel mass (Summers, 1990).

Given 2021 local prices of wheat grain (≈ 201.70 euros per metric t), and the largest impact on yield measured in our study (0.68 metric t/ha, cf. Table 1), the maximum economic loss from unregulated waterfowl grazing (no exclosure and no scaring) amounted to: 0.68 * 201.70 ≈ 137 euros per ha. Naturally, this loss should only be related to the parts of fields that were actually grazed. Based on our study fields with regular scaring and one sampling plot per ha, 53.1% of the area of fields were grazed in winter and 7.6% were grazed both winter and spring. While there may of course always be examples of more extreme grazing events leading to higher economic losses, these findings suggest that given the conditions in our study area, substantial economic impacts from grazing waterfowl are rare. This may in part be due to the fact that the majority of barnacle geese (the most numerous species) switch to salt marshes and fresh meadows during spring (Madsen et al., 2022), and that many birds leave the area in due time (approx. four months before harvest) for the crops to recover and compensate for the damage early on. This probably relates to a decrease in palatability (in terms of nitrogen and digestibility) of the winter wheat crop as growth increase (Justes et al., 1994), and a preference for natural marshes during spring, which are rare in the area.

The results from the 30 fields with scaring of waterfowl indicated that the negative effect of grazing was limited to crops being grazed both winter and spring, which may indicate that recurrent grazing after the spring growth of winter wheat kicks in may be of special concern. The exclosure experiment did not obviously support this, but as no droppings were found in the plots with exclosures after mid-March, this may hamper the interpretation of impacts from grazing in late spring on these fields. The fact that all plots grazed in spring had previously been grazed.
During winter, indicated that re-growth of previously bitten crops was more sought-after than a higher ungrazed and well-developed crop (Drent and van der Wal, 1999).

Among previous studies on the effect of waterfowl grazing on winter wheat yield, Parrott and McKay (2001) found that grazing by mute swans (Cygnus olor) in late winter/early spring had no effect on grain yield. Summers (1990) found a 6 – 10% reduction in yield (after a 75% reduction in biomass over winter) on fields grazed by brent geese (Branta bernicla) and Petkov et al. (2017) demonstrated reductions in wheat yield ranging from 0% to 13% after grazing by mixed flocks of goose during winter. Collectively, these studies indicate that the effect of waterfowl grazing on winter wheat is likely to vary as a result of local conditions such as waterfowl numbers, soil quality, timing of grazing, developmental stage of crops and local weather (for an extensive review see Fox et al., 2017). Uprooting of crops by geese might lead to substantial economic impacts due to the need for re-sowing (Petkov et al., 2017), but no examples of uprooting were seen in our studies. In some areas, grazing of the early developmental stages of wheat is practiced in order to fraternize the crop resulting in more shoots from the same seed (Virgona et al., 2006). While this could potentially counterbalance other negative effects on grain yield, the lack of an effect of grazing on the number of ears per m² does not support this as significant in our enclosure experiment.

Due to differences in the type of data assessing the level of waterfowl grazing (droppings and counts, respectively), we cannot directly compare the intensity of grazing on fields with exclosures and fields subject to scaring. However, dropping counts from the study area in 2019 (Madsen et al., 2020 and unpubl. data), revealed that dropping densities in that year varied from 6.28 to 13.13 droppings per m², and, consequently, it seems reasonable to assume that they were representative of highly exploited fields in the study area. Previously published dropping densities in studies of goose grazing on winter wheat by Summers (1990) and Petkov et al. (2017) vary between 1 and 23 droppings per m² (mean ± SD: 11.2 ± 8.4), but it should be noted that high-end figures in this interval generally relates to the morphologically smaller brent goose.

In addition to the effect on grain yield, we also found a reduction in protein content of the harvested grain crop in our enclosure experiments. The higher content of starch in the grains from grazed plots should be seen in connection with this, so that grain with a lower content of protein contain additional starch instead. In our study area, the vast majority of the produced wheat is used for pig feed, and although the reduction in protein and increase in starch may give an equal overall energy content of the food, the lower content of protein will need to be compensated by soy meal or other protein in order to ensure optimal pig forage. As a result, the decrease in protein content reflects an additional (albeit small) cost to local farmers. Protein content has rarely been studied in relation to damage from waterfowl, but Summers (1990) looked at differences in nitrogen content of the grain in grazed and ungrazed plots and did not find a significant difference.

When comparing the effect of “field” with the effect of “grazing history” in both experiments, it was clear that the effect of waterfowl grazing was almost negligible in comparison to the among-field differences related to variation in soil quality, water content etc., which accounted for 71% and 73% of the variation in our models, respectively. The large proportion of variation explained by differences between individual fields (that were not related to goose grazing), was likely the explanation that no significant association was found in the simple relationship between waterfowl counts and average yield across individual fields. The variation in yield among individual fields was simply much larger than the relatively small effect of grazing, and this highlights the importance of accounting for among-field variation when assessing damage from waterfowl grazing. The drivers of among-field differences cannot be fully accounted for, but differences in soil types and distance to the coast are known to be important in the area. In addition, different management practices of individual farmers may play a role. In terms of partitioning the variation in yield between different fields and different grazing histories, the substantial explanatory power of “field” may be somewhat confounded with a potential effect of different combines. For instance, calibration of the different combines may vary between farmers, and hence fields, which may affect

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Table 2

| Factor                     | Sum of squares | F-ratio | P-value |
|----------------------------|----------------|---------|---------|
| Grazing history            | 2.553          | 1.388   | 0.251   |
| Field                      | 942.627        | 46.596  | < 0.001 |
| Grazing history            |                |         |         |
| No grazing                 | 10.087         | 0.103   |         |
| Grazed winter              | 9.966          | 0.077   | 0.185   |
| Grazed winter and spring   | 9.583          | 0.264   | 0.049   |

Fig. 5. Average crop height of winter wheat in plots with three different grazing histories (no grazing, grazed only in winter and grazed both winter and spring) in the fields subject to scaring, at three assessments in late winter, late spring and prior to harvest, respectively. Please note that for the assessment in late winter only two histories are possible as this took place prior to spring. Error bars indicate the 95% confidence limits.
the variation explained by the variable “field” in our data from fields subject to scaring. Nonetheless, the same result was found in the enclosure experiments that were harvested by hand. Furthermore, different calibrations between combines were unlikely to lead to a bias in the effect of grazing. Minor variations in harvesting efficiency (e.g., harvesting with less than 100% header width due to the presence of tractor tracks) were probably too small to be detected as obvious artefacts when inspecting the data visually and could hence not be accounted for. This may have led to an increase in variation of the grain yield data, but should not result in biases when assessing the effect of grazing from waterfowl.

The fact that we found similar effects of grazing on crop height and grain yield in enclosure experiments and the fields subject to scaring, indicate that well-organized scaring two times a day was insufficient to prevent waterfowl grazing. A similar lack of an effect of scaring on yield was described by Summers (1990). Nonetheless, scaring might have played a role in limiting the effect of winter grazing, as we found no yield reduction on fields subject to scaring that were grazed only in winter, despite a negative effect of this in the enclosure experiments. While the organized scaring could potentially have led to waterfowl leaving the study area earlier than they would have done otherwise, this seems unlikely as the timing of declining waterfowl numbers was the same in previous years with no coordinated scaring efforts (Madsen et al., 2020). Finally, we cannot completely rule out that the presence of the enclosures on the undisturbed fields might have had an impact on waterfowl grazing within blocks, which could have led to a less than full exploitation of these plots. However, when visiting these fields, grazing was evident right up to the wire mesh. This indicated that a potential scaring effect of the enclosures was minor.

In terms of damage from waterfowl grazing, Simonsen et al. (2017) described that farmers’ perception of the problem with waterfowl grazing often does not match the scale of the problem. In continuation of this, prior to our study many of the landowners involved expressed that the economic losses were “substantial”, but were positively surprised. However, the effect of waterfowl grazing may be higher in years with unfavorable growing conditions, and some farmers stated that a few years back the impact (in terms of damage to crops) seemed to be higher. In the area with fields subject to scaring, this may partly be attributed to the lack of accommodation areas in previous years. At the time of this study, such accommodation areas had been established and could play a role in reducing damage (Madsen et al., 2020). Given the relatively minor effect of the considerable scaring scheme documented in this study, future decision making in relation to scaring efforts may benefit from studies looking in-depth at costs and benefits associated with such efforts. Especially given the premise that birds subject to scaring may need to forage more to balance the added energetic costs of frequent flights (Nolet et al., 2016). When waterfowl grazing leads to an immediate decline in biomass of a valuable resource (often the case with grass), the presence of these birds can lead to immediate economic losses (Clausen et al., 2019; Bjørke et al., 2021). In the case of winter wheat, however, and especially in temperate areas where waterfowl leave the crop prior to the main period of spring growth, substantial economic losses from waterfowl grazing might be relatively rare. We urge further studies to quantify how yield might be affected by waterfowl grazing under different climatic conditions, preferably targeting specifically how differences in temporal exploitation of waterfowl may affect the economic value of the winter wheat crop.

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.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2022.107936.

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